FORTRAN PROGRAMS FOR

CHEMICAL PROCESS DESIGN, ANALYSIS, AND SIMULATION

A. Kayode Coker

Fortran Programs for Chemical Process Design, Analysis, and Simulation

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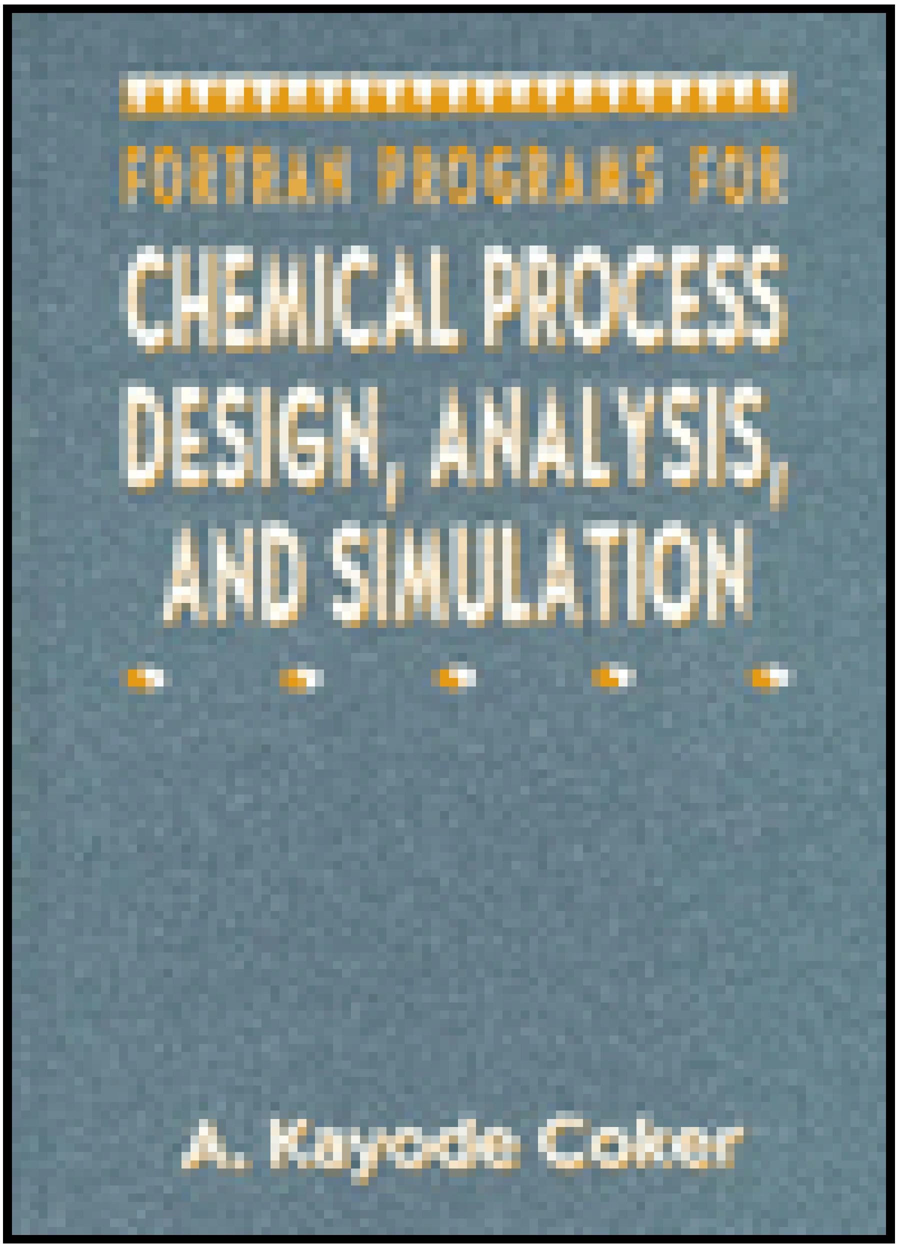

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A. Kayode Coker

Preface

The increased use of personal computers by engineers has greatly revolutionized and expedited the design of process plants and equipment in the chemical process industries. In addition, the availability of expensive flowsheeting packages has reduced to some extent the requirement of programming languages. However, situations often occur where either a package is not readily available, too expensive, or of a limited scope, and the design problem lies beyond the boundary of the flowsheeting packages. The designer is often required to review other alternatives or develop his or her own specific program for the application. This requirement is even more necessary when personal computers are used. A textbook analyzing the fundamental theory with equations, tables, and figures is not readily available to the designer.

My aim in writing this text is to present fundamental theory, along with computer programs, to solve a wide range of design problems. This text will provide consultants, designers, technologists, and practicing process engineers with structured programs that can be used to solve a wide range of process engineering problems and thus analyze and optimize process equipment on a regular basis. This book will also serve as a guide to practicing engineers and chemical engineering students who are interested in applying mathematical modeling and computer techniques to solve problems in process plant operations. This book is unique in that adequate information (theory, equations, figures, and tables) is provided to enable the reader to perform either hand calculations or to write alternative programs.

FORTRAN is still recognized as the most versatile programming language, even forty years after its introduction. It is a powerful general purpose language specially suited to complex, scientific, mathematical, engineering, and financial algorithms. The earlier versions of the

FORTRAN language (FORTRAN IV, F66) could only be used on large mainframe systems that accepted programs in batch. Turnaround was slow; interaction was nil. The availability of microcomputers (IBM personal computers or compatible) has made it easier for numerical techniques, simulation, and design problems to be developed. Computer software can now be used interactively on such systems.

This book is unique in that to date no textbook on chemical process deign and simulation using microcomputers and the FORTRAN programming language has been published. FORTRAN 90 is a major development of the FORTRAN language and includes all the computer programs in this text as a subset. To assist the user and to demonstrate the validity of the methods, worked examples of practical industrial relevance are provided throughout the text.

A listing of all the programs is presented in the book, and source codes for these programs are provided on a floppy diskette. A FORTRAN compiler is required to compile and run these source codes. A menu driven software program for calculating the pressure drop of incompressible single-phase fluids (PIPECAL) is provided in Chapter 3.

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CHAPTER 1

Numerical Computation

INTRODUCTION

Engineers, technologists, and scientists have employed numerical methods of analysis to solve a wide range of steady and transient problems. The fundamentals are essential in the basic operations of curve fitting, approximation, interpolation, numerical solutions of simultaneous linear and nonlinear equations, numerical differentiation and integration. These requirements are greater when new processes are designed. Engineers also need theoretical information and data from published works to construct mathematical models that simulate new processes. Developing mathematical models with personal computers sometimes involves experimental programs to obtain the required information for the models. Developing an experimental program is strongly dependent on the knowledge of the process with theory, where the whole modification can be produced by some form of mathematical models or regression analyses. Figure 1-1 shows the relationship between mathematical modeling and regression analysis.

Texts [1-5] with computer programs and sometimes with supplied software are now available for scientists and engineers. They must fit a function or functions to measure data that fluctuate, which result from random error of measurement. If the number of data points equals the order of the polynomial plus one, we can exactly fit a polynomial to the data points. Fitting a function to a set of data requires more data than the order of a polynomial. The accuracy of the fitted curve depends on the large number of experimental data. In this chapter, we will develop

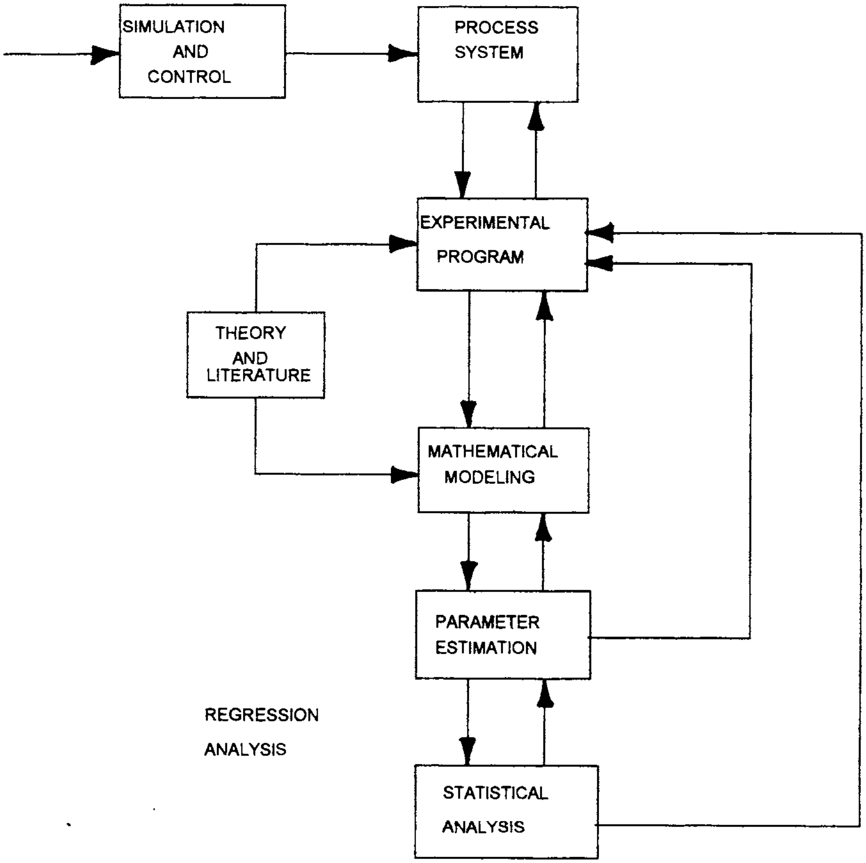


Figure 1-1. Mathematical modeling and regression analysis. By permission, A. Constantinides, *Applied Numerical Methods With Personal Computers,* McGraw-Hill Book Co., 1987.

least-squares curve fitting programs. Also, we will use linear regression analyses to develop statistical relationships involving two or more variables. The most common type of relation is a linear function. By transforming nonlinear functions, many functional relations are made linear.

For the program, we will correlate X-Y data for the following equations:

$$Y = a + bX \qquad (1\text{-}1)$$

$$Y = a + bX^2 \qquad (1\text{-}2)$$

$$Y = a + b/X \qquad (1\text{-}3)$$

$$Y = a + bX^{0.5} \tag{1-4}$$

$$Y = aX^{b} \tag{1-5}$$

$$Y = ae^{bX} \tag{1-6}$$

$$Y = a + b \log X \tag{1-7}$$

$$Y = a + be^{x} \tag{1-8}$$

We can transform the nonlinear equations (1-5, 1-6, and 1-8) by linearizing as follows:

$$Y = aX^{b} \qquad \ln Y = \ln a + b \ln X \tag{1-9}$$

$$Y = ae^{bX} \qquad \ln Y = \ln a + bX \tag{1-10}$$

$$Y = a + be^{x} \qquad \ln Y = \ln a + (\ln b)X \tag{1-11}$$

LINEAR REGRESSION ANALYSIS

Regression analysis uses statistical and mathematical methods to analyze experimental data and to fit mathematical models to these data. We can solve for the unknown parameters after fitting the model to the data. Suppose we want to find a linear function that involves paired observations on two variables, X the independent variable and Y the dependent variable. Where

n = the number of observations
X_i = the ith observation of the independent variable
Y_i = the ith observation of the dependent variable

We can develop a linear regression model that expresses Y as a function of X. We can further derive formulae to determine the values of a and b that give the best fit of the equations. For each experimental point corresponding to an X-Y pair, there will be an element that represents the difference between the corresponding calculated value $\hat{Y}$ and the original value of Y. This is expressed as:

$$r_i = \hat{Y}_i - Y \tag{1-12}$$

r_i may be either positive or negative depending on the side of the fitted curve of X-Y points. Here, we can minimize the sum of the squares of the residuals by the following expression:

$$SRS = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} \zeta_i^2 = \text{minimum} \tag{1-13}$$

where

n is the number of observations of X-Y points

$$\hat{Y}_i = a + bX_i \tag{1-14}$$

$$r_i = a + bX_i - Y_i \tag{1-15}$$

and

$$SRS = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} (a + bX_i - Y_i)^2 \tag{1-16}$$

The problem is reduced to finding the values of a and b so that the summation of Equation 1-16 is minimized. We can obtain this by taking the partial derivative of Equation 1-16 with respect to each variable a and b and set the result to zero.

$$\frac{\partial \sum r_i^2}{\partial a} = 0 \quad \text{and} \quad \frac{\partial \sum r_i^2}{\partial b} = 0 \tag{1-17}$$

Substituting Equation 1-16 into Equation 1-17, we obtain

$$\frac{\partial \sum (a + bX_i - Y_i)^2}{\partial a} = 0 \tag{1-18}$$

and

$$\frac{\partial \sum (a + bX_i - Y_i)^2}{\partial b} = 0 \tag{1-19}$$

This is equivalent to

$$\frac{2\sum (a + bX_i - Y_i)\partial \sum (a + bX_i - Y_i)}{\partial a} = 0 \tag{1-20}$$

and

(1-21)

Since b, X, and Y are not functions of a, and the partial derivative of a with respect to itself is unity, Equation 1-20 reduces to

$$\sum a + \sum bX_i = \sum Y_i \tag{1-22}$$

Similarly, a, X, and Y are not functions of b. Therefore, Equation 1-21 becomes

$$\sum aX_i + \sum bX_i^2 = \sum X_iY_i \tag{1-23}$$

where a and b are constants. Equations 1-18 and 1-19 are expressed as:

$$an + b\sum X_i = \sum Y_i \tag{1-24}$$

and

$$a\sum X_i + b\sum X_i^2 = \sum X_iY_i \tag{1-25}$$

We have now reduced the problem of finding a straight line through a set of X – Y data points to one of solving two simultaneous equations 1-24 and 1-25. Both equations are linear in X, Y, and n, and the unknowns a and b. Using Cramer's rule for the simultaneous equations, we have

$$a = \frac{\begin{vmatrix} \sum Y_i & \sum X_i \\ \sum X_iY_i & \sum X_i^2 \end{vmatrix}}{\begin{vmatrix} n & \sum X_i \\ \sum X_i & \sum X_i^2 \end{vmatrix}} \tag{1-26}$$

and

$$b = \frac{\begin{vmatrix} n & \sum Y_i \\ \sum X_i & \sum X_iY_i \end{vmatrix}}{\begin{vmatrix} n & \sum X_i \\ \sum X_i & \sum X_i^2 \end{vmatrix}} \tag{1-27}$$

Solving Equations 1-26 and 1-27 gives

$$a = \frac{\sum X_i^2 \sum Y_i - \sum X_i \sum X_i Y_i}{n \sum X_i^2 - \sum X_i \sum X_i} \tag{1-28}$$

and

$$b = \frac{n \sum X_i Y_i - \sum X_i \sum Y_i}{n \sum X_i^2 - \sum X_i \sum X_i} \tag{1-29}$$

respectively, where all the sums are taken over all experimental observations.

Also, we can construct a table with columns headed X_i, Y_i, X_i^2, $X_i Y_i$ as an alternative to obtain the values of a and b. The sums of the columns will then give all the values required to Equations 1-28 and 1-29.

METHODS FOR MEASURING REGRESSION

Linear Regression

From the values of a, b, and X_i, the independent variable, we can now calculate the corresponding estimated value of Y, designated as $\hat{Y}_i$.

$$\hat{Y}_i = a + b.X_i \tag{1-30}$$

Figure 1-2 illustrates this equation known as the regression line. The variation of the observed Y's about the mean of the observed Y's is the total sum of squares, and can be expressed as:

$$SST = \sum (Y_i - \overline{Y})^2 \tag{1-31}$$

where

$$\overline{Y} = \frac{\sum Y_i}{N} \tag{1-32}$$

Figure 1-3 shows the differences between Y and $\overline{Y}$, which is the total sum of squares. This is the sum of these squared differences. The total sum of squares can be expressed as:

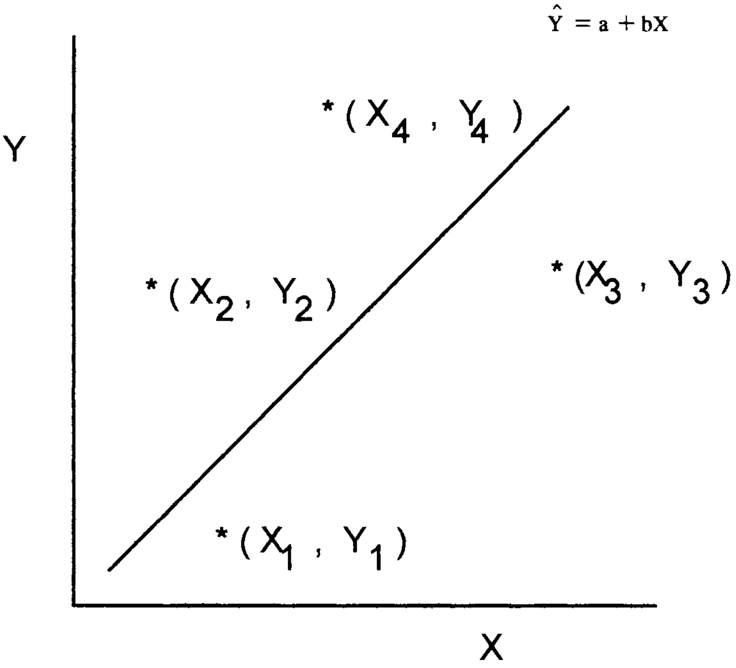


Figure 1-2. Regression line.

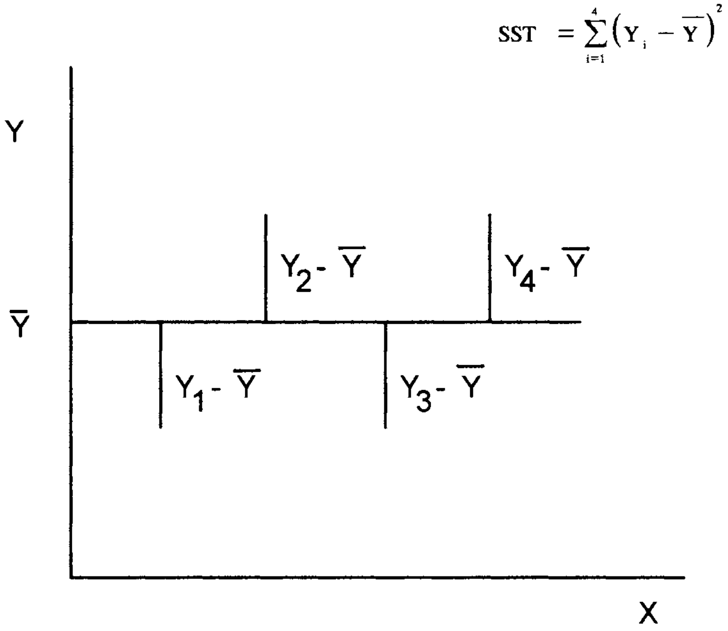


Figure 1-3. Total sum of squares.

$$\mathrm{SST} = \sum (Y_i - \overline{Y})^2 \tag{1-33}$$

$$= \sum \left[(Y_i - \hat{Y}_i) + (\hat{Y}_i - \overline{Y})\right]^2 \tag{1-34}$$

$$= \sum (Y_i - \hat{Y}_i)^2 + 2\sum (Y_i - \hat{Y}_i)(\hat{Y}_i - \overline{Y})$$

$$+ \sum (\hat{Y}_i - \overline{Y})^2 \tag{1-35}$$

and since

$$2\sum (Y_i - \hat{Y}_i)(\hat{Y}_i - \overline{Y}) = 0$$

then

$$\mathrm{SST} = \sum (Y_i - \hat{Y}_i)^2 + \sum (\hat{Y}_i - \overline{Y})^2 \tag{1-36}$$

$$= \mathrm{SSE} + \mathrm{SSR}$$

where

$$\mathrm{SSE} = \sum (Y_i - \hat{Y}_i)^2 \tag{1-37}$$

and

$$\mathrm{SSR} = \sum (\hat{Y}_i - \overline{Y})^2 \tag{1-38}$$

SSE is the error (or residual) sum of squares. This is the quantity represented by Equation 1-13, that is, the equation we want to minimize. It is the sum of the differences squared between the observed Y's and the estimated (or computed) $\hat{Y}$'s. Figure 1-4 shows the differences between the Y's and $\hat{Y}$'s. SSR is the regression sum of squares and measures the variation of the estimated values, $\hat{Y}$, about the mean of the observed Y's and $\overline{Y}$. Figure 1-5 shows the differences between Y's and $\overline{Y}$. The regression sum of squares is the sum of the squared differences.

The ratio of the regression sum of squares to the total sum of squares is used in calculating the coefficient of determination. This shows how well a regression line fits the observed data. The coefficient of determination is:

$$SSE = \sum_{i=1}^{4}\left(Y_i - \hat{Y}_i\right)^2$$

$$\hat{Y} = a + bX$$

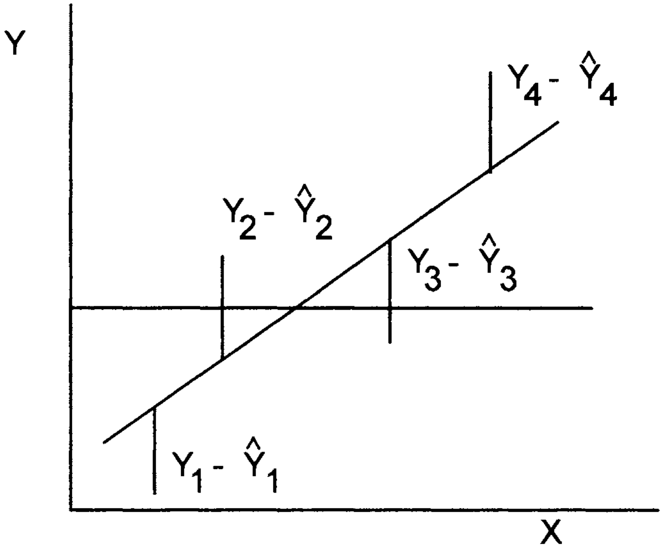


Figure 1-4. Error sum of squares.

$$SSR = \sum_{i=1}^{4}\left(\hat{Y}_i - \overline{Y}\right)^2 \qquad \hat{Y} = a + bX$$

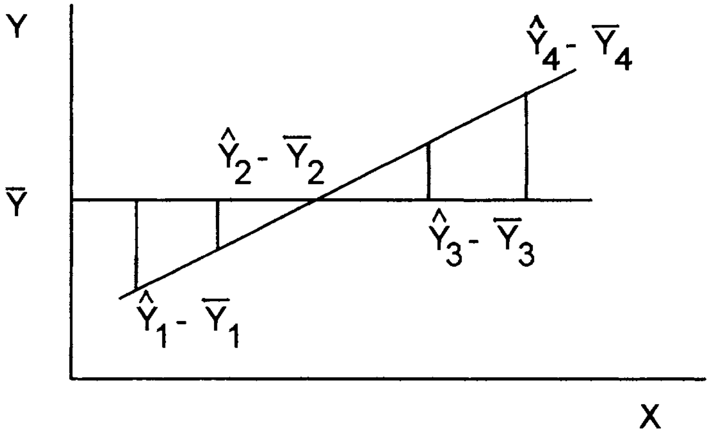


Figure 1-5. Regression sum of squares.

$$r^2 = \frac{SSR}{SST} \qquad (1\text{-}39)$$

and since SSR = SST – SSE

$$r^2 = 1 - \frac{SSE}{SST} \qquad (1\text{-}40)$$

The coefficient of determination has the following properties:

1. $0 \le r^2 \le 1$
2. If $r^2 = 1$ all ξ_i are zero. The observed Y's and the estimated $\hat{Y}$'s are the same and this indicates a perfect fit.
3. If $r^2 = 0$, no linear functional relationship exists.
4. As r^2 approaches one, the better the fit. The closer r^2 approaches zero, the worse the fit. The correlation coefficient r is:

$$r = \left(1 - \frac{SSE}{SST}\right)^{0.5} \qquad (1\text{-}41)$$

Although the correlation coefficient gives a measure of the accuracy of fit, we should treat this method of analysis with great caution. Because r is close to one does not always mean that the fit is necessarily good. It is possible to obtain a high value of r when the underlying relationship between X and Y is not even linear. Draper and Smith [6] provide an excellent guidance of assessing results of linear regression.

THE ANALYSIS OF VARIANCE TABLE FOR LINEAR REGRESSION

Each sum of squares SSR, SSE, and SST corresponds to many degrees of freedom. This is the number of observations, n minus the number of independent quantities. The error sum of squares SSE has N-2 degrees of freedom since

$$SSE = \sum (Y_i - \hat{Y}_i)^2$$

and

$$\hat{Y} = a + b.X$$

then

$$SSE = \sum [Y_i - (a + bX_i)]^2 \tag{1-42}$$

where a and b represent two independent quantities calculated from a set of N observations giving the error sum of squares N-2 degrees of freedom.

The error mean squares, MSE, is an estimate of the variance of the error of observation, ξ, and is:

$$MSE = \frac{SSE}{N - 2} \tag{1-43}$$

The number of degrees of freedom for the total sums of squares SST is N-1 since

$$SST = \sum (Y_i - \overline{Y}_i)^2$$

$\overline{Y}$ represents a quantity from a set of N observations. This gives the total sum of squares N-1 degrees of freedom. The total mean squares, MST, is an estimate of the variance of the dependent variable Y and is:

$$MST = \frac{SST}{N - 1} \tag{1-44}$$

The regression sum of squares, SSR, has one degree of freedom. Since

$$\begin{aligned} SSR &= SST - SSE \\ &= (N - 1) - (N - 2) \\ &= 1 \end{aligned}$$

The regression mean squares, MSR, is an estimate of the variance of the estimates, $\hat{Y}$, and since the regression sum of squares has one degree of freedom, the regression mean squares is

$$MSR = SSR \tag{1-45}$$

Table 1-1 shows the variance table for linear regression.

The test statistics for linear regression is:

$$F = \frac{MSR}{MSE} \tag{1-46}$$

Table 1-1
Variance Table for Linear Regression

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares
Total	$N - 1$	$SST = \sum (Y_i - \bar{Y})^2$	$MST = \frac{SST}{N - 1}$
Regression	1	$SSR = \sum (\hat{Y} - \bar{Y})^2$	$MSR = SSR$
Error	$N - 2$	$SSE = \sum (Y_i - \hat{Y}_i)^2$	$MSE = \frac{SSE}{N - 2}$

The F-distribution has one degree of freedom in the numerator and N-2 degree of freedom in the denominator.

MULTIPLE REGRESSION ANALYSIS

Inadequate results are sometimes obtained with a single independent variable. This shows that one independent variable does not provide enough information to predict the corresponding value of the dependent variable. We can approach this problem, if we use additional independent variables and develop a multiple regression analysis to achieve a meaningful relationship. Here, we can employ a linear regression model in cases where the dependent variable is affected by two or more controlled variables.

The linear multiple regression equation is expressed as:

$$Y = C_0 + C_1X_1 + C_2X_2 + \ldots + C_KX_K \qquad (1\text{-}47)$$

where Y = the dependent variable
$X_1, X_2, \ldots X_K$ = the independent variables
K = the number of independent variables
$C_0, C_1, C_2, \ldots C_K$ = the unknown regression coefficients

The unknown coefficients are estimated based on n observation for the dependent variable Y, and for each of the independent variables X_i's where $i = 1,2,3, \ldots K$.

These observations are of the form:

$$Y_j = C_0 = C_1X_{1j} + C_2X_{2j} + \ldots + C_KX_{Kj} + \xi_j \tag{1-48}$$

for $j = 1, 2, \ldots N$

where Y_j = the j_{th} observation of the dependent variable

$X_{1j}, \ldots X_{Kj}$ = the j_{th} observation of the $X_1, X_2, \ldots X_K$ independent variables

We can use a least squares technique to calculate estimates of $\hat{C}_0, \hat{C}_1, \ldots \hat{C}_K$ of the coefficients $C_0, C_1, \ldots C_K$ by minimizing the following equation:

$$S = \sum_{j=1}^{N}\left[Y_j - (\hat{C}_0 + \hat{C}_1X_{1j} + \ldots + \hat{C}_KX_{Kj})\right]^2 = \sum_{j=1}^{N}\xi_j^2 \tag{1-49}$$

Taking the partial derivatives of S with respect to $\hat{C}_0, \hat{C}_1, \ldots \hat{C}_K$, that is $\partial s/\partial\hat{C}_0$, $\partial s/\partial\hat{C}_1, \ldots \partial s/\partial\hat{C}_K$ and setting them equal to zero, we obtain the following set of equations:

$$N\hat{C}_0 + \left(\sum X_{1j}\right)\hat{C}_1 + \ldots + \left(\sum X_{Kj}\right)\hat{C}_K = \sum Y_j$$

$$\left(\sum X_{1j}\right)\hat{C}_0 + \left(\sum X_{1j}^2\right)\hat{C}_1 + \ldots + \left(\sum X_{1j}X_{kj}\right)\hat{C}_K = \sum X_{1j}Y_j$$

$$\left(\sum X_{2j}\right)\hat{C}_0 + \left(\sum X_{1j}X_{2j}\right)\hat{C}_1 + \ldots + \left(\sum X_{2j}X_{Kj}\right)\hat{C}_K = \sum X_{2j}Y_j$$

$$\vdots$$

$$\vdots$$

$$\vdots$$

$$\vdots$$

$$\left(\sum X_{Kj}\right)\hat{C}_0 + \left(\sum X_{1j}X_{Kj}\right)\hat{C}_1 + \ldots + \left(\sum X_{Kj}^2\right)\hat{C}_K = \sum X_{Kj}Y_j \tag{1-50}$$

Equation 1-50 can be expressed in matrix form as:

$$U\hat{C} = V$$

where

$$U = \begin{bmatrix} N & \sum X_{1j} & \cdots\ \cdots & \sum X_{Kj} \\ \sum X_{1j} & \sum X_{1j}^2 & \cdots\ \cdots & \sum X_{1j} X_{Kj} \\ \vdots & & & \\ \vdots & & & \\ \sum X_{Kj} & \sum X_{1j} X_{Kj} & & \sum X_{Kj}^2 \end{bmatrix}$$

$$\hat{C} = \begin{bmatrix} \hat{C}_0 \\ \hat{C}_1 \\ \vdots \\ \vdots \\ \hat{C}_K \end{bmatrix} \qquad V = \begin{bmatrix} \sum Y_j \\ \sum X_{1j} Y_j \\ \vdots \\ \vdots \\ \sum X_{Kj} Y_j \end{bmatrix}$$

U is a symmetric matrix.

We can obtain estimates for the coefficients $\hat{C}_0, \hat{C}_1, \ldots \hat{C}_K$ by successive elimination or by solving for the inverse of U. That is

$$\hat{C} = U^{-1} V$$

where

U^{-1} = the inverse of U

After solving for $\hat{C}_0, \hat{C}_1, \ldots \hat{C}_K$, the estimates of the dependent variable observations $\hat{Y}_j$ can be obtained as follows:

$$\hat{Y}_j = \hat{C}_0 = \hat{C}_1 X_{1j} + \ldots + \hat{C}_K X_{Kj} \qquad (1\text{-}51)$$

The power equations have often been derived to calculate the parameters of experimental data. Such an equation can be expressed in the form:

$$Y = C_0 . X_1^{C_1} . X_2^{C_2} \ldots X_K^{C_K} \qquad (1\text{-}52)$$

We can calculate the coefficients of the independent variables, if Equation 1-52 is linearized by taking its natural logarithm to give

$$\ln Y = \ln C_0 + C_1 \ln X_1 + C_2 \ln X_2 + \ldots + C_K \ln X_K \qquad (1\text{-}53)$$

The coefficients $C_0, C_1, C_2, \ldots C_K$ can then be obtained by Gaussian elimination. Table 1-2 shows the variance table for linear multiple regression.

The coefficient of determination is

$$r^2 = 1 - \frac{SSE}{SST} \qquad (1\text{-}54)$$

and the correlation coefficient is

$$r = \left(1 - \frac{SSE}{SST}\right)^{0.5} \qquad (1\text{-}55)$$

The test statistic is the F - ratio, which we can define as:

$$F = \frac{MSR}{MSE} \qquad (1\text{-}56)$$

POLYNOMIAL REGRESSION

Some engineering data are often poorly represented by a linear regression. If we know how Y depends on X, then we can develop some form of nonlinear regression [7], although total convergence of this iterative regression procedure can not be guaranteed. However, if the form of dependence is unknown, then we can treat Y as a general function of X by trigonometric terms (Fourier analysis) or polynomial function. The

Table 1-2
Analysis of Variance Table for Linear Multiple Regression

Source of Variance	Degree of Freedom	Sum of Squares	Mean Squares
Total	$N - 1$	$SST = \sum (Y_j - \bar{Y})^2$	$MST = \frac{SST}{N - 1}$
Regression	K	$SSR = \sum (\hat{Y}_j - \bar{Y})^2$	$MSR = \frac{SSR}{K}$
Error	$N - K - 1$	$SSE = \sum (Y_j - \hat{Y}_j)^2$	$MSE = \frac{SSE}{N - K - 1}$

least squares procedure can be readily extended to fit the data to an nth-degree polynomial:

$$Y = C_0 + C_1X + C_2X^2 + \ldots C_nX^n \tag{1-57}$$

where $C_0, C_1, C_2, \ldots C_n$ are constants.

For this case, the sum of the squares of the residuals is minimized:

$$S = \sum_{j=1}^{N} \left[Y_j - C_0 - C_1X_j - C_2X_j^2 - \ldots - C_nX_j^n\right]^2 \tag{1-58}$$

At the minimum, all the partial derivatives with respect to the chosen constants are zero; i.e.,

$$\frac{\partial S}{\partial C_0}, \frac{\partial S}{\partial C_1}, \ldots \frac{\partial S}{\partial C_n} - 0$$

This gives a system of (n+1) linear equations in (n+1) unknowns, C_0, $C_1, \ldots C_n$

$$\frac{\partial S}{\partial C_0} = 0 = \sum_{j=1}^{N} 2(Y_j - C_0 - C_1X_j - C_2X_j^2 - \ldots - C_nX_j^n)(-1)$$

$$\frac{\partial S}{\partial C_1} = 0 = \sum_{j=1}^{N} 2(Y_j - C_0 - C_1X_j - C_2X_j^2 - \ldots - C_nX_j^n)(-X_j)$$

$$\frac{\partial S}{\partial C_2} = 0 = \sum_{j=1}^{N} 2(Y_j - C_0 - C_1X_j - C_2X_j^2 - \ldots - C_nX_j^n)(-X_j^2)$$

$$\vdots$$

$$\vdots$$

$$\vdots$$

$$\frac{\partial S}{\partial C_n} = 0 = \sum_{j=1}^{N} 2(Y_j - C_0 - C_1X_j - C_2X_j^2 - \ldots - C_nX_j^n)(-X_j^n)$$

(1-59)

The above equations are set to equal zero and can be rearranged in the following set of normal equations.

$$
\begin{aligned}
&C_0 N + C_1 \sum X_j + C_2 \sum X_j^2 + \ldots + C_n \sum X_j^n = \sum Y_j \\
&C_0 \sum X_j + C_1 \sum X_j^2 + C_2 \sum X_j^3 + \ldots + C_n \sum X_j^{n+1} = \sum X_j Y_j \\
&C_0 \sum X_j^2 + C_1 \sum X_j^3 + C_2 \sum X_j^4 + \ldots + C_n \sum X_j^{n+2} = \sum X_j^2 Y_j \\
&\vdots \\
&\vdots \\
&\vdots \\
&C_0 \sum X_j^n + C_1 \sum X_j^{n+1} + C_2 \sum X_j^{n+2} + \ldots + C_n \sum X_j^{2n} = \sum X_j^n Y_j
\end{aligned}
\tag{1-60}
$$

Equation 1-60 in matrix form, becomes

$$UC=V$$

$$
U = \begin{bmatrix}
N & \sum X_j & \sum X_j^2 & \ldots & \sum X_j^n \\
\sum X_j & \sum X_j^2 & \sum X_j^3 & \ldots & \sum X_j^{n+1} \\
\sum X_j^2 & \sum X_j^3 & \sum X_j^4 & \ldots & \sum X_j^{n+2} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\sum X_j^n & \sum X_j^{n+1} & \sum X_j^{n+2} & \ldots & \sum X_j^{2n}
\end{bmatrix}
$$

$$
C = \begin{bmatrix} C_0 \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{bmatrix}
\qquad
V = \begin{bmatrix} \sum Y_j \\ \sum X_j Y_j \\ \sum X_j^2 Y_j \\ \vdots \\ \sum X_j^n Y_j \end{bmatrix}
$$

Linear equations generated by polynomial regression can be ill-conditioned when the coefficients have very small and very large numbers. This results in smooth curves that fit poorly. Ill-conditioning often happens if the degree of the polynomial is large and if the Y values cover a wide range. We can determine the error of polynomial regression by a standard error of the estimate as

$$\sigma^2 = \frac{\sum SSE}{N - n - 1} \tag{1-61}$$

where
n = the degree of polynomial
N = the number of data pairs

The coefficient of determination can be expressed as:

$$r^2 = 1 - \frac{SSE}{SST}$$

$$= 1 - \frac{\sum_{j=1}^{N} (Y_j - \hat{Y}_j)^2}{\sum_{j=1}^{N} (Y_j - \overline{Y}_j)^2} \tag{1-62}$$

The correlation coefficient is given by

$$r = \left(1 - \frac{SSE}{SST}\right)^{0.5} \tag{1-63}$$

The numerator of Equation 1-61 should continually decrease as the degree of the polynomial is raised. Alternatively, the denominator of Equation 1-61 causes σ^2 to increase as we move away from the optimum degree.

SOLUTION OF SIMULTANEOUS LINEAR EQUATIONS

Analyses of physiochemical systems often give us a set of linear algebraic equations. Also, methods of solution of differential equations and nonlinear equations use the technique of linearizing the models. This requires repetitive solutions of sets of linear algebraic equations. Linear equations can vary from a set of two to a set having 100 or more equations. In most cases, we can employ Cramer's rule to solve a set of two or three linear algebraic equations. However, for systems of many linear equations, the algebraic computation becomes too complex and may require other methods of analysis.

We will analyze two methods of solving a set of linear algebraic equations, namely Gauss elimination and Gauss-Seidel iteration methods. Gauss elimination is most widely used to solve a set of linear algebraic equations. Other methods of solving linear equations are Gauss-Jordan and LU decomposition. Table 1-3 illustrates the main advantages and disadvantages of using Gauss, Gauss-Jordan and LU decomposition.

Gaussian elimination method is based upon the principle of converting a set of N equations of N unknowns represented by

$$
\begin{aligned}
&a_{1,1}X_1 + a_{1,2}X_2 + a_{1,3}X_3 + \ldots + a_{1,N}X_N = Y_1 \\
&a_{2,1}X_1 + a_{2,2}X_2 + a_{2,3}X_3 + \ldots + a_{2,N}X_N = Y_2 \\
&\vdots \\
&\vdots \\
&a_{N,1}X_1 + a_{N,2}X_2 + a_{N,3}X_3 + \ldots + a_{N,N}X_N = Y_N
\end{aligned}
\tag{1-64}
$$

Table 1-3
Comparison of Three Methods of Linear Equations

Method	Advantages	Disadvantages
Gauss elimination	The most fundamental solution algorithm.	Solution of one set of linear equations at a time.
Gauss-Jordan	Basis for computing inverse; can solve multiple sets of equations.	Less efficient for a single set of equations.
LU decomposition	Efficient if one set of linear equations is repeatedly solved with different inhomogeneous terms (e.g., in the inverse power method.)	Less efficient and more cumbersome than Gauss elimination if used only once.

Source: S. Nakamura, *Applied Numercial Methods With Software*, Prentice-Hall Int. Ed., N.J., 1991. [2]

to a triangular set of the form

$$\begin{aligned} a_{1,1}X_1 + a_{1,2}X_2 + a_{1,3}X_3 + \ldots + a_{1,N}X_N &= Y_1 \\ a'_{2,2}X_2 + a'_{2,3}X_3 + \ldots + a'_{2,N}X_N &= Y'_2 \\ a''_{3,3}X_3 + \ldots + a''_{3,N}X_N &= Y''_3 \\ &\vdots \\ a^{(N-1)}_{N,N}X_N &= Y^{(N-1)}_N \end{aligned} \qquad (1\text{-}65)$$

The process involves converting the general form

$$aX = Y$$

to the triangular form

$$UX = Y'$$

where U is the upper triangular matrix. After completing the forward elimination process, we then employ the back substitution method starting with the last equation to obtain the solution of the set of the remaining equations. The solution of X_N is obtained from the last equation

$$X_N = \frac{Y^{(N-1)}_N}{a^{(N-1)}_{N,N}}$$

subsequent solutions are

$$X_{N-1} = \frac{\left[Y^{(N-2)}_{N-1} - a^{(N-1)}_{N-1,N}X_N\right]}{a^{(N-2)}_{N-1,N-1}}$$

$$\vdots$$

$$X_1 = \frac{\left[Y_1 - \sum_{j=2}^{N} a_{1,j}X_j\right]}{a_{1,1}} \qquad (1\text{-}66)$$

This procedure completes the Gauss elimination. We can carry out the elimination process by writing only the coefficients and the matrix vector in an array as

$$\begin{matrix} a_{1,1} & a_{1,2} & a_{1,3} & \cdots & a_{1,N-1} & a_{1,N} & Y_1 \\ a_{2,1} & a_{2,2} & a_{2,3} & \cdots & a_{2,N-1} & a_{2,N} & Y_2 \\ \vdots & & & & & & \vdots \\ a_{N,1} & a_{N,2} & a_{N,3} & \cdots & a_{N,N-1} & a_{N,N} & Y_N \end{matrix} \qquad (1\text{-}67)$$

The array after the forward elimination becomes

$$\begin{matrix} a_{1,1} & a_{1,2} & a_{1,3} & \cdots & a_{1,N-1} & a_{1,N} & Y_1 \\ 0 & a'_{2,2} & a'_{2,3} & \cdots & a'_{2,N-1} & a'_{2,N} & Y'_2 \\ 0 & 0 & a''_{3,3} & \cdots & a''_{3,N-1} & a''_{3,N} & Y''_3 \\ \vdots & & & & & & \\ 0 & 0 & 0 & \cdots & a^{(N-2)}_{N-1,N-1} & a^{(N-2)}_{N-1,N} & Y^{(N-2)}_{N-1} \\ 0 & 0 & 0 & \cdots & 0 & a^{(N-1)}_{N,N} & Y^{(N-1)}_{N} \end{matrix} \qquad (1\text{-}68)$$

We can summarize the operations of Gauss elimination in a form suitable for a computer program as follows:

1. Augment the N × N coefficient matrix with the vector of right hand sides to form a N × (N–1) matrix.
2. Interchange the rows if required such that a_{11} is the largest magnitude of any coefficient in the first column.
3. Create zeros in the second through N^th rows in the first column by subtracting a_{i1}/a_{11} times the first row from the /ith row. Store the a_{i1}/a_{11} in a_{i1}, i=2, 3, . . . N.
4. Repeat Steps 2 and 3 for the second through the $(N-1)^{st}$ rows, putting the largest-magnitude coefficient on the diagonal by interchanging rows (considering only rows j to N). Then subtract a_{ij}/a_{jj} times the j^th row from the i^th row to create zeros in all the positions of the j^th column below the diagonal. Store the a_{ij}/a_{jj} in a_{ij}, i=j+1 . . . N. At the end of this step, the procedure is an upper triangular.
5. Solve for X_N from the N^th equation by

$$X_N = \frac{a_{N,N+1}}{a_{N,N}}$$

6. Solve for X_{N-1}, X_{N-2}, . . . ,X_1 from the $(N-1)^{st}$ through the first equation in turn by

$$X_i = \frac{a_{i,N+1} - \sum_{j=i+1}^{N} a_{ij} \cdot X_j}{a_{ii}}$$

The Guass-Seidel Iterative Method

Some engineering problems give sets of simultaneous linear equations that are diagonally dominant. This involves the computation of finite difference equations, derived from the approximation of partial differential equations. A diagonally dominant system of linear equations has coefficients on the diagonal that are larger in absolute value than the sum of the absolute values of the other coefficients.

Solving a system of N linear equations using the Gauss-Seidel iterative method, we can rearrange the rows so that the diagonal elements have larger absolute value than the sum of the absolute values of the other coefficients in the same row. This is defined as

$$AX=Y$$

We start with an initial approximation to the solution vector, $X^{(1)}$, and then calculate each component of $X^{(n+1)}$, for i = 1, 2, 3, . . . N by

$$X_i^{(n+1)} = \frac{Y_i}{a_{II}} - \sum_{j=1}^{i-1} \frac{a_{ij}}{a_{ii}} X_j^{(n+1)} - \sum_{j=i+1}^{N} \frac{a_{ij}}{a_{ii}} X_j^{n}, \quad n = 1, 2 \ldots \qquad (1\text{-}69)$$

A necessary condition for convergence is that

$$|a_{ii}| > \sum_{\substack{i=1,\\ j\neq 1}}^{N} |a_{ij}| \qquad i = 1, 2, \ldots N$$

When this condition exists, X^N will converge to the correct solution no matter what initial vector is used.

The Gauss-Seidel iterative method requires an initial approximation of the values of the unknowns X_1 to X_N. We use these values in Equation 1-69 to start calculation of new estimates of X's. Each newly calculated X_i replaces its previous value in subsequent calculations. The iteration continues until all the newly calculated X's converge to a convergence criterion, ε, of the previous values. The Gauss-Seidel method is very efficient because of this faster convergence and should be used when the system is diagonally dominant. This method is widely used in the solution of engineering problems. However, the iterative method will not converge for all sets of equations or for all possible rearrangements of the equations. Assume that we are given a set of N simultaneous linear equations:

$$\begin{gathered} a_{1,1}X_1 + a_{1,2}X_2 + \ldots + a_{1,N}X_N = a_{1,N+1} \\ a_{2,1}X_1 + a_{2,2}X_2 + \ldots + a_{2,N}X_N = a_{2,N+1} \\ \vdots \\ a_{N,1}X_1 + a_{N,2}X_2 + \ldots + a_{N,N}X_N = a_{N,N+1} \end{gathered} \qquad (1\text{-}70)$$

in which a_{ij}'s are constants.

Method of Solution

We first normalize the coefficients of Equation 1-70 to reduce the number of divisions required in the calculations. This is achieved by dividing all elements in row i by a_{ii}, i =1, 2, . . . N to produce an augmented coefficient matrix given by

$$\begin{bmatrix} 1 & a'_{1,2} & a'_{1,3} & \cdots & a'_{1,N} & a'_{1,N+1} \\ a'_{2,1} & 1 & a'_{2,3} & \cdots & a'_{2,N} & a'_{2,N+1} \\ \vdots & & & & & \\ a'_{N,1} & a'_{N,2} & a'_{N,3} & \cdots & 1 & a'_{N,N+1} \end{bmatrix} \qquad (1\text{-}71)$$

where $a'_{i,j} = \dfrac{a_{i,j}}{a_{i,i}}$

The approximation to the solution vector after the kth iteration is

$$X_k = [X_{1,k}, X_{2,k} \ldots X_{N,K}]$$

This is modified by the algorithm

$$X_{i,k+1} = a'_{i,N+1} - \sum_{j=1}^{i-1} a'_{ij} . X_{j,K+1} - \sum_{j=i+1}^{N} a'_{ij} . X_{jk} \qquad (1\text{-}71)$$

where i = 1, 2, . . . N

The next approximation yields

$$X_{K+1} = [X_{1,K+1}, X_{2,K+1} \ldots X_{N,K+1}]$$

The iteration subscript K can be omitted because the new values $X_{i,K+1}$ replace the old values during computation and Equation 1-71 becomes

$$X_i = a'_{i,N+1} - \sum_{\substack{i=1 \\ j \neq 1}}^{N} a'_{ij} . X_j, \quad i = 1, 2, \ldots N \tag{1-72}$$

The X_i values calculated by iterating with Equation 1-71 will converge to the solution of Equation 1-72, if the convergence criterion is

$$\left| X_{i,K+1} - X_i \right| < \varepsilon, \quad i = 1, 2, \ldots N \tag{1-73}$$

provided that no element of the solution vector may have its magnitude changed by an amount greater than ε as a result of one Gauss-Seidel iteration. We can introduce an upper limit on the number of iterations, K_{max}, to terminate the iterative sequence when convergence does not occur.

SOLUTION OF NONLINEAR EQUATIONS

Solving problems in chemical engineering and science often requires finding the real root of a single nonlinear equation. Examples of such computations are in fluid flow, where pressure loss of an incompressible turbulent fluid is evaluated. The Colebrook [8] implicit equation for the Darcy friction factor, f_D, for turbulent flow is expressed

$$\frac{1}{f_D^{0.5}} = -2 \log \left\{ \frac{\varepsilon / D}{3.7} + \frac{2.51}{N_{Re} f_D^{0.5}} \right\} \tag{1-74}$$

where ε/D is the pipe roughness in feet, f_D is the Darcy friction factor, which is four times the Fanning friction factor, and N_{Re} is the Reynolds number. Equation 1-74 is nonlinear and involves trial and error solutions to achieve a solution for f_D; i.e., the root of the equation.

Equation 1-74 can be further expressed as:

$$F(f_D) = \frac{1}{f_D^{0.5}} + 2 \log \left\{ \frac{\varepsilon / D}{3.7} + \frac{2.51}{N_{Re} f_D^{0.5}} \right\} \tag{1-75}$$

In the form of natural logarithm, Equation 1-75 is

$$F(f_D) = \frac{1}{f_D^{0.5}} + 0.86858 \ln\left\{\frac{\varepsilon / D}{3.7} + \frac{2.51}{N_{Re} f_D^{0.5}}\right\} \tag{1-76}$$

The derivative of Equation 1-76 is

$$F'(f_D) = -\frac{0.5}{f_D^{1.5}} - \frac{4.03329}{\left[N_{Re} f_D^{1.5} \frac{\varepsilon}{D} + 9.287 f_D\right]} \tag{1-77}$$

In thermodynamics, the pressure-volume temperature relationships of real gases are described by the equation of state. The compressibility factor from the reduced pressure and temperature can be rearranged from Redlich and Kwong [9] to two constant state equations in the form

$$Z = 1 + A - \frac{AB}{A + Z} + \frac{A^2 B}{AZ + Z^2} \tag{1-78}$$

where

$$A = \frac{0.0867 p_r}{T_r} \quad \text{and} \quad B = \frac{4.934}{T_r^{1.5}}$$

Equation 1-78 is also nonlinear and can be expressed as:

$$F(Z) = Z - 1 - A + \frac{AB}{A + Z} - \frac{A^2 B}{AZ + Z^2} \tag{1-79}$$

The derivative of Equation 1-79 is

$$F'(Z) = 1 - \frac{AB}{(A + Z)^2} + \frac{A^2 B(A + 2Z)}{(AZ + Z^2)^2} \tag{1-80}$$

For multicomponent separations, it is often necessary to estimate the minimum reflux ratio of a fractionating column. A method developed for this purpose by Underwood [10] requires the solution of the equation

$$f(\theta) = \sum_{i=1}^{N} \frac{\alpha_i x_i}{(\alpha_i - \theta)} - 1 + q = 0 \tag{1-81}$$

where i = 1, 2, . . . N

and

N = the number of components in the feed
x_i = the mole fraction of component i
α_i = the relative volatility of component i
q = the thermal condition of the feed

Equation 1-81 is highly nonlinear and must be solved for θ, the Underwood parameter, or the root of the equation. It has a singularity at each value of $\theta = \alpha_i$. If we can determine with some precision the degree of vaporization of the feed and the distillation composition, then we can also obtain a single value of θ by an iterative solution. The value of θ is generally bounded between the relative volatilites of the light and heavy keys.

That is

$$\theta_{LK} < \theta < \theta_{HK}$$

Gjumbir and Olujic [11], Tao [12], and Sargent [13] have published articles for solving nonlinear problems. We will discuss some of the methods used in solving nonlinear equations, and employ one of the methods to solve Equation 1-66. Equation 1-81 uses the bisection method to solve for θ in Chapter 7.

The Bisection Method

The method assumes that f(x) is continuous over the interval (x_1,x_2) with $f(x_1)$ and $f(x_2)$ having opposite signs; i.e., $f(x_1).f(x_2) < 0$. There is at least one root of f(x) = 0 in this interval. If $f(x_1) < 0$, then $f(x_2) > 0$. Therefore the interval between these two points can be bisected. If I_1 represents the subinterval (x_2,x_3) at whose end points f(x) takes opposite signs and $x_3 = (x_1 + x_2)/2$, I_1 can be bisected to give an interval I_2, at whose endpoints f(x) still has opposite signs. We can continue with this process until a root of the equation is found.

The midpoint of interval I_m, is

$$x_{m+1} = (x_{m-1)} + x_m)/2 \tag{1-82}$$

which is selected as an approximation to the root. The advantages are its simplicity and the number of iterations that can be predicted, because the chosen interval is halved during each iteration.

$$i = \log\left(\frac{x_2 - x_1}{\varepsilon}\right)\Big/\log 2 \tag{1-83}$$

where i is the number of iterations and ε is the tolerance.

Algorithm for the Bisection Method

Determining a root of $f(x) = 0$, accurate within a specified tolerance value, requires given values of x_1 and x_2 such that $f(x_1)$ and $f(x_2)$ are of opposite signs. i is the iteration index, imax is the maximum number of iterations, ε is the tolerance, and x_3 is the subinterval midpoint.

```
Step 1.         Set $i = 1$
Step 2. (i)     Set $x_3 = x_1 + (x_2 - x_1)/2$
        (ii)    If $|x_3 - x_1| < \varepsilon$ then go to Step 3
        (iii)   If $f(x_1)f(x_3) > 0$, then $x_1 = x_3$, else $x_2 = x_3$ (set new interval
                bounds)
        (iv)    $i = i + 1$
        (v)     If $i >$ imax, then quit, else repeat Step 2i – v
Step 3.         Output $x_3, f(x_3)$
```

The final value of x_3 approximates the root. The method may give a false root if f(x) is discontinuous on (x_1, x_2).

Method of Linear Interpolation (Regula-Falsi Method)

An initial guess, x_1, is made and function, f_1, is calculated. We then evaluate the function f_2 at another point, x_2, such that the two functions have opposite signs; i.e., $f_1 f_2 < 0$. We can calculate a new interval value, x_3, by linear interpolation, and then evaluate the function f_3.

From similar triangles,

$$\frac{x_2 - x_3}{x_2 - x_1} = \frac{f_2}{f_2 - f_1} \tag{1-84}$$

rearranging, we have

$$x_3 = x_2 - \frac{f_2}{f_2 - f_1}(x_2 - x_1) \tag{1-85}$$

Generalizing, we obtain the recursive algorithm

$$x_{n+1} = x_n - \frac{f_n}{f_n - f_{n-1}}(x_n - x_{n-1}) \tag{1-86}$$

where n = 1, 2, 3, . . . N

If $f_n f_{n+1} < 0$, then the righthand interval contains the root, and x_{n+1} becomes the new x_{n-1} for the next iteration. However, if $f_{n-1}f_{n+1} < 0$, the true root of the equation lies between x_{n-1} and x_{n+1}. x_{n+1} then becomes the new x_n for the next iteration.

Algorithm for the Modified Linear Interpolation Method

```
Step 1. Set SAVE = $f(x_1)$; set $F_1 = f(x_1)$ and $F_2 = f(x_2)$
Step 2. DO WHILE $|x_1 - x_2| \geq$ tolerance value 1, or
                 $|f(x_3)| \geq$ tolerance value 2
Step 3. $x_3 = x_2 - F_2(x_2 - x_1) / (F_2 - F_1)$
        If $f(x_3)$ of opposite sign to $F_1$, then
        $x_2 = x_3$, $F_2 = F_3$,
        If $f(x_3)$ of same sign as SAVE; then
        $F_1 = F_2/2$
        ENDIF
        ELSE
        $x_1 = x_3$, $F_1 = f(x_3)$
        If $f(x_3)$ of same sign as SAVE, then
        $F_2 = F_2/2$
        ENDIF
        ENDIF
        SAVE = $f(x_3)$
```

The Newton-Raphson Method

The Newton-Raphson method is widely used in finding the root of nonlinear equations. This method uses the derivative of f(x) at x to estimate a new value of the root. The tangent at x is then extended to intersect the x-axis, and the value of x at this intersection is the new estimate of the root. The desired precision is reached by iteration.

Suppose that f(x), f'(x) and f"(x) are continuous and that f(x) and f'(x) do not vanish for the same value of x, if x^r is an approximation to the root of f(x) = 0.

The second mean value theorem can be expressed as:

$$0 = f(x^r + h) = f(x^r) + hf'(x^r) + \frac{h^2}{2} f''(x^r + O_2 h) \qquad (1\text{-}87)$$

Neglecting higher order terms, we have

$$h = -\frac{f(x^r)}{f'(x^r)} \qquad (1\text{-}88)$$

Therefore, the next approximation to the root is given by

$$x^{r+1} = x^r - \frac{f(x^r)}{f'(x^r)} \qquad (1\text{-}89)$$

The procedure is repeated until $|x^r| < \varepsilon$, where ε is a preset tolerance.

This method converges much faster than the bisection technique. However, its rate of convergence does not necessarily correlate with the nearness of the initial starting of the root. The main advantages of this technique are that it converges rapidly (i.e., quadratic convergence) and needs only a single starting point. Its disadvantages are sensitivity to local maxima and minima and a potentially narrow convergence range.

Algorithm for the Newton-Raphson Method

```
Step 1. Set $i = 1$
Step 2. $x_i = -f(x_i)/f'(x_i)$
Step 3. If $|x_{i+1} - x_i| < \varepsilon$, then print root $x_{i+1}$, quit
Step 4. $i = i+1$
        If $i > imax$, then quit, else repeat Steps 2-4
```

The Secant Method

In cases where the first derivative cannot easily be determined by the Newton-Raphson method, a simple method to approximate the first derivative can be used. The secant method can be determined from two prior estimates.

$$f'(x_i) = \frac{f(x_i) - f(x_{i-1})}{x_i - x_{i-1}} \qquad (1\text{-}90)$$

and the iteration process becomes

$$x_{i+1} = x_i + f(x_{i+1})\frac{x_i - x_{i-1}}{f(x_i) - f(x_{i-1})} \quad (1\text{-}91)$$

The advantages of this method are that it offers rapid convergence without requiring the first derivative. Convergence is between linear and quadratic, i.e., a power ranging from 1 to 2. The value is an approximation of the tangent of the secant. The value depends upon the steepness of the curve. Because the denominator always approaches zero near the root, this method is prone to instability. It also requires two initial estimates to start.

INTERPOLATIONS

Experimental and physical property data sometimes require values of their unknown functions that correspond to certain values of their independent variables. In certain cases, we may want to determine the behavior of the function. Alternatively, we may want to approximate other values of the function at values of the independent variables that are not tabulated. We can achieve these objectives either by interpolation or extrapolation of a polynomial that fits a selected set of points of both variables (x_i, $f(x_i)$). Also, we can assume after finding a polynomial that fits a selected set of points (x_i, $f(x_i)$ that the polynomial and the function behave over a given interval in question. The values of the polynomial will be estimates of the values of the unknown function.

Generally, the experimental data are approximated by a polynomial, the degree of which can often be calculated by constructing a difference table. The difference column that gives approximate constant value shows the degree of the polynomial that can be fitted to the data. When the polynomial is of the first degree, we have a linear interpolation. For polynomials of higher degrees, we can approximate functions if we construct a table with wider spacing. Such a table is known as a difference table.

A Difference Table

We can obtain a table of values, if the dependent variable f(x) is a function of the independent variable X. If we let h be the uniform difference in the x-values, $h = \Delta x$, we can define the first differences of the function as:

$$\begin{aligned} \Delta f(x_1) &= f(x_2) - f(x_1) \\ \Delta f(x_2) &= f(x_3) - f(x_2) \\ &\vdots \\ \Delta f(x_i) &= f(x_{i+1}) - f(x_i) \end{aligned} \tag{1-92}$$

or

$$\Delta f_i = f_{i+1} - f_i \tag{1-93}$$

The second difference is the difference of the first differences and can be expressed as:

$$\Delta^2 f(x) = \Delta\big(\Delta f(x_1)\big) \tag{1-94}$$

$$\begin{aligned} &= \Delta\big(\Delta f(x_2) - \Delta f(x_1)\big) \\ &= \big(f(x_3) - f(x_2)\big) - \big(f(x_2) - f(x_1)\big) \end{aligned} \tag{1-95}$$

or

$$\begin{aligned} \Delta^2 f_1 &= (f_3 - f_2) - (f_2 - f_1) \\ &= f_3 - 2f_2 + f_1 \end{aligned} \tag{1-96}$$

$$\Delta^2 f_i = f_{i+2} - 2f_{i+1} + f_i \tag{1-97}$$

$$\begin{aligned} \Delta^3 f_1 &= \Delta(\Delta^2 f_2 - \Delta^2 f_1) \\ &= (f_4 - 2f_3 + f_2) - (f_3 - 2f_2 + f_1) \\ &= f_4 - 2f_3 + f_2 - f_3 + 2f_2 - f_1 \end{aligned} \tag{1-98}$$

$$\Delta^3 f_1 = f_4 - 3f_3 + 3f_2 - f_1 \tag{1-99}$$

$$\Delta^3 f_i = f_{i+3} - 3f_{i+2} + 3f_{i+1} - f_i \tag{1-100}$$

We then have a general formula given by

$$\Delta^n f_i = f_{i+1} - \binom{n}{1} f_{i+n-1} + \binom{n}{2} f_{i+n-2} - \binom{n}{3} f_{i+n-3} + \dots$$

$$= f_{i+1} - n f_{i+n-1} + \frac{n!}{2!(n-2)!} f_{i+n-2} - \frac{n!}{3!(n-3)!} f_{i+n-3} + \dots$$

$$= f_{i+1} - n f_{i+n-1} + \frac{n(n-1)}{2!} f_{i+n-2} - \frac{n(n-1)(n-2)}{3!} f_{i+n-3} + \dots \tag{1-101}$$

Equation 1-101 is the array of coefficients in the binomial expansion.

Table 1-4 shows how the differences in the dependent variables are arranged.

Interpolating Polynomials

When the tabulated function resembles a polynomial of a constant value in the n^th^ order differences, we can approximate the function by constructing a polynomial. Various formulas have been expressed for the n^th^ degree polynomial that passes through n + 1 pairs of points (x_i, f_i), where i = 1, 2 . . . n + 1.

When the data points are available at equal intervals of the independent variable, we can use the Newton-Gregory forward polynomial.

Table 1-4
Diagonal Difference Table

x	f(x)	Δf	$\Delta^2 f$	$\Delta^3 f$	$\Delta^4 f$
x_0	f_0				
		Δf_0			
x_1	f_1		$\Delta^2 f_0$		
		Δf_1		$\Delta^3 f_0$	
x_2	f_2		$\Delta^2 f_1$		$\Delta^4 f_0$
		Δf_2		$\Delta^3 f_1$	
x_3	f_3		$\Delta^2 f_2$		
		Δf_3			
x_4	f_4				

$$P_n(x_s) = f_0 + \binom{s}{1}\Delta f_0 + \binom{s}{2}\Delta^2 f_0 + \binom{s}{3}\Delta^3 f_0$$

$$+ \binom{s}{4}\Delta^4 f_0 + \ldots + \binom{s}{n}\Delta^n f_0$$

$$= f_0 + s\Delta f_0 + \frac{s(s-1)}{2!}\Delta^2 f_0 + \frac{s(s-1)(s-2)}{3!}\Delta^3 f_0$$

$$+ \frac{s(s-1)(s-2)(s-3)}{4!}\Delta^4 f_0$$

$$+ \ldots + \frac{1}{n!}s(s-1)(s-2)\ldots(s-n+1) \tag{1-102}$$

where $x = x_0 + sh$ and $h = x_{i+1} - x_i = x_2 - x_1$

The Newton-Gregory backward polynomial can be expressed as:

$$P_n(x_s) = f_0 + \binom{s}{1}\nabla f_0 + \binom{s+1}{2}\nabla^2 f_0 + \binom{s+2}{3}\nabla^3 f_0$$

$$+ \binom{s+3}{4}\nabla^4 f_0 + \ldots + \binom{s+n-1}{n}\nabla^n f_i$$

$$= f_0 + s\nabla f_0 + \frac{s(s+1)}{2!}\nabla^2 f_0 + \frac{s(s+1)(s+2)}{3!}\nabla^3 f_0$$

$$+ \frac{s(s+1)(s+2)(s+3)}{4!}\Delta^4 f_0 + \ldots$$

$$+ \frac{1}{n!}(s+n-1)(s+n-2)\ldots s(s+1)\nabla^n f_i \tag{1-103}$$

where s is a local coordinate defined by

$$s = \frac{x - x_i}{h}$$

$\binom{s+n-1}{n}$ is a binomial coefficient and $\nabla^n f_i$ is the backward difference.

Stirling central differences represent a horizontal line using averages of the differences; i.e.,

$$\delta f_i = f_{i+1/2} - f_{i-1/2}$$

or

$$\delta f_{i+1/2} = f_{i+1} - f_i$$

where

$$f_{i+1/2} = f\left(x_i + \frac{h}{2}\right)$$

$$p_n(x) = f_0 + \binom{s}{1}\frac{\Delta f_{-1} + \Delta f_0}{2} + \frac{\binom{s+1}{2} + \binom{s}{2}\Delta^2 f_{-1}}{2}$$

$$+ \binom{s+1}{3}\frac{\Delta^3 f_{-2f} + \Delta^3 f_{-1}}{2} + \frac{\binom{s+2}{4} + \binom{s+1}{4}}{2}\Delta^4 f_{-2} + \quad (1\text{-}104)$$

The forward and the backward difference approximations give the derivatives of the Newton interpolation polynomial at the edges of the interpolation range. However, the central difference is derived from the Newton interpolation at the center of the range of interpolation. Accuracy of an interpolation formula based on equispaced points is highest at the center of the interpolation range. Therefore, the central difference interpolation formula is always more accurate than the forward or backward difference approximations.

SOLUTION OF INTEGRATION

We frequently use numerical techniques to integrate a function given in both analytical and tabular forms. For instance, we can use an integral method to determine the volumetric rate of a gas through a duct from the linear velocity distribution. In fluid mixing with residence time distribution theory, Danckwerts [14] showed that the fraction of material in the outlet stream that has been in the system for a period between t and t+dt is equal to Edt. E is a function of t, and E(t) is the residence time distribution function. We can express E(t) in integral form as:

$$\int_0^{\infty} E(t)dt = 1 \qquad (1\text{-}105)$$

The average time spent by material flowing at a rate, q, through a volume, V, equals V/q.

$$\text{The mean residence time, } \bar{t} = \frac{V}{q}$$

We can also express Equation 1-105 in the form of dimensionless time where $\theta = tq/V$, and this becomes:

$$\int_0^{\infty} E(\theta)d\theta = 1 \qquad (1\text{-}106)$$

Figure 1-6 shows a residence time distribution from a tracer experiment studying the mixing characteristics of a nozzle-type reactor [15] that behaves nonideally.

Numerical integral methods can be used to calculate areas under this or similar distribution functions.

The Trapezoidal Rule

This is a numerical integration method derived by integrating the linear interpolation formula. It is expressed as:

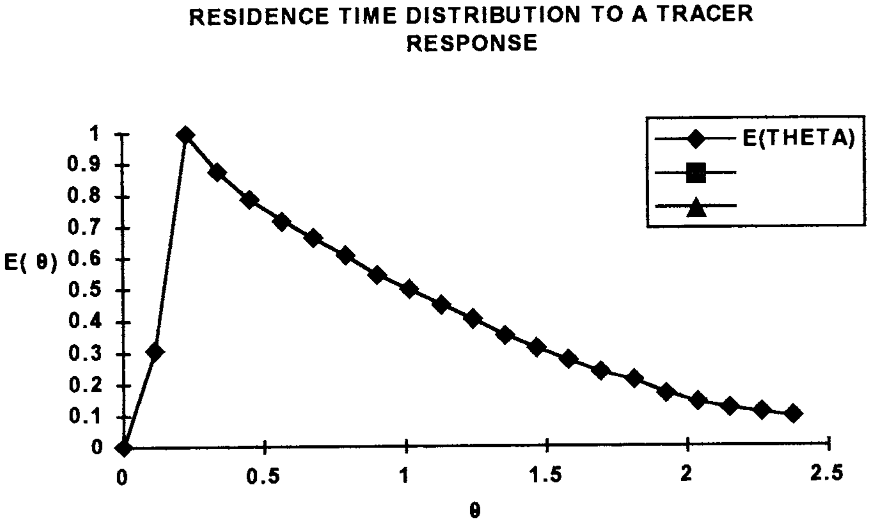

RESIDENCE TIME DISTRIBUTION TO A TRACER RESPONSE

Figure 1-6. Residence time distribution in a nozzle type reactor. Source: A. K. Coker, *A Study of Fast Reactions in Nozzle Type Reactors,* Ph.D. thesis, Univ. of Aston, Birmingham, U.K., 1985.

$$I = \int_{x_i}^{x_{i+1}} f(x)dx = \frac{f(x_i) + f(x_{i+1})}{2}(\Delta x) \qquad (1\text{-}106)$$

$$= \frac{h}{2}(f_i + f_{i+1})$$

For (a, b) subdivided into sub-intervals of size h, we can express the area as:

$$I = \int_a^b f(x)dx = \sum_{i=1}^{n} \frac{h}{2}(f_i + f_{i+1})$$

$$= \frac{h}{2}(f_1 + 2f_2 + 2f_3 + \ldots + 2f_n + f_{n+1}) + E \qquad (1\text{-}107)$$

$$= \text{width} \times \text{average height}$$

E represents the local error, $E \cong -\left(\frac{b - a}{12}\right)h^2 f''(\varepsilon)$ where $a \le \varepsilon \le b$

Simpson's 1/3 Rule

Simpson's 1/3 rule is based on quadratic polynomial interpolation. For a quadratic integrated over two Δx intervals that are of uniform width or panels, we can express the area as:

$$I = \int_a^b f(x)dx = \frac{h}{3}(f_1 + 4f_2 + 2f_3 + 4f_4 +$$

$$2f_5 + \ldots + 2f_{n-1} + 4f_n + f_{n+1}) + E \qquad (1\text{-}108)$$

$$= \text{width} \times \text{average height}$$

$$E \cong -\frac{(b - a)}{180} h^4 f^{iv}(\varepsilon), \qquad a \le \varepsilon \le b$$

Simpson's 3/8 Rule

Simpson's 3/8 rule is derived by integrating a third-order polynomial interpolation formula. For a domain (a,b) divided into three intervals, it is expressed as:

$$I = \int_a^b f(x)dx = \frac{3h}{8}(f_1 + 3f_2 + 3f_3 + 2f_4 + 3f_5 + 3f_6$$

$$+ \ldots + 2f_{n-2} + 3f_{n-1} + 3f_n + f_{n+1}) + E \qquad (1\text{-}109)$$

$$= \text{width } \times \text{average height}$$

$$E \cong -\frac{(b-a)}{80}h^4 f^{iv}(\varepsilon), \qquad a \le \varepsilon \le b$$

Gaussian Quadrature

Gauss quadratures are numerical integration methods that employ Legendre points. Gauss quadrature cannot integrate a function given in a tabular form with equispaced intervals. It is expressed as:

$$I = \int_{-1}^{1} f(x)dx = af(x_1) + bf(x_2) + E \qquad (1\text{-}110)$$

where the limits of integration are a to b. To use the tabulated Gaussian quadrature parameters, we must change the interval of integration to (−1,1).

If we let

$$t = \frac{(b-a)x + b + a}{2} \quad \text{and} \quad dt = \left(\frac{b-a}{2}\right)dx$$

then

$$\int_a^b f(t)dt = \int_{-1}^{1} f(t)\left(\frac{dt}{dx}\right)dx$$

$$= \left(\frac{b-a}{2}\right)\int_{-1}^{1} f\left\{\frac{(b-a)x + b + a}{2}\right\}dx \qquad (1\text{-}111)$$

Table 1-5 summarizes the advantages and disadvantages of numerical integration techniques.

SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS

In certain cases, we may need to find out the behavior of many dynamic and physical processes. This is often expressed mathematically

Table 1-5
Advantages and Disadvantages of Numerical Integration Techniques

Method	Advantages	Disadvantages
Trapezoidal rule	Simplicity. Optimal for improper integrals.	Needs a large number of subintervals for good accuracy.
Simpson's 1/3 rule	Simplicity. Higher accuracy than the trapezoidal rule.	Even number of intervals only.
Simpson's 3/8 rule	Same order of accuracy as the 1/3 rule.	Intervals or panels in multiples of three only.
Gaussian quadrature	Functional data at two end points are not used.	Data points are not equispaced.

by ordinary differential equations. The solutions of these equations are of great value to engineers and scientists. Many differential equations can be solved by well-known analytical methods, although many physically differential equations are impossible to solve analytically. Numerical techniques can be developed to solve these equations. We shall consider the numerical techniques for solving differential equations.

N^{th} Order Ordinary Differential Equations

We consider the solutions of the Nth order differential equations of the form:

$$F\left(x, y, \frac{dy}{dx}, \frac{d^2y}{dx^2}, \frac{d^3y}{dx^3}, \ldots \frac{d^{n-1}y}{dx^{n-1}}, \frac{d^ny}{dx^n}\right) = 0 \qquad (1\text{-}112)$$

Equation 1-112 has the highest derivative of the order n, and is ordinary because there is only one independent variable, x. We can obtain a unique solution when some additional information such as values of y(x) and its derivatives at some specific values of x are known. Therefore, for an N^{th} order equation, we require such N conditions to arrive at the unique solution y(x). If all N conditions are known at the same value of x, we can classify the problem as an initial value problem. However, when more than one value of x is involved, the problem is classified as a boundary value problem.

Solution of First Order Ordinary Differential Equations

We express a first order equation as:

$$\frac{dy}{dx} = f(x, y) \tag{1-113}$$

and we require a solution y(x) that satisfies Equation 1-113 and one initial condition. Here, we can subdivide the interval in the independent variable in x into steps over which a solution is required (a,b). The value of the exact solution y(x) is then approximated at N+1 evenly spaced values of x; i.e., $(x_0, x_1, \ldots x_{n-1}, x_n)$. The step size, h, is expressed as:

and

$$x_i = x_0 + ih, \qquad i = 0, 1, \ldots n$$

If we let the true solution y(x) be $y(x_i)$, and the computed approximations of y(x) at these same points be y_i, so that

$$y_i = y(x_i)$$

then, the exact derivative dy/dx can be approximated by $f(x_i,y_i)$ and represented as f_i such that

$$f_i = f(x_i, y_i) = f\big(x_i, y(x_i)\big) \tag{1-114}$$

The difference between the computed value y_i and the true value $y(x_i)$ is ε_i and can be expressed as:

$$\varepsilon_i = y_i - y(x_i) \tag{1-115}$$

ε_i is the local truncation error.

Taylor Series Expansion

We can develop a relation between x and y by finding the coefficients of the Taylor series. Expanding y about the point $x = x_0$, we obtain

$$y(x) = y(x_0) + f'(x_0)(x - x_0) + \frac{f''(x_0)(x - x_0)^2}{2!}$$

$$+ \frac{f'''(x_0)(x - x_0)^3}{3!} + \ldots \tag{1-116}$$

where $f'(x)$ represents $\frac{d}{dx}f(x)$

If we let $x - x_0 = h$

We can express the series as:

$$y(x) = y(x_0) + hf'(x_0) + \frac{f''(x_0)h^2}{2!} + \frac{f'''(x_0)h^3}{3!} + \ldots \qquad (1\text{-}117)$$

Since $y(x_0)$ is our initial condition, the first term is known from the initial condition $y(0) = 1$. The error term of the Taylor series after the h^4 term is

$$E = \frac{y^{v}\varepsilon h^5}{5!} \qquad 0 < \varepsilon < h$$

Euler and Modified Euler Methods

Using the Taylor's series,

$$y(x_0 + h) = y(x_0) + hf'(x_0) + \frac{f''(\varepsilon)h^2}{2} \qquad (1\text{-}118)$$

$$x_0 < \varepsilon < x_0 + h$$

The value of $y(x_0)$ is given by the initial condition and $f'(x_0)$ is evaluated from $f(x_0, y_0)$, given by the differential equation

$$\frac{dy}{dx} = f(x, y)$$

The Euler method can be expressed as:

$$y_{n+1} = y_n + hf'_n + O(h^2)\text{ error} \qquad (1\text{-}119)$$

For the modified Euler method, we expand the Taylor series as

$$y_{n+1} = y_n + f'_n h + \frac{f''_n}{2}h^2 + \frac{f'''_n}{6}h^3, \qquad x_n < \varepsilon < x_{n+h} \qquad (1\text{-}120)$$

Replacing the second derivative by the forward difference approximation for f" that is

$$f'' = \frac{f'_{n+1} - f'_n}{h}$$

having an error of O(h), we have

$$y_{n+1} = y_n + h\left\{f'_n + \frac{1}{2}\left[\frac{f'_{n+1} - f'_n}{h} + O(h)\right]h\right\} + O(h^3) \qquad (1\text{-}121)$$

$$y_{n+1} = y_n + h\left\{f'_n + \frac{1}{2}f'_{n+1} - \frac{1}{2}f'_n\right\} + O(h^3)$$

$$= y_n + \frac{h(f'_n + f'_{n+1})}{2} + O(h^3) \qquad (1\text{-}122)$$

Runge-Kutta Methods

The solution of a differential equation by direct Taylor's expansion cannot be easily obtained, if we retain the derivatives of higher order. We can develop one-step procedures that involve only first-order derivative evaluations and produce results equivalent in accuracy to higher order Taylor formulas. These algorithms are named the Runge-Kutta methods after the German mathematicians Runge and Kutta. The second-order Runge-Kutta algorithm for the first-order differential equation can be expressed as:

$$\frac{dy}{dx} = f(x, y)$$

$$k_1 = hf(x_i, y_i)$$

$$k_2 = hf(x_i + h, y_i + k_i)$$

$$y_{n+1} = y_n + \frac{1}{2}(k_1 + k_2) + O(h^3) \qquad (1\text{-}123)$$

The third-order Runge-Kutta method is

$$k_1 = hf(x_i, y_i)$$

$$k_2 = hf\left(x_i + \frac{h}{2}, y_i + \frac{k_1}{2}\right)$$

$$k_3 = hf(x_i + h, y_i + 2k_2 - k_1)$$

$$y_{n+1} = y_n + \frac{1}{6}(k_1 + 4k_2 + k_3) + O(h^4) \qquad (1\text{-}124)$$

The fourth-order Runge-Kutta method is widely used in computer solutions of differential equations.

$$
\begin{aligned}
k_1 &= hf(x_i, y_i) \\
k_2 &= hf\left(x_i + \frac{h}{2}, y_i + \frac{k_1}{2}\right) \\
k_3 &= hf\left(x_i + \frac{h}{2}, y_i + \frac{k_2}{2}\right) \\
k_4 &= hf(x_i + h, y_i + k_3) \\
y_{n+1} &= y_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) + O(h^5)
\end{aligned}
\qquad (1\text{-}125)
$$

k_1, k_2, k_3, k_4 are approximate derivative values computed on the interval $x_i \le x \le x_{i+1}$ and h is the step size.

$$x_{i+1} = x_i + h$$

The local error term for the fourth-order Runge-Kutta is $O(h^5)$.

Runge-Kutta-Gill Method

Runge-Kutta-Gill method is the most widely used single-step method for solving ordinary differential equations.

$$
\begin{aligned}
k_1 &= hf(x_i, y_i) \\
k_2 &= hf\left(x_i + \frac{h}{2}, y_i + \frac{1}{2}k_1\right) \\
k_3 &= hf\left(x_i + \frac{h}{2}, y_i + \left[\frac{-1}{2} + \frac{1}{\sqrt{2}}\right]k_1 + \left[1 - \frac{1}{\sqrt{2}}\right]k_2\right) \\
k_4 &= hf\left(x_i + h, y_i - \frac{1}{\sqrt{2}}k_2 + \left[1 + \frac{1}{\sqrt{2}}\right]k_3\right) \\
y_{n+1} &= y_n + \frac{1}{6}\left(k_1 + 2\left[1 - \frac{1}{\sqrt{2}}\right]k_2 + 2\left[1 + \frac{1}{\sqrt{2}}\right]k_3 + k_4\right) + O(h^5)
\end{aligned}
$$

(1-126)

Runge-Kutta-Gill method provides an efficient algorithm for solving a system of first-order differential equations and makes use of much less computer memory when compared with other numerical methods.

Runge-Kutta-Merson Method

Runge-Kutta-Merson outlines a process for deciding the step size for a better predetermined accuracy. For this method, five functions are evaluated at every step. The algorithm is

$$
\begin{aligned}
k_1 &= hf(x_i, y_i) \\
k_2 &= hf\left(x_i + \frac{h}{3}, y_i + \frac{k_1}{3}\right) \\
k_3 &= hf\left(x_i + \frac{h}{3}, y_i + \frac{k_1}{6} + \frac{k_2}{6}\right) \\
k_4 &= hf\left(x_i + \frac{h}{2}, y_i + \frac{k_1}{8} + \frac{3k_3}{8}\right) \\
k_5 &= hf\left(x_i + h, y_i + \frac{k_1}{2} - \frac{3k_3}{2} + 2k_4\right) \\
y_{n+1} &= y_n + \frac{1}{6}(k_1 + 4k_4 + k_5) + O(h^5)
\end{aligned}
\qquad (1\text{-}127)
$$

We can estimate the local error from a weighted sum of the individual estimate.

$$E = \frac{1}{30}(2k_1 - 9k_3 + 8k_4 - k_5) \qquad (1\text{-}128)$$

Multistep Methods

The multistep methods use past values of y and y' = f(x,y) to construct a polynomial that approximates the derivative function and extrapolates this into the next interval. We can achieve an accurate estimate of y_{n+1} based on a polynomial that fits past values of the gradient. Also, we end with a slope equal to that at the predicted point. This forms the basis of predictor-corrector formulae.

Fourth Order Milne's Method

Values of y_n, y_{n-1}, y_{n-2} and y_{n-3} are required to calculate y_{n+1}. Milne's method uses Newton-Cotes formula for the predictor and Simpson's rule for the corrector.

Predictor

$$y^p_{n+1} = y_{n-3} + \frac{4h}{3}\big[2f(x_n, y_n) - f(x_{n-1}, y_{n-1})$$

$$+ 2f(x_{n-2}, y_{n-2})\big] + O(h^5) \qquad (1\text{-}129)$$

Corrector

$$y_{n+1} = y_{n-1} + \frac{h}{3}\big[f(x_{n+1}, y^p_{n+1}) + 4f(x_n, y_n)$$

$$+ f(x_{n-1}, y_{n-1})\big] + O(h^5) \qquad (1\text{-}130)$$

Local truncation error

$$O(h^5) = -\frac{h^5}{90} f^v(\varepsilon), \qquad x_{n-1} < \varepsilon < x_{n+1}$$

Adams-Moulton Fourth-Step Method

Predictor

$$y^p_{n+1} = y_n + \frac{h}{24}\big[55f(x_n, y_n) - 59f(x_{n-1}, y_{n-1})$$

$$+ 37f(x_{n-2}, y_{n-2}) - 9f(x_{n-3}, y_{n-3})\big] + O(h^5) \qquad (1\text{-}131)$$

$$n = 3, 4, \ldots m - 1$$

Corrector

$$y_{n+1} = y_n + \frac{h}{24}\big[9f(x_{n+1}, y^p_{n+1}) + 19f(x_n, y_n) - 5f(x_{n-1}, y_{n-1})$$

$$+ f(x_{n-2}, y_{n-2})\big] + O(h^5) \qquad n = 2, 3, \ldots m - 1 \qquad (1\text{-}132)$$

Local truncation error

$$O(h^5) = -\frac{19}{720}h^5f^{v}(\varepsilon), \qquad x_{n-2} < \varepsilon < x_{n+1}$$

The predictor calls for four previous values in Adams-Moulton and Milne's algorithms. We obtain these by the fourth-order Runge-Kutta method. Also, we can reduce the step size to improve the accuracy of these methods. Milne's method is unstable in certain cases because the errors do not approach zero as we reduce the step size, h. Because of this instability, the method of Adams-Moulton is more widely used.

The primary advantage of the single-step methods is that they are self starting. We can also vary the step sizes. In contrast, the multistep methods require a single-step formula to start the calculations. Step size variation is difficult. However, the efficiency of both the Milne's and Adams-Moulton methods is about twice that of the single-steps methods. We need two function evaluations per step in the former while four or five are required with the single step.

PROBLEMS AND SOLUTIONS

Problem 1-1

An experimental result in a liquid mixing experiment for the power correlation using a pitched-blade turbine shows that in the viscous regime, the power number is related to the Reynolds number by the following data:

Table P1-1

Reynolds number, N_{Re} $\frac{D^2N\rho}{\mu}$	Power number, P_o $\frac{Pg_c}{\rho N^3D^5}$
1.0	50.0
3.0	18.0
5.0	11.0
7.0	7.9
9.0	6.2
13.0	5.0

Use the regression analysis to determine the best fit for the data.

Solution

Program PROG11.FOR determines the slope, intercept, and correlation coefficient for the above experimental data. The results show that Equation **Y=A+B*1/X** gives the best fit with the slope B = 49.01 and a correlation coefficient r = 0.9998. Figure 1-7 gives a plot of Reynolds number against power number. The figure shows that Equation 1-3 gives a perfect fit of the experimental data.

Problem 1-2

In a fluid flow experiment, the volumetric rate of fluid through a pipe is dependent on the pipe diameter and slope by the following equation.

$$Q = C_0 D^{C_1} D^{C_2} \tag{1-133}$$

where Q = flow rate, ft^3/sec
D = pipe diameter, ft
S = slope, ft/ft

Determine the flow rate of fluid for a pipe with a diameter of 3.25 ft and a slope of 0.025 ft.

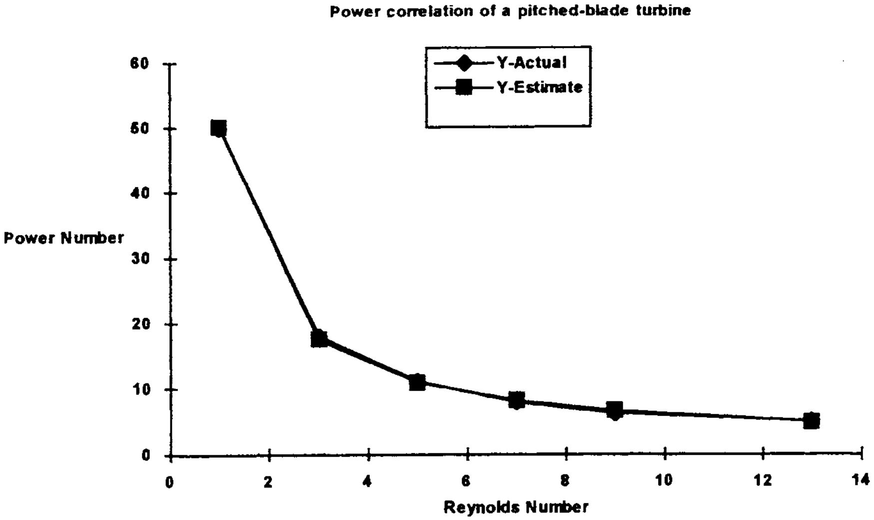


Figure 1-7. A characteristic impeller curve of power number as a function of Reynolds number.

Table P1-2

Diameter ft X_1	Slope, ft/ft X_2	Flowrate, ft^3/s Y
1.0	0.001	1.5
2.5	0.005	9.0
3.0	0.010	25.0
4.0	0.010	5.0
1.0	0.050	30.0
3.5	0.050	100.0

Solution

Program PROG12 determines the values of the coefficients C_0, C_1, and C_2 and the correlation coefficient. The coefficients are:

$$C_0 = 563.24$$
$$C_1 = 0.2725$$
$$C_2 = 0.8696$$

The correlation coefficient r = 0.9045.

The predicted flow for a pipe with a diameter of 3.25 ft and a slope of 0.03 ft/ft is 36.81 ft^3/sec.

Problem 1-3

The following data are obtained from $y(x) = x^4 + 3x^3 + 2x^2 + x + 5$. Show that a fourth-degree polynomial provides the best least squares approximation to the given data. Determine this polynomial.

Table P1-3

X	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Y	5.123	5.306	5.569	5.938	6.437	7.098	7.949	9.025	10.363

Solution

Program PROG13 calculates (i) the coefficients for each degree of the polynomial, (ii) the variance, (iii) error sum of squares, (iv) total sum of squares, (v) coefficient of determination, and (vi) the correlation coefficient. The program shows that the fourth degree gives the lowest value of the variance, and therefore shows the best fit. The results are:

(i) the variance = 0.5557E-06
(ii) the error sum of squares = 0.2223E-05
(iii) the total sum of squares = 0.2620E+02
(iv) the correlation coefficient = 1.00

The calculated polynomial is:

$$y(x) = 4.999 + 1.011x + 1.965x^2 + 3.047x^3 + 0.977x^4$$

Problem 1-4

The final product from a chemical factory is made by blending four liquids (α, β, γ, δ) together. Each of these liquids contains four components A, B, C, and D. The product leaving the factory has to have a closely specified composition. Determine the relative quantities of α, β, γ, and δ required to meet the blend specifications in the following data:

Table P1-4

Component	w/w composition of α	β	γ	δ	w/w composition of specification
A	51.30	43.20	56.40	47.40	48.80
B	11.30	11.50	15.50	8.50	11.56
C	29.40	31.50	22.50	30.40	29.43
D	8.00	10.30	5.60	13.70	10.21

Source: B.Sc. Final year 1978, Aston University, Birmingham, U.K.

Solution

Program PROG14 uses the Gaussian elimination method to determine the quantities of each of α, β, γ, and δ and required to meet the blending specification. Answers:

$\alpha = 0.1172$

$\beta = 0.3789$

$\gamma = 0.2117$

$\delta = 0.3054$

Problem 1-5

A chemical reaction takes place in a series of four continuous stirred tank reactors arranged as shown. The chemical reaction is a first-order irreversible reaction of the type.

$$A \xrightarrow{k_i} B$$

The conditions of temperature in each reactor are such that the values of k_i and V_i are given in Table P1-5. Figure 1-8 shows four continuous stirred tanks with recycle streams.

The following assumptions are:

1. The system is at steady state.
2. The reactions are in the liquid phase.

Table P1-5

Reactor	Volume, V_i L	Rate Constant, k_i h^{-1}
1	1000	0.1
2	1500	0.2
3	100	0.4
4	500	0.3

Source: A. Constantinides [1], Applied Numerical Methods With Personal Computers, *Courtesy of McGraw-Hill Book Co., 1987.*

$$A \xrightarrow{k_i} B$$

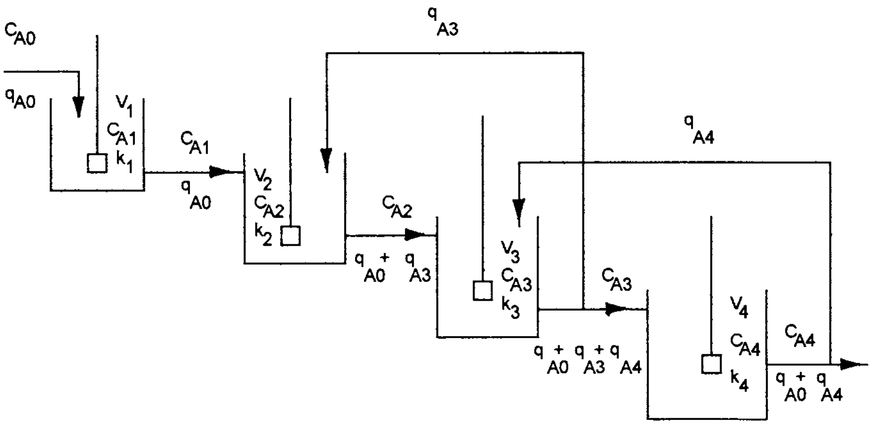


Figure 1-8. Chemical reaction with recycles in four continuous stirred tanks.

3. There is no change in volume or density of the liquid.
4. The rate of disappearance of component A in each in reactor is given by:

$$(-r_A) = kC_A$$

Set up the material balance equations for each of the four reactors, and use the Gauss-Seidel method to determine the exit concentration from each reactor.

Solution

The general unsteady state material balance for each reactor is:

Input = output + disappearance + accumulation by reaction

Mass balance for reactor 1.

$$q_{A0}C_{A0} = q_{A0}C_{A1} + (-r_A)V_1 + V_1 \frac{dC_{A1}}{dt}$$

Because the system is at steady state, the accumulation is zero, the above equation becomes

$$q_{A0}C_{A0} = q_{A0}C_{A1} + k_1 C_{A1} V_1$$

Mass balance for reactor 2.

$$q_{A0}C_{A1} + q_{A3}C_{A3} = (q_{A0} + q_{A3})C_{A2} + k_2C_{A2}V_2$$

Mass balance for reactor 3.

$$(q_{A0} + q_{A3})C_{A2} + q_{A4}C_{A4} = (q_{A0} + q_{A3} + q_{A4})C_{A3} + k_3V_3C_{A3}$$

Mass balance for reactor 4.

$$(q_{A0} + q_{A4})C_{A3} = (q_{A0} + q_{A4})C_{A4} + k_4V_4C_{A4}$$

where

$$q_{A0} = 1000\frac{\text{liters}}{\text{h}}, C_{A0} = 1\frac{\text{mol}}{\text{liter}}$$

$$q_{A3} = 100\frac{\text{liters}}{\text{h}}$$

$$q_{A4} = 100\frac{\text{liters}}{\text{h}}$$

$$(1000)(1) = 1000C_{A1} + (0.1)(C_{A1})(1000)$$

$$1000C_{A1} + 100C_{A3} = 1100C_{A2} + (0.2)(C_{A2})(1500)$$

$$1100C_{A2} + 100C_{A4} = 1200C_{A3} + (0.4)(C_{A3})(100)$$

$$1100C_{A3} = 1100C_{A4} + (0.3)(C_{A4})(500)$$

Rearranging the above equations:

$$\begin{array}{lllllr}
1100C_{A1} & & & & = & 1000 \\
1000C_{A1} & -1400C_{A2} & +100C_{A3} & & = & 0 \\
 & 1100C_{A2} & -1240C_{A3} & +100C_{A4} & = & 0 \\
 & & 1100C_{A3} & -1250C_{A4} & = & 0
\end{array}$$

The above is a set of four simultaneous linear algebraic equations. This is a diagonal system of equations because the coefficients on the diagonal are larger in above value than the sum of the absolute values of the other coefficients. Therefore, the best method of solution for a diagonal system of linear algebraic equations is the Gauss-Seidel method. PROG15 is the Gauss-Seidel computer program for solving the above equations. The four material balance equations are rearranged to solve for the unknown on the diagonal position of each equation.

$$C_{A1} = \frac{1000}{1100}$$

$$C_{A2} = \frac{1000C_{A1} + 100C_{A3}}{1400}$$

$$C_{A3} = \frac{1100C_{A2} + 100C_{A4}}{1240}$$

$$C_{A4} = \frac{1100C_{A3}}{1250}$$

An initial guess of C_{A1}, C_{A2}, C_{A3} and $C_{A4} = 0.5$ is used to start the Gauss-Seidel iterative method. The method converges after five iterations to the solutions:

$$C_{A1} = 0.9091$$

$$C_{A2} = 0.6969$$

$$C_{A3} = 0.6654$$

$$C_{A4} = 0.5856$$

Problem 1-6

The Colebrook implicit equation for the Darcy friction factor, f_D, for turbulent flow is:

$$F(f_D) = \frac{1}{f_D^{0.5}} + 0.86858 \ln\left[\frac{\varepsilon / D}{3.7} + \frac{2.51}{N_{Re} f_D^{0.5}}\right]$$

Determine the friction factor for $N_{Re} = 184000$, $\varepsilon = 0.00015$ ft and $D = 0.17225$ft (2.067 inch).

Solution

PROGRAM PROG16 solves the above implicit equation. The program uses Newton-Raphson method to give $f_D = 0.02063$ after three iterations.

Problem 1-7

In a fire tube boiler where gas flows inside the tubes and a steam-water mixture flows on the outside, the heat transfer coefficient inside h_i(Btu/ft^{2}hr.°F) can be expressed as:

$$h_i = 2.44 \frac{w^{0.8} F_1}{d^{0.8}}$$

where factors F_1, F_2, and F_3 are:

$$F_1 = \left(\frac{C_p}{\mu}\right)^{0.4} k^{0.6}$$

$$F_2 = \left(\frac{C_p}{\mu}\right)^{0.3} k^{0.7}$$

$$F_3 = \left(\frac{F_2}{C_p}\right) \mu^{=0.15}$$

Table P1-6 shows F_1, F_2, and F_3 for flue gas at a temperature range 200°F ≤ T ≤ 1200°F. Determine the values of F_1, F_2, and F_3 if the film temperature is 575°F.

Table P1-6

Temperature °F	F_1	F_2	F_3
200	0.1700	0.0954	0.5851
300	0.1770	0.1015	0.6059
400	0.1835	0.1071	0.6208
600	0.1943	0.1170	0.6457
800	0.2051	0.1264	0.6632
1000	0.2136	0.1340	0.6735
1200	0.2216	0.1413	0.6849

Source: V. Ganapathy, "Simplified Approach to Designing Heat Transfer Equipment," Courtesy of Chem. Eng., *April 13, 1987, pp. 88–87.*

Solution

PROG17 uses the interpolation methods of determine the values of F_1, F_2, and F_3 at t = 575°F. The values from the Stirling's central difference formula are:

$F_1 = 0.1932$
$F_2 = 0.1160$
$F_3 = 0.6431$

These values give the best interpolation at t = 575°F rather than the Newton-Gregory's forward or backward interpolation formulae.

Problem 1-8

A tracer experiment was carried out in a nozzle type reactor of volume V = 5.13L with liquid rate at 2.9 l/min. Table P1-7 shows data for the exit age distribution E(θ) against the dimensionless residence time θ. Determine the area under the distribution curve.

Table P1-7

θ	E(θ)	θ	E(θ)
0.000	0.000	1.243	0.403
0.113	0.308	1.356	0.355
0.226	0.995	1.469	0.313
0.339	0.876	1.582	0.275
0.452	0.786	1.695	0.237
0.565	0.720	1.808	0.213
0.678	0.663	1.921	0.171
0.791	0.606	2.034	0.142
0.904	0.545	2.147	0.123
1.017	0.497	2.260	0.109
1.130	0.450	2.373	0.095

Source: A. K. Coker, Ph.D., "A Study of Fast Reactions in Nozzle Type Reactors," 1985, Aston University, Birmingham, U.K.

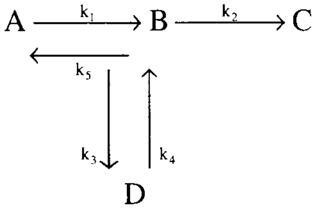
Solution

Program PROG18 uses Simpson's rule to compute the area of the exit age distribution of a tracer from a nozzle reactor.

The area under the distribution curve $\int_{0.0}^{2.373} E(\theta) = 1.0037$

Problem 1-9

Design of a batch reactor for complex reactions of the type



Determine the concentrations of A, B, C, and D over a period of ten minutes. The following rate constants and initial amounts for first-order reactions are:

Table P1-8

Rate Constant h^{-1}	Concentration at time t = 0 $\frac{mol}{m^3}$
$k_1 = 0.45$	$C_{A0} = 9.90$
$k_2 = 0.16$	$C_{B0} = 0.0$
$k_3 = 0.12$	$C_{C0} = 0.0$
$k_4 = 0.08$	$C_{D0} = 0.5$
$k_5 = 0.10$	

Solution

The mass balances for the batch reactor involving components A, B, C, and D are:

$$(-r_A)_{net} = k_1 C_A - k_5 C_B = -\frac{dC_A}{dt}$$

$$(-r_B)_{net} = (k_2 + k_3 + k_5)C_B - k_1C_A - k_4C_D = -\frac{dC_B}{dt}$$

$$(r_C)_{net} = k_2C_B = \frac{dC_C}{dt}$$

$$(-r_D)_{net} = k_4C_D - k_3C_B = -\frac{dC_D}{dt}$$

Rearranging the above equations

$$\frac{dC_A}{dt} = k_5C_B - k_1C_A$$

$$\frac{dC_B}{dt} = k_1C_A + k_4C_D - (k_2 + k_3 + k_5)C_B$$

Table P1-9
Runge-Kutta Fourth Order Method for a System of Ordinary Differential Equations

TIME	CONC. CA	CONC. CB	CONC. CC	CONC. CD
.00	9.90	.00	.00	.50
.50	8.15	1.65	.07	.54
1.00	6.77	2.72	.25	.66
1.50	5.68	3.39	.50	.83
2.00	4.82	3.77	.78	1.03
2.50	4.12	3.95	1.09	1.23
3.00	3.55	4.00	1.41	1.44
3.50	3.09	3.94	1.73	1.64
4.00	2.71	3.83	2.04	1.82
4.50	2.39	3.68	2.34	1.99
5.00	2.12	3.51	2.63	2.14
5.50	1.89	3.33	2.90	2.27
6.00	1.69	3.15	3.16	2.39
6.50	1.52	2.97	3.41	2.49
7.00	1.38	2.80	3.64	2.58
7.50	1.25	2.64	3.86	2.65
8.00	1.14	2.49	4.06	2.71
8.50	1.04	2.34	4.26	2.76
9.00	.96	2.21	4.44	2.79
9.50	.88	2.09	2.61	2.82
10.00	.81	1.97	4.77	2.84

$$\frac{dC_C}{dt} = k_2 C_B$$

$$\frac{dC_D}{dt} = k_3 C_B - k_4 C_D$$

where F(1) = dC_A/dt, F(2) = dC_B/dt, F(3) = dC_C/dt and F(4) = dC_D/dt and X(1) = C_A, X(2) = C_B, X(3) = C_C and X(4) = C_D.

Thus, we can express the differential equations in the form of x-arrays as:

$F(1) = k_5.X(2) - k_1.X(1)$
$F(2) = k_1.X(1) + k_4.X(4) - (k_2 + k_3 + k_5).X(2)$
$F(3) = k_2.X(2)$
$F(4) = k_3.X(2) - k_4.X(4)$

Program PROG19 uses the Runge-Kutta fourth-order to solve the differential equations F(1), F(2), F(3), and F(4). Table P1-9 gives the computer printouts of C_A, C_B, C_C, and C_D from t= 0 to t=10 minutes. Figure 1-9 shows the profiles of concentrations from the start of the batch reaction to the final time of ten minutes.

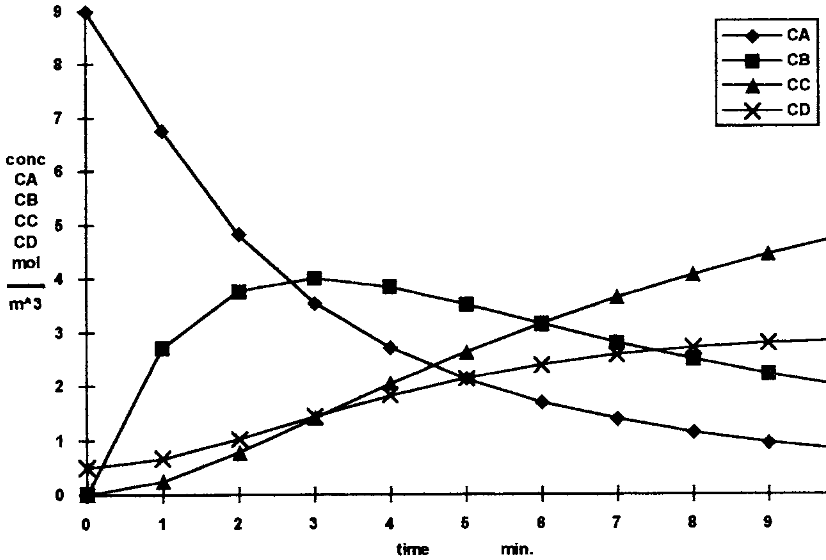


Figure 1-9. Concentration profiles of A, B, C, and D as a function of time in a batch reactor.

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```
      PROGRAM PROG11
C     ******************************************************************
C     *  THE PROGRAM DETERMINES A RELATIONSHIP BETWEEN TWO VARIABLES    *
C     *  i.e. ONE DEPENDENT AND ONE INDEPENDENT VARIABLE. THE PROGRAM   *
C     *  SELECTS THE CURVE OF BEST FIT BY TESTING THE DATA AGAINST      *
C     *  EQUATIONS OF THE FORM: Y=a+b.F(x)                               *
C     *  THE PROGRAM GIVES THE CONSTANTS FOR THE EQUATION AND THE       *
C     *  CORRELATION COEFFICIENT.                                        *
C     ******************************************************************

C     THIS PROGRAM WILL CORRELATE X-Y DATA FOR THE FOLLOWING EQUATIONS:

C     1.  Y=a+b.X
C     2.  Y=a+b.X^2
C     3.  Y=a+b.X^0.5
C     4.  Y=a.exp(b.X)
C     5.  Y=a+b.ln(X)
C     6.  Y=a.X^b
C     7.  Y=a+b.(1/X)
C     8.  1/Y=a+b.(1/X)

C     X     =   VECTOR OF INDEPENDENT VARIABLE
C     Y     =   VECTOR OF DEPENDENT VARIABLE
C     YCAL  =   VECTOR OF THE ESTIMATED DEPENDENT VARIABLE
C     N     =   NUMBER OF DATA
C     A, B  =   CONSTANTS FOR THE EQUATION
C     COR   =   CORRELATION COEFFICIENT


C     *****************************************************************


        DIMENSION X(1:50),Y(1:50)

        DIMENSION YCAL1(1:50), YCAL2(1:50), YCAL3(1:50), YCAL4(1:50)
        DIMENSION YCAL5(1:50), YCAL6(1:50), YCAL7(1:50), YCAL8(1:50)

        COMMON/DATA/N,X,Y
        COMMON/DATA1/YCAL1,A1,B1
        COMMON/DATA2/YCAL2,A2,B2
        COMMON/DATA3/YCAL3, A3, B3
        COMMON/DATA4/YCAL4, A4, B4
        COMMON/DATA5/YCAL5, A5, B5
        COMMON/DATA6/YCAL6, A6, B6
        COMMON/DATA7/YCAL7, A7, B7
        COMMON/DATA8/YCAL8, A8, B8

        INTEGER N


        OPEN (UNIT=3, FILE=’DATA11.DAT’, STATUS=’OLD’, ERR=18)
        OPEN(UNIT=1,FILE=’PRN’)


        READ (3, *, ERR=19)N
        READ (3, *, ERR=19)(X(I), Y(I), I=1,N)
```

```
        GO TO 2

  18    WRITE (1, 111)
 111    FORMAT (//,6X, 'FILE DOES NOT EXIST')
        GO TO 999
 19     WRITE (1, 222)
 222    FORMAT (//,6X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

 2      WRITE(1, 100)
 100    FORMAT(//,1H0,25X,'CURVE FITTING FOR TWO VARIABLES',
     *          /1H ,78(1H*))

        WRITE(1, 110)
 110    FORMAT(//,1H0,25X,'X',15X,'Y',/1H ,78(1H-))

        DO 10 I=1,N

        WRITE(1, 120)I,X(I),Y(I)
 120    FORMAT(1H0,4X,I4,6X,F14.3,6X,E14.6)
 10     CONTINUE

        WRITE (1, 125)
 125    FORMAT (1H ,78(1H-))


        WRITE(1, 130)
 130    FORMAT(//, 1H ,25X,'THE RESULTS ARE:',/1H ,78(1H*))

        WRITE(1, 140)
 140    FORMAT(/,10X,'EQUATION',10X,'REGRESSION COEFFICIENTS',
     *          5X,'CORRELATION')

        WRITE(1, 150)
 150    FORMAT (28X,'INTECEPT: A',5X,'SLOPE: B',4X,'COEFFICIENT',
     *            /1H ,78(1H*))


         J=1

 4      GO TO (5,15,25,35,45,55,65,75),J


C       CURVE FITTING FOR : Y=A+BX


  5     CALL LINFIT(X, Y, N, A1, B1, COR1)

        WRITE (1, 160)A1, B1, COR1
  160   FORMAT(2X,'1.',5X,'Y=A+BX',10X,3(E10.4,5X))

        DO 30 I=1,N
        YCAL1(I)=A1+B1*X(I)
 30     CONTINUE

        J=J+1

        IF (J .EQ. 2) THEN
            GO TO 4
        ELSE
```

```
        GO TO 800
        ENDIF

C       CURVE FITTING FOR Y=A+BX^2

  15    DO 40 I=1,N
        X(I)=X(I)*X(I)
 40     CONTINUE
        CALL LINFIT(X, Y, N, A2, B2, COR2)

        WRITE(1, 170) A2, B2, COR2
 170    FORMAT (2X,'2.',5X,'Y=A+B*X^2',7X,3(E10.4,5X))

        DO 44 I=1,N
        YCAL2(I)=A2+B2*X(I)**2
   44   CONTINUE


        J=J+1
        IF (J .EQ. 3) THEN
        GO TO 4
        ELSE
        GO TO 800
        ENDIF


C       CURVE FITTING FOR Y=A+B.X^0.5

 25     DO 50 I=1,N
        X(I)=X(I)**0.5
 50     CONTINUE
        CALL LINFIT(X, Y, N, A3, B3, COR3)

        WRITE(1, 180) A3, B3, COR3
 180    FORMAT(2X,'3.',5X,'Y=A+B*X^0.5',5X,3(E10.4,5X))

        DO 54 I=1,N
        YCAL3(I)=A3+B3*X(I)**0.5
 54     CONTINUE


        J=J+1
        IF (J .EQ. 4) THEN
            GO TO 4
            ELSE
            GO TO 800
        ENDIF


C       CURVE FITTING FOR Y=A.EXP(B.X)
C       LINEARIZE TO Ln(Y)=Ln(A)+BX

 35     DO 60 I=1,N
```

```
       Y(I)=ALOG(Y(I))
 60    CONTINUE

       CALL LINFIT(X, Y, N, A4, B4, COR4)
       A4=EXP(A4)

       WRITE(1, 190) A4, B4, COR4
 190   FORMAT(2X,'4.',5X,'Y=A*EXP(B*X)',4X,3(E10.4,5X))

       DO 61 I=1,N
       Y(I)=EXP(Y(I))
       YCAL4(I)=A4*EXP(B4*X(I))
 61    CONTINUE


       J=J+1
       IF (J .EQ. 5) THEN
           GO TO 4
           ELSE
           GO TO 800
       ENDIF


C      CURVE FITTING FOR Y=A+B.Ln(X)



 45    DO 70 I=1,N
       X(I)=ALOG(X(I))
 70    CONTINUE
       CALL LINFIT(X, Y, N, A5, B5, COR5)

       WRITE(1, 200)A5, B5, COR5
 200   FORMAT(2X,'5.',5X,'Y=A+B*Ln(X)',5X,3(E10.4,5X))

       DO 71 I=1,N
       X(I)=EXP(X(I))
       YCAL5(I)=A5+B5*ALOG(X(I))
 71    CONTINUE

       J=J+1
       IF (J .EQ. 6) THEN
           GO TO 4
           ELSE
           GO TO 800
       ENDIF


C      CURVE FITTING FOR Y=A.X^B
C      LINEARIZE TO Ln(Y)=Ln(A)+B*Ln(X)


 55    DO 80 I=1,N
       X(I)=ALOG(X(I))
       Y(I)=ALOG(Y(I))
 80    CONTINUE

       CALL LINFIT(X, Y, N, A6, B6, COR6)
       A6=EXP(A6)
```

```
        WRITE(1,210)A6, B6, COR6
210     FORMAT(2X,'6.',5X,'Y=A*X^B',9X,3(E10.4,5X))

        DO 85 I=1,N
        X(I)=EXP(X(I))
        Y(I)=EXP(Y(I))
        YCAL6(I)=A6*(X(I)**B6)
 85     CONTINUE


        J=J+1
        IF (J .EQ. 7) THEN
            GO TO 4
            ELSE
            GO TO 800
        ENDIF


C       CURVE FITTING FOR Y=A+B.1/X


 65     DO 90 I=1,N
        X(I)=1/X(I)
 90     CONTINUE
        CALL LINFIT(X, Y, N, A7, B7, COR7)
        WRITE(1,220)A7, B7, COR7
  220   FORMAT(2X,'7.',5X,'Y=A+B*1/X',7X,3(E10.4,5X))

        DO 95 I=1,N
        X(I)=1/X(I)
        YCAL7(I)=A7+B7*1/X(I)
 95     CONTINUE


        J=J+1

        IF (J .EQ. 8) THEN
            GO TO 4
            ELSE
            GO TO 800
        ENDIF

C       CURVE FITTING FOR 1/Y=A+B.1/X


 75     DO 96 I=1,N
        X(I)=1/X(I)
        Y(I)=1/Y(I)
 96     CONTINUE

        CALL LINFIT(X, Y, N, A8, B8, COR8)

        WRITE(1, 230)A8, B8, COR8
 230    FORMAT(2X,'8.',5X,'1/Y=A+B*1/X',5X,3(E10.4,5X))


        DO 97 I=1,N
        X(I)=1/X(I)
        Y(I)=1/Y(I)
        YCAL8(I)=X(I)/(A8*X(I)+B8)
```

```
 97     CONTINUE

 800    CALL COMP(X, Y, N, COR1,COR2,COR3,COR4,COR5,COR6,COR7,COR8)

        CLOSE (3, STATUS='KEEP')
        CLOSE(1)

 999    STOP
        END

C       ****************************************************************
C       THIS PROGRAM PERFORMS A LINEAR REGRESSION ANALYSIS ON A SET
C       OF X-Y VALUES.
C       ****************************************************************

        SUBROUTINE LINFIT(X, Y, N, A,B,COR)
        DIMENSION X(1:50),Y(1:50)

        INTEGER N

        SUMX=0.0
        SUMY=0.0
        SUMXY=0.0
        SUMX2=0.0
        SUMY2=0.0
        DO 10 I=1,N
        XI=X(I)
        YI=Y(I)
        SUMX=SUMX+XI
        SUMY=SUMY+YI
        SUMXY=SUMXY+XI*YI
        SUMX2=SUMX2+XI*XI
        SUMY2=SUMY2+YI*YI
 10     CONTINUE
        SXX=N*SUMX2-SUMX*SUMX
        SXY=N*SUMXY-SUMX*SUMY
        SYY=N*SUMY2-SUMY*SUMY

C       CALCULATE THE CONSTANTS FOR THE EQUATION

        B=SXY/SXX
        XMEAN=SUMX/N
        YMEAN=SUMY/N

C       THIS PRINTS THE RESULTS ON THE SCREEN.

        WRITE(*, 50)XMEAN,YMEAN
 50     FORMAT(6X,'XMEAN:',F12.3,3X,'YMEAN:',F12.4)

        A=YMEAN-B*XMEAN

C       CALCULATE THE CORRELATION COEFFICIENT

        COR=ABS(SXY/SQRT(SXX*SYY))

        WRITE(*, 60)A, B, COR
```

```
 60     FORMAT(6X,'A=',F12.3,3X,'B=',F12.3,3X,'COR=',F12.4)

        RETURN
        END

C       ***************************************************************
C
C       THIS PROGRAM COMPARES THE VALUES OF THE CORRELATION COEFFICIENT
C       OF THE REGRESSION ANALYSES
C       ***************************************************************

      SUBROUTINE COMP(X, Y, N, COR1,COR2,COR3,COR4,COR5,COR6,COR7,COR8)
      DIMENSION X(1:50), Y(1:50)
      DIMENSION YCAL1(1:50), YCAL2(1:50), YCAL3(1:50), YCAL4(1:50)
      DIMENSION YCAL5(1:50), YCAL6(1:50), YCAL7(1:50), YCAL8(1:50)

      INTEGER N
      COMMON/DATA1/YCAL1,A1,B1
      COMMON/DATA2/YCAL2,A2,B2
      COMMON/DATA3/YCAL3,A3,B3
      COMMON/DATA4/YCAL4,A4,B4
      COMMON/DATA5/YCAL5,A5,B5
      COMMON/DATA6/YCAL6,A6,B6
      COMMON/DATA7/YCAL7,A7,B7
      COMMON/DATA8/YCAL8,A8,B8

C     FIND THE MAXIMUM VALUE OF THE CORRELATION COEFFICIENTS


      CORR=AMAX1(COR1,COR2,COR3,COR4,COR5,COR6,COR7, COR8)

      WRITE(1,100)CORR
 100  FORMAT(//,2X,'MAXIMUM CORRELATION COEFFICIENT:',F12.4)

C     COMPARE THIS VALUE WITH THE CALCULATED VALUES OF THE
C     REGRESSION ANALYSES.

      IF (CORR .EQ. COR1) THEN
          CALL OUTPUT(X, Y, YCAL1, N, A1,B1,COR1)
          GO TO 10
      ELSEIF (CORR .EQ. COR2) THEN

          CALL OUTPUT(X, Y, YCAL2, N, A2, B2, COR2)
          GO TO 10

      ELSEIF (CORR .EQ. COR3) THEN
        CALL OUTPUT(X, Y, YCAL3, N, A3, B3, COR3)
        GO TO 10

        ELSEIF (CORR .EQ. COR4) THEN
        CALL OUTPUT (X, Y, YCAL4, N, A4, B4, COR4)
        GO TO 10

        ELSEIF (CORR .EQ. COR5) THEN
        CALL OUTPUT(X, Y, YCAL5, N, A5, B5, COR5)
        GO TO 10

        ELSEIF (CORR .EQ. COR6) THEN
        CALL OUTPUT(X, Y, YCAL6, N, A6, B6, COR6)
```

```
        GO TO 10

        ELSEIF (CORR .EQ. COR7) THEN
        CALL OUTPUT (X, Y, YCAL7, N, A7, B7, COR7)
        GO TO 10

        ELSE IF (CORR .EQ. COR8) THEN
        CALL OUTPUT(X, Y, YCAL8, N, A8, B8, COR8)
        ENDIF

 10     RETURN
        END

C       ************************************************************
C       THIS PROGRAM OUTPUTS THE RESULTS OF THE REGRESSION ANALYSIS
C       WITH THE ESTIMATED VALUE OF THE DEPENDENT VARIABLE,
C       THE CONSTANTS AND THE CORRELATION COEFFICIENT.
C       ************************************************************

        SUBROUTINE OUTPUT (X, Y, YCAL, N, A, B, COR)
        DIMENSION X(1:50), Y(1:50), YCAL(1:50)
        INTEGER N

        WRITE(1, 100)
 100    FORMAT(/,1H0, 21X,'X-ACTUAL', 13X,'Y-ACTUAL', 11X,'Y-ESTIMATE',
     *          /,1H ,78(1H-))
        DO 10 I = 1,N

        WRITE(1, 110) I, X(I), Y(I), YCAL(I)
 110    FORMAT(1H0,4X,I4,6X,F14.3,2(6X,F14.6))
 10     CONTINUE

        WRITE (1, 120)
 120    FORMAT (1H ,78(1H-))

        WRITE (1, 130)A, B, COR
 130    FORMAT(//,1H0,6X,'CONSTANTS FOR THE EQUATION:',/1H0,6X,
     *          'A:', 6X, F12.4, /1H0, 6X, 'B:', 6X, F12.4,/1H0, 6X,
     *          'CORRELATION COEFFICIENT:',F12.4/,1H ,78(1H-))
        RETURN
        END
```

```
DATA11.DAT
------------
6
1.0  50.0
3.0  18.0
5.0  11.0
7.0  7.90
9.0  6.20
13.0  5.0
```

```
                         CURVE FITTING FOR TWO VARIABLES
******************************************************************************


                         X                Y
------------------------------------------------------------------------------

       1                1.000          .500000E+02

       2                3.000          .180000E+02

       3                5.000          .110000E+02

       4                7.000          .790000E+01

       5                9.000          .620000E+01

       6               13.000          .500000E+01
------------------------------------------------------------------------------


                         THE RESULTS ARE:
******************************************************************************

         EQUATION              REGRESSION COEFFICIENTS     CORRELATION
                               INTECEPT: A      SLOPE: B    COEFFICIENT
******************************************************************************
 1.      Y=A+BX               .3577E+02     -.3066E+01     .7735E+00
 2.      Y=A+B*X^2            .2553E+02     -.1650E+00     .6036E+00
 3.      Y=A+B*X^0.5          .3577E+02     -.3066E+01     .7735E+00
 4.      Y=A*EXP(B*X)         .3605E+02     -.1792E+00     .9150E+00
 5.      Y=A+B*Ln(X)          .4416E+02     -.1772E+02     .9496E+00
 6.      Y=A*X^B              .4913E+02     -.9203E+00     .9986E+00
 7.      Y=A+B*1/X            .1123E+01      .4901E+02     .9998E+00
 8.      1/Y=A+B*1/X          .1575E+00     -.1559E+00     .8137E+00

 MAXIMUM CORRELATION COEFFICIENT:         .9998

                       X-ACTUAL            Y-ACTUAL            Y-ESTIMATE
------------------------------------------------------------------------------

       1                1.000            50.000010            50.130660

       2                3.000            18.000000            17.459000
```

```
     3               5.000          11.000000          10.924670

     4               7.000           7.900001           8.124240

     5               9.000           6.200000           6.568446

     6              13.000           5.000000           4.892976
-----------------------------------------------------------------------------


     CONSTANTS FOR THE EQUATION:

     A:             1.1232

     B:            49.0075

     CORRELATION COEFFICIENT:       .9998
-----------------------------------------------------------------------------
```

```
      PROGRAM PROG12
C     ***************************************************************
C     LINEAR MULTIPLE REGRESSION ANALYSIS
C     THE PROGRAM PERFORMS A LINEAR MULTIPLE REGRESSION ANALYSIS
C     INVOLVING TWO OR MORE INDEPENDENT VARIABLES AND ONE DEPENDENT
C     VARIABLE USING THE GAUSS-ELIMINATION METHOD.
C
C     THE LINEAR MULTIPLE REGRESSION EQUATION IS OF THE FORM
C     Y=Co+C1*x1+C2*x2+......+Ck*Xk
C
C     DEPENDING ON THE NUMBER OF THE INDEPENDENT VARIABLES,
C     SIMULTANEOUS SOLUTION BY GAUSS ELIMINATION IS EMPLOYED TO
C     CALCULATE THE UNKNOWN REGRESSION CO-EFFICIENTS.
C
C
C     ***************************************************************
C
C     X1,.....Xk = THE INDEPENDENT VARIABLES
C     Y          = THE DEPENDENT VARIBALE
C     CO,C1,..Ck = THE UNKNOWN REGRESSION COEFFICIENTS
C     k          = THE NUMBER OF INDEPENDENT VARIABLES.
C     N          = THE NUMBER OF DATA VALUES
C     N1         = THE NUMBER OF EQUATIONS
C
C     ***************************************************************
C
C
      DIMENSION A(1:50,1:50),B(1:50),X1(1:50),X2(1:50)
      DIMENSION Y(1:50),YCAL(1:50)
      REAL MEANY


      DATA N/6/, N1/3/

      DATA X1(1)/1.00/, X2(1)/0.001/, Y(1)/1.5/
      DATA X1(2)/2.50/, X2(2)/0.005/, Y(2)/9.0/
      DATA X1(3)/3.00/, X2(3)/0.010/, Y(3)/25.0/
      DATA X1(4)/4.00/, X2(4)/0.010/, Y(4)/5.0/
      DATA X1(5)/1.00/, X2(5)/0.050/, Y(5)/30.0/
      DATA X1(6)/3.50/, X2(6)/0.050/, Y(6)/100.0/

C     THIS OPEN STATEMENT PRINTS THE RESULTS ONTO A PRINTER

      OPEN (UNIT=1, FILE='PRN')

C     LINEAR MULTIPLE REGRESSION ANALYSIS FOR AN EQUATION
C     Y=C0+C1*X1+C2*X2

      WRITE(1, 100)
  100 FORMAT(//,20X,'LINEAR MULTIPLE REGRESSION ANALYSIS',/1H ,20X,
     *'FOR AN EQUATION : Y=C0+C1*X1+C2*X2',/1H ,74(1H*))

      WRITE(1, 110)
  110 FORMAT(/,1H0,25X,'X1',15X,'X2',15X,'Y',/,1H ,74(1H-))

      DO 20 I=1,N
      WRITE(1, 115)I,X1(I),X2(I),Y(I)
  115 FORMAT(6X,I4,3(6X,F12.4))
   20 CONTINUE
```

```
      WRITE (1, 120)
  120 FORMAT (1H ,74(1H-))

C     LINEARIZE BOTH THE INDEPENDENT AND DEPENDENT VARIABLES.

      DO 12 J = 1, N
      X1(J)   = ALOG(X1(J))
      X2(J)   = ALOG(X2(J))
      Y(J)    = ALOG(Y(J))
 12   CONTINUE

      WRITE(1,121)
 121  FORMAT(/,1H ,20X,'LINEARIZED INDEPENDENT AND DEPENDENT VARIABLES')
      WRITE(1,122)
 122  FORMAT(/,3X,70(1H*)//,1H0,25X,'X1',15X,'X2',15X,'Y',/,1H ,74(1H-))


      DO 15 I = 1,N
      WRITE(1, 125)I, X1(I), X2(I), Y(I)
 125  FORMAT(6X,I4,3(6X,F12.4))
 15   CONTINUE

      WRITE (1, 126)
 126  FORMAT (1H ,74(1H-))

      WRITE(1, 130)N1
 130  FORMAT(//,1H0,6X,'THE NUMBER OF EQUATIONS:',3X,I4)


C     CALCULATE THE COEFFICIENTS OF MATRIX : A AND R.H.S. VECTOR : Y


   25 SX1=0.0
      SX2=0.0
      SX1X2=0.0
      SX1SQ=0.0
      SX2SQ=0.0
      SY=0.0
      SX1Y=0.0
      SX2Y=0.0
      DO 30 J=1,N
      SX1=SX1+X1(J)
      SX2=SX2+X2(J)
      SX1X2=SX1X2+X1(J)*X2(J)
      SX1SQ=SX1SQ+X1(J)**2
      SX2SQ=SX2SQ+X2(J)**2
      SY=SY+Y(J)
      SX1Y=SX1Y+X1(J)*Y(J)
      SX2Y=SX2Y+X2(J)*Y(J)
   30 CONTINUE
      MEANY=SY/N

      WRITE(*, 140)SX1,SX2,SY
  140 FORMAT(3X,'SUMX1=',F10.4,6X,'SUMX2=',F10.4,6X,'SUMY=',F10.4)

C     AUGMENT THE COEFFICIENTS OF MATRIX A WITH THE R.H.S. VECTOR Y

      A(1,1)=FLOAT(N)
```

```
      A(2,1)=SX1
      A(3,1)=SX2
      A(1,2)=A(2,1)
      A(2,2)=SX1SQ
      A(3,2)=SX1X2
      A(1,3)=A(3,1)
      A(2,3)=A(3,2)
      A(3,3)=SX2SQ
      A(1,4)=SY
      A(2,4)=SX1Y
      A(3,4)=SX2Y

C     NUMBER OF EQUATION: N1

      M=N1+1

      CALL GAUSS(A,B,N1,M,TEST)
      IF (TEST .EQ. 0.0) THEN
      GO TO 40
      ELSE
      WRITE(1, 160)
  160 FORMAT(//,1H0,6X,'ERROR FLAG')
      ENDIF
      GO TO 999

   40 WRITE(1, 165)
  165 FORMAT(//,1H0,74(1H*))
      CO=B(1)
      C1=B(2)
      C2=B(3)

C     CALCULATE THE ESTIMATED VALUES OF THE DEPENDENT VARIABLES

      DO 45 I=1,N
      YCAL(I)=CO+C1*X1(I)+C2*X2(I)
   45 CONTINUE

C     CALCULATE THE CORRELATION COEFFICIENT: COR

C     REGRESSION SUM OF SQUARES: SSR
C     TOTAL SUM OF SQUARES: SST
C     ERROR (OR RESIDUAL) SUM OF SQUARES: SSE

      SSR=0.0
      SST=0.0
      SSE=0.0
      DO 50 I=1,N
      SSR=SSR+(YCAL(I)-MEANY)**2
      SST=SST+(Y(I)-MEANY)**2
      SSE=SSE+(Y(I)-YCAL(I))**2
   50 CONTINUE
C
C     THE CORRELATION COEFFICIENT: COR
      COR=SQRT(1.0-(SSE/SST))
      CALL OUTPUT(X1,X2,Y,YCAL,B,N,SSR,SSE,SST,COR)
      CLOSE (UNIT= 1)

 999  STOP
      END
```

```
C
C     ****************************************************************
C     THIS PROGRAM SOLVES A SET OF LINEAR EQUATIONS USING THE
C     GAUSSIAN ELIMINATION METHOD.  A SEARCH IS MADE IN EACH COLUMN
C     FOR THE LARGEST ELEMENT.
C     ****************************************************************

      SUBROUTINE GAUSS(A,X,N,NP1,TEST)
      DIMENSION A(1:50,50),X(1:50)
      NM1=N-1
      DO 10 I=1,NM1
      KP1=I+1
      L=I
      DO 20 J=KP1,N
      IF(ABS(A(J,I)) .LE. ABS(A(L,I))) THEN
      GO TO 20
      ELSE
      L=J
      ENDIF
   20 CONTINUE
      IF(L .EQ. I) THEN
      GO TO 30
      ELSE
      IF(ABS(A(L,I)) .LE. 1E-7) THEN
      GO TO 40
      ELSE
      ENDIF
C
C     INTERCHANGE THE VALUES
C
      DO 50 J=1,NP1
      TEMP=A(I,J)
      A(I,J)=A(L,J)
      A(L,J)=TEMP
   50 CONTINUE
      ENDIF
C
C
C     ELIMINATE ALL ELEMENTS IN THE COLUMN BELOW MAIN DIAGONAL
C
   30  D=A(I,I)
      DO 60 J=1,NP1
      A(I,J)=A(I,J)/D
   60 CONTINUE
      DO 70 L=KP1,N
      E=A(L,I)
      DO 80 J=1,NP1
      A(L,J)=A(L,J)-E*A(I,J)
   80 CONTINUE
   70 CONTINUE
   10 CONTINUE

      IF(ABS(A(N,N)) .LE. 1E-7) THEN
      GO TO 40
      ELSE

C     BACK SUBSTITUTION

      X(N)=A(N,NP1)/A(N,N)
      ENDIF
```

```
      DO 85 J=1,NM1
      J1=N-J
      X(J1)=A(J1,NP1)
      DO 90 K=J1+1,N
      X(J1)=X(J1)-A(J1,K)*X(K)
   90 CONTINUE
   85 CONTINUE
      TEST=0.0
      RETURN
   40 TEST=1.0
      RETURN
      END

C     ***************************************************************
C     THIS PROGRAM GIVES THE RESULTS OF THE REGRESSION ANALYSIS WITH
C     THE ESTIMATED VALUE OF THE DEPENDENT VARIABLE, THE CONSTANTS
C     FOR THE EQUATION AND THE CORRELATION COEFFICIENT.
C     ***************************************************************

      SUBROUTINE OUTPUT(X1,X2,Y,YCAL,B,N,SSR,SSE,SST,COR)
      DIMENSION X1(1:50),X2(1:50),Y(1:50),YCAL(1:50),B(1:50)
      WRITE(1, 100)
  100 FORMAT(//,1H0,18X,'X1-ACTUAL',7X,'X2-ACTUAL',7X,'Y-ACTUAL',7X,
     *'Y-ESTIMATE',/,1H ,74(1H-))
      DO 10 I=1,N
      WRITE(1,110)I,X1(I),X2(I),Y(I),YCAL(I)
  110 FORMAT(1H0,4X,I4,6X,F10.3,6X,F10.3,6X,F10.4,6X,F10.4)
   10 CONTINUE

      WRITE (1, 115)
 115  FORMAT (1H ,74(1H-))

      CO=EXP(B(1))
      C1=B(2)
      C2=B(3)


C     CALCULATE THE PREDICTED FLOW FOR A PIPE WITH A DIAMETER OF 3.25ft.
C     AND A SLOPE OF 0.03 ft./ft.
C     Q=CO.D^C1.S^C2


      Q=CO*(3.25**C1)*(0.03**C2)
      WRITE(1, 120)CO,C1,C2
  120 FORMAT(//,1H0,6X,'COEFFICIENTS FOR THE EQUATION:',/1H0,6X,
     *'CO=',3X,F12.4,/1H0,6X,'C1=',3X,F12.4,/1H0,6X,'C2=',3X,F12.4)
      WRITE(1,130)SSR,SSE,SST,COR
  130 FORMAT(/,1H0,6X,'REGRESSION SUM OF SQUARES:',F12.4,/1H0,6X,
     *'ERROR SUM OF SQUARES:',F12.4,/1H0,6X,
     *'TOTAL SUM OF SQUARES:',F12.4,/1H0,6X,
     *'CORRELATION COEFFICIENT:',F12.4)


      WRITE(1, 140)Q
 140  FORMAT(//,1H ,6X,'THE PREDICTED FLOW FOR A PIPE WITH A DIAMETER',
     */1H ,6X,'OF 3.25ft AND SLOPE OF 0.03 ft/ft IS:',F8.2,1X,'ft.^3/s')

      WRITE (1, 150)
 150  FORMAT (1H ,74(1H-))

      RETURN
      END
```

```
                   LINEAR MULTIPLE REGRESSION ANALYSIS
                    FOR AN EQUATION : Y=CO+C1*X1+C2*X2
*************************************************************************

                            X1               X2                Y
-------------------------------------------------------------------------
        1              1.0000            .0010            1.5000
        2              2.5000            .0050            9.0000
        3              3.0000            .0100           25.0000
        4              4.0000            .0100            5.0000
        5              1.0000            .0500           30.0000
        6              3.5000            .0500          100.0000
-------------------------------------------------------------------------

                    LINEARIZED INDEPENDENT AND DEPENDENT VARIABLES

  *********************************************************************

                            X1               X2                Y
-------------------------------------------------------------------------
        1               .0000          -6.9078             .4055
        2               .9163          -5.2983            2.1972
        3              1.0986          -4.6052            3.2189
        4              1.3863          -4.6052            1.6094
        5               .0000          -2.9957            3.4012
        6              1.2528          -2.9957            4.6052
-------------------------------------------------------------------------


      THE NUMBER OF EQUATIONS:       3


*************************************************************************


                     X1-ACTUAL       X2-ACTUAL       Y-ACTUAL       Y-ESTIMATE
-------------------------------------------------------------------------

       1               .000          -6.908           .4055            .3269

       2               .916          -5.298          2.1972           1.9761

       3              1.099          -4.605          3.2189           2.6286

       4              1.386          -4.605          1.6094           2.7069

       5               .000          -2.996          3.4012           3.7287

       6              1.253          -2.996          4.6052           4.0701
-------------------------------------------------------------------------
```

```
      COEFFICIENTS FOR THE EQUATION:

      CO=       563.2403

      C1=          .2725

      C2=          .8696

      REGRESSION SUM OF SQUARES:      8.9989

      ERROR SUM OF SQUARES:      2.0016

      TOTAL SUM OF SQUARES:     11.0006

      CORRELATION COEFFICIENT:       .9045

      THE PREDICTED FLOW FOR A PIPE WITH A DIAMETER
      OF 3.25ft AND SLOPE OF 0.03 ft/ft IS:   36.81 ft.^3/s
--------------------------------------------------------------------------
```

```
      PROGRAM PROG13
C     *****************************************************************
C     THIS PROGRAM IS USED IN FITTING A POLYNOMIAL TO A SET OF DATA
C     N PAIRS OF THE INDEPENDENT AND DEPENDENT VARIABLES, X AND Y
C     ARE READ AND THE COEFFICIENTS OF THE NORMAL EQUATIONS FOR THE
C     LEAST SQUARES METHOD:
C
C     PARAMETERS ARE:-
C         X,Y      =   ARRAY OF X AND Y VALUES
C         N        =   NUMBER OF DATA PAIRS
C         MS, MF   =   THE RANGE OF DEGREE OF POLYNOMIALS TO BE COMPUTED
C         A        =   AUGMENTED ARRAY OF THE COEFFICIENTS OF THE NORMAL
C                  =   EQUATIONS
C         C        =   ARRAY OF COEFFICIENTS OF THE LEAST SQUARES
C                      POLYNOMIAL
C     ****************************************************************


      DIMENSION X(1:100), Y(1:100), C(1:10), A(1:10,1:11)
      DIMENSION XN(1:100)


      OPEN (UNIT = 1, FILE='PRN')


      DATA N/9/
      DATA X(1)/0.1/, Y(1)/5.123/, X(2)/0.2/, Y(2)/5.306/
      DATA X(3)/0.3/, Y(3)/5.569/, X(4)/0.4/, Y(4)/5.938/
      DATA X(5)/0.5/, Y(5)/6.437/, X(6)/0.6/, Y(6)/7.0988/
      DATA X(7)/0.7/, Y(7)/7.949/, X(8)/0.8/, Y(8)/9.025/
      DATA X(9)/0.9/, Y(9)/10.363/



      DATA MS/1/, MF/4/

      WRITE(1,100)
 100  FORMAT(//,1H ,20X,'POLYNOMIAL REGRESSION ANALYSIS',/1H ,20X,
     *        'FOR AN EQUATION TO AN Nth DEGREE',/1H ,20X,
     *        ': Y=C0+C1.X+C2.X^2+C3.X^3+........+Cn.X^n',/1H ,
    * 74(1H*))


      IF (MF .LE.  (N-1)) THEN
      GO TO 5
      ELSE
      MF = N-1
      WRITE(*,*)

      WRITE(*,*) 'DEGREE OF POLYNOMIAL CANNOT EXCEED N-1.'
      WRITE(*,*) 'REQUESTED MAXIMUM DEGREE TOO LARGE- REDUCED TO',MF
      ENDIF

 5    MFP1 = MF+1
      MFP2 = MF+2

      DO 10 I =1,N
      XN(I) =1.
```

```
10      CONTINUE

        YBAR = 0.0
        DO 11 J = 1,N
        YBAR = YBAR + Y(J)
 11     CONTINUE

        YBAR = YBAR/N


        DO 30 I = 1, MFP1
        A(I,1) = 0.0
        A(I, MFP2) = 0.

        DO 20 J = 1,N
        A(I,1) = A(I,1)+XN(J)
        A(I,MFP2) = A(I,MFP2)+Y(J)*XN(J)
        XN(J)=XN(J)*X(J)

20      CONTINUE
30      CONTINUE

        DO 50 I = 2,MFP1
        A(MFP1,I) = 0.

        DO 40 J = 1,N
        A(MFP1,I) = A(MFP1,I)+XN(J)
        XN(J) = XN(J)*X(J)

40      CONTINUE
50      CONTINUE

        DO 70 J = 2,MFP1
        DO 60 I = 1,MF
        A(I,J) = A(I+1,J-1)

60      CONTINUE
70      CONTINUE


        CALL LUDCMQ (A, MFP1, 10)


        MSP1 = MS +1
        DO 95 I = MSP1,MFP1
        DO 90 J = 1,I
        C(J) = A(J,MFP2)

90      CONTINUE

        CALL SOLNQ ( A, C, I, 10)
        IM1 = I - 1
        WRITE (1,110)IM1,(C(J), J=1,I)

110     FORMAT(//1H ,3X,'POLYNOMIAL OF DEGREE',I2,
     *         /1H ,3X,'COEFFICIENTS ARE:',3X,7F10.3)

        SSE = 0.0
        SST = 0.0
```

```
        DO 94 IPT = 1,N
        SUM = 0.0

            DO 93 ICOEF = 2,I
                JCOEF = I - ICOEF + 2

                SUM = (SUM + C(JCOEF))*X(IPT)

 93         CONTINUE


C       CALCULATE THE ERROR SUM OF SQUARES AND TOTAL SUM OF SQUARES

            SUM = SUM + C(1)
            SSE = SSE + (Y(IPT) - SUM)**2
            SST = SST + (Y(IPT) -YBAR)**2

 94     CONTINUE


C       CALCULATE THE VARIANCE


        VAR = SSE/(N-I)


        WRITE(1,120)VAR,SSE,SST

 120    FORMAT(/,1H ,3X,'VARIANCE IS:',11X,E12.4
     *         /,1H ,3X,'ERROR SUM OF SQUARES:', 2X,E12.4,
     *         /,1H ,3X,'TOTAL SUM OF SQUARES:',2X,E12.4)


C       CALCULATE CORRELATION OF DETERMINATION AND CORRELATION
C       COEFFICIENT.

        CORD = (1.0 - SSE/SST)
        COR = CORD**0.5


        WRITE(1,125)CORD, COR
 125    FORMAT(/,1H ,3X,'COEFFICIENT OF DETERMINATION IS:',2X, F10.4,
     *         /,1H ,3X,'CORRELATION COEFFICIENT:',2X,F10.4,
     *         /1H ,74(1H-))

 95     CONTINUE

        CLOSE (UNIT=1)

        STOP
        END
C       *****************************************************************
C       THIS PROGRAM FORMS  THE LU EQUIVALENT OF THE SQUARE
C       COEFFICIENT MATRIX A.  THE LU, IS THEN RETURNED IN THE
C       A MATRIX SPACE.  THE UPPER TRIANGULAR MATRIX U HAS ONES
C       ON ITS DIAGONAL.  THESE VALUES ARE NOT INCLUDED IN THE RESULT.
C       *****************************************************************

        SUBROUTINE LUDCMQ (A, N, NDIM)
```

```
      DIMENSION A(1:NDIM, 1:NDIM)

      DO 30 I = 1,N
      DO 30 J = 2,N
      SUM = 0.0
      IF (J .GT. I) THEN
      GO TO 15
      ELSE
      JM1 = J-1
      ENDIF

      DO 10 K = 1,JM1
      SUM = SUM + A(I,K)* A(K,J)
 10   CONTINUE
      A(I,J) = A(I,J) - SUM
      GO TO 30

 15   IM1 = I - 1

      IF (IM1 .EQ. 0.) THEN
      GO TO 25
      ELSE
      DO 20 K = 1, IM1
      SUM = SUM + A(I,K)*A(K,J)
 20   CONTINUE
      ENDIF

 25   IF (ABS(A(I,I)) .LT. 1.E-10) THEN
      GO TO 99
      ELSE
      A(I,J) = (A(I,J) - SUM)/A(I,I)
      ENDIF
 30   CONTINUE
      RETURN

 99   WRITE(*,*)'REDUCTION NOT COMPLETED AS SMALL VALUE FOUND '
      WRITE(*,*)'FOR DIVISOR IN ROW',I
      RETURN
      END
C     ******************************************************************
C     THIS PROGRAM FINDS THE SOLUTION TO A SET OF N LINEAR EQUATIONS
C     THAT CORRESPONDS TO THE RIGHT HAND SIDE VECTOR B.
C     THE A MATRIX IS THE LU DECOMPOSITION EQUIVALENT TO THE
C     COEFFICIENT MATRIX OF THE ORIGINAL EQUATIONS PRODUCED BY
C     LUDMQ.  THE SOLUTION VECTOR IS RETURNED IN THE B VECTOR.
C     DO THE REDUCTION STEP.
C     *******************************************************************

      SUBROUTINE SOLNQ ( A, B, N, NDIM)
      DIMENSION A(1:NDIM, 1:NDIM), B(1:NDIM)


      B(1) = B(1)/A(1,1)
      DO 20 I = 2,N
      IM1 = I - 1
      SUM = 0.0
      DO 10 K = 1, IM1
      SUM = SUM + A(I,K)*B(K)
```

```
 10       CONTINUE
          B(I) = (B(I) - SUM ) / A(I,I)

 20       CONTINUE

C         BACK SUBSTITUTION

          DO 40 J = 2,N
          NMJP2 = N - J + 2
          NMJP1 = N - J + 1
          SUM = 0.0

          DO 30 K = NMJP2, N
          SUM = SUM + A(NMJP1,K)*B(K)
 30       CONTINUE
          B(NMJP1) = B(NMJP1) - SUM
 40       CONTINUE
          RETURN
          END
```

```
                    POLYNOMIAL REGRESSION ANALYSIS
                    FOR AN EQUATION TO AN Nth DEGREE
                    : Y=C0+C1.X+C2.X^2+C3.X^3+........+Cn.X^n
*************************************************************************


   POLYNOMIAL OF DEGREE 1
   COEFFICIENTS ARE:        3.809     6.340

   VARIANCE IS:              .2982E+00
   ERROR SUM OF SQUARES:     .2087E+01
   TOTAL SUM OF SQUARES:     .2620E+02

   COEFFICIENT OF DETERMINATION IS:       .9203
   CORRELATION COEFFICIENT:       .9593
-------------------------------------------------------------------------


   POLYNOMIAL OF DEGREE 2
   COEFFICIENTS ARE:        5.305    -1.822     8.162

   VARIANCE IS:              .5950E-02
   ERROR SUM OF SQUARES:     .3570E-01
   TOTAL SUM OF SQUARES:     .2620E+02

   COEFFICIENT OF DETERMINATION IS:       .9986
   CORRELATION COEFFICIENT:       .9993
-------------------------------------------------------------------------


   POLYNOMIAL OF DEGREE 3
   COEFFICIENTS ARE:        4.975     1.339      .659     5.002

   VARIANCE IS:              .1281E-04
   ERROR SUM OF SQUARES:     .6405E-04
   TOTAL SUM OF SQUARES:     .2620E+02

   COEFFICIENT OF DETERMINATION IS:      1.0000
   CORRELATION COEFFICIENT:      1.0000
-------------------------------------------------------------------------


   POLYNOMIAL OF DEGREE 4
   COEFFICIENTS ARE:        4.999     1.011     1.965     3.047      .977

   VARIANCE IS:              .5557E-06
   ERROR SUM OF SQUARES:     .2223E-05
   TOTAL SUM OF SQUARES:     .2620E+02

   COEFFICIENT OF DETERMINATION IS:      1.0000
   CORRELATION COEFFICIENT:      1.0000
-------------------------------------------------------------------------
```

```
      PROGRAM PROG14
C     ******************************************************************
C     THIS PROGRAM SOLVES A SET OF LINEAR EQUATIONS USING
C     THE GAUSS ELIMINATION METHOD WITH PARTIAL PIVOTING.
C
C     AB       = COEFFICIENT MATRIX AUGMENTED WITH R.H.S VECTORS.
C     N        = NUMBER OF EQUATIONS.
C     NP       = TOTAL NUMBER OF COLUMNS IN THE AUGMENTED MATRIX
C     NDIM     = FIRST DIMENSION OF MATRIX AB IN THE CALLING PROGRAM.
C                THE SOLUTION VECTORS ARE RETURNED IN THE AUGMENTATION
C                COLUMNS OF A
C     ******************************************************************

      DIMENSION A(1:10, 1:11)

      OPEN (UNIT=1, FILE='PRN')

      DATA N/4/
      DATA (A(1,J), J=1,5) /51.30, 43.20, 56.40, 47.40, 48.80/
      DATA (A(2,J), J=1,5) /11.30, 11.50, 15.50, 8.50, 11.56/
      DATA (A(3,J), J=1,5) /29.40, 31.50, 22.50, 30.40, 29.43/
      DATA (A(4,J), J=1,5) /8.00, 10.30, 5.60, 13.70, 10.21/


      WRITE(1,100)
 100  FORMAT(1H ,10X,'GAUSSIAN ELIMINATION METHOD FOR A SET OF',\)
      WRITE(1,105)
 105  FORMAT(' LINEAR EQUATIONS',/1H ,70(1H*),//)


      WRITE(1,110)
 110  FORMAT(30X,'AUGMENTED MATRIX',//)

      DO 10 I=1,N
      WRITE(1,120)(A(I,J),J=1,N+1)
 120  FORMAT(1X,1P6E12.4)

      NP =N +1
 10   CONTINUE

      DET=1.0
C
C     CALL THE GAUSSIAN ELIMINATION

      CALL GAUSS (A, N, NP, 10, DET)

      WRITE(1,125)DET
 125  FORMAT(//, 10X,'DETERMINANT=', 1X,E12.4)


      WRITE(1,130)
 130  FORMAT(//,30X,'SOLUTION', /1H ,70(1H-))
      WRITE(1,140)
 140  FORMAT(//,10X,'    I                  X(I)', /1H ,70(1H-))


      DO 20 I =1, N

      WRITE(1,150) I, A(I,N+1)
```

```
 150    FORMAT(10X,I5,10X,1PE16.6)
  20    CONTINUE
        WRITE(1,160)
 160    FORMAT(1H ,70(1H-))
        CLOSE (UNIT=1)
        STOP
        END


C       **********************************************************

        SUBROUTINE GAUSS (AB, N, NP, NDIM, DET)

        DIMENSION AB(1:NDIM, 1:NP)

C       BEGIN THE REDUCTION

        NM1=N-1

        DO 35 I=1,NM1

C       FIND THE ROW NUMBER OF THE PIVOT ROW AND THEN INTERCHANGE
C       ROWS INORDER TO PLACE THE PIVOT ELEMENT ON THE DIAGONAL.

        IPVT = I
        IP1 = I+1
        DO 10 J = IP1, N
        IF (ABS(AB(IPVT,I)) .LT. ABS(AB(J,I))) THEN
        IPVT =J
        ELSE
        ENDIF
  10    CONTINUE


C       CHECK THAT THE PIVOT ELEMENT IS NOT TOO SMALL. OTHERWISE
C       PRINT A MESSAGE AND RETURN

        IF ((ABS(AB(IPVT, I)) .LT. 1.E-5)) THEN
        DET=0.0
        GO TO 99
        ELSEIF( IPVT .EQ. I) THEN
        GO TO 25
        ENDIF

        DO 20 JCOL = I,NP
            SAVE=AB(I,JCOL)
            AB(I,JCOL)= AB(IPVT, JCOL)
            AB(IPVT,JCOL)=SAVE
  20    CONTINUE
        DET=-DET

C       REDUCE ALL ELEMENTS BELOW THE DIAGONAL IN THE I-TH ROW.
C       CHECK FIRST TO SEE IF A ZERO ALREADY PRESENT. IF SO,
C       SKIP REDUCTION FOR THAT ROW.

  25    DO 32 JROW = IP1,N
            IF (AB(JROW, I) .EQ. 0.0) THEN
            GO TO 32
            ELSE
            RATIO=AB(JROW,I)/AB(I,I)
```

```
            ENDIF

            DO 30 KCOL = IP1,NP
                AB(JROW, KCOL) = AB(JROW,KCOL)-RATIO*AB(I,KCOL)

 30         CONTINUE
 32     CONTINUE
 35     CONTINUE


C       WE STILL NEED TO CHECK A(N,N) FOR SIZE.

        IF (ABS(AB(N,N)). LT. 1.E-5) THEN
        GO TO 99
        ELSE
        ENDIF

C       BACK SUBSTITUTION

        NP1=N+1
        DO 50 KCOL =NP1,NP
            AB(N,KCOL)=AB(N,KCOL)/AB(N,N)
            DO 45 J= 2,N
            NVBL = NP1-J
            L=NVBL+1
            VALUE = AB(NVBL,KCOL)
            DO 40 K= L,N
                VALUE=VALUE-AB(NVBL,K)*AB(K,KCOL)
 40         CONTINUE
            AB(NVBL,KCOL)=VALUE/AB(NVBL,NVBL)

 45         CONTINUE
 50     CONTINUE


C       CALCULATE THE DETERMINANT OF THE MATRIX

        DO 60 I=1,N
        DET=DET*AB(I,I)
 60     CONTINUE
        RETURN


C       MESSAGE FOR A NEAR SINGULAR MATRIX.
 99     WRITE(1,100)
 100    FORMAT(//,10X,'SOLUTION NOT FEASIBLE. A NEAR ZERO PIVOT WAS',\)
        WRITE(1,110)
 110    FORMAT(' ENCOUNTERED')

        RETURN
        END
```

```
          GAUSSIAN ELIMINATION METHOD FOR A SET OF LINEAR EQUATIONS
**********************************************************************


                             AUGMENTED MATRIX


  5.1300E+01  4.3200E+01  5.6400E+01  4.7400E+01  4.8800E+01
  1.1300E+01  1.1500E+01  1.5500E+01  8.5000E+00  1.1560E+01
  2.9400E+01  3.1500E+01  2.2500E+01  3.0400E+01  2.9430E+01
  8.0000E+00  1.0300E+01  5.6000E+00  1.3700E+01  1.0210E+01


         DETERMINANT=   -.1149E+05

                             SOLUTION
----------------------------------------------------------------------


             I                  X(I)
----------------------------------------------------------------------
             1              1.172198E-01
             2              3.789395E-01
             3              2.117474E-01
             4              3.053561E-01
----------------------------------------------------------------------
```

```
        PROGRAM PROG15
C       *****************************************************************
C       GAUSS-SEIDEL ITERATION FOR N SIMULTANEOUS LINEAR EQUATIONS
C       THE ARRAY A CONTAINS THE N x N+1 AUGMENTED COEFFICIENT MATRIX
C       THE VECTOR X CONTAINS THE LATEST APPROXIMATION TO THE SOLUTION
C       THE COEFFICIENT MATRIX SHOULD BE DIAGONALLY DOMINANT.
C       AN INITIAL APPROXIMATION IS SENT TO THE SUBROUTINE IN THE VECTOR
C       X.  THE SOLUTION, AS APPROXIMATED BY THE SUBROUTINE IS RETURNED
C       IN X.  THE ITERATIONS ARE CONTINUED UNTIL THE MAXIMUM CHANGE IN
C       ANY X COMPONENT IS LESS THAN THE TOLERANCE, TOL.  IF THIS CANNOT
C       BE ACCOMPLISHED IN NITER ITERATIONS, A MESSAGE IS PRINTED.
C       IN TERMINATING THE ITERATIONS, NO ELEMENT OF X MAY UNDERGO A
C       MAGNITUDE CHANGE GREATER THAN TOLERANCE TOL FROM ONE ITERATION
C       TO THE NEXT.
C       *******************************************************************
C
C       PARAMETERS:
C
C       A     - AUGMENTED COEFFICIENT MATRIX
C       X     - INITIAL APPROXIMATION TO SOLUTION, ALSO RETURNS RESULTS
C       N     - NUMBER OF SIMULTANEOUS LINEAR EQUATIONS
C       NITER - LIMIT TO THE NUMBER OF ITERATIONS
C       TOL - TEST VALUE TO STOP THE ITERATING SOLUTION
C
C       *****************************************************************


        DIMENSION A(1:20,1:20), X(20)


        INTEGER N, NITER, I, J

        OPEN (UNIT=1, FILE='PRN')

        DATA N, NITER, TOL/4, 15, 0.0001/


        DATA A(1,1)/1100.0/, A(1,2)/0.0/, A(1,3)/0.0/, A(1,4)/0.0/
        DATA A(1,5)/1000.0/, A(2,1)/1000.0/, A(2,2)/-1400.0/
        DATA A(2,3)/100.0/, A(2,4)/0.0/, A(2,5)/0.0/, A(3,1)/0.0/
        DATA A(3,2)/1100.0/, A(3,3)/-1240.0/, A(3,4)/100.0/
        DATA A(3,5)/0.0/, A(4,1)/0.0/, A(4,2)/0.0/, A(4,3)/1100.0/
        DATA A(4,4)/-1250.0/, A(4,5)/0.0/


C       INITIAL GUESS VALUES

        DATA X(1), X(2), X(3), X(4)/0.5, 0.5, 0.5, 0.5/


        NP1 = N+1

        WRITE(1, 120)
 120    FORMAT(5X, 'SOLUTION OF SIMULTANEOUS LINEAR EQUATIONS BY',\)
        WRITE(1,125)
 125    FORMAT(' GAUSS-SEIDEL METHOD', /5X, 70(1H*))

        WRITE(1,130) N, NITER, TOL
 130    FORMAT(//, 10X, 'NUMBER OF LINEAR EQUATIONS:',I4,/,
```

```
    + 10X,'MAXIMUM ITERATIONS',I4,/,10X,'CONVERGING TOLERANCE:',E14.6)

       WRITE(1,140)
 140   FORMAT(//,10X,'THE COEFFICIENT MATRIX A(1,1)...A(N+1,N+1) IS:',/
    +  5X, 70(1H-))

       DO 10  I = 1,N
       WRITE(1,150)(A(I,J),J=1,NP1)

 150   FORMAT(/,5(3X,F12.4),5X)

 10    CONTINUE
       WRITE(1,155)
 155   FORMAT(/,5X,70(1H-))

       WRITE(1,160)
 160   FORMAT(//,10X,'THE STARTING VECTOR X(1)....X(N) IS:')

       WRITE(1,170)(X(I),I=1,N)
 170   FORMAT(/,15X,1PE14.6)

       CALL GSITER (A, X, N, NITER, NP1, TOL)

       CLOSE (UNIT=1)
       STOP
       END


       SUBROUTINE GSITER (A, X, N, NITER, NP1, TOL)
       DIMENSION A(1:20, 1:20), X(20)
       INTEGER N, NITER, FLAG


C      NORMALIZE DIAGONAL ELEMENTS IN EACH ROW

       DO 10 I =1, N
       ASTAR = A(I,I)
       DO 10 J = 1,NP1
       A(I,J) = A(I,J)/ASTAR

 10    CONTINUE


C      NOW WE PERFORM THE ITERATIONS

       DO 30 ITER =1, NITER
       FLAG = 1
       DO 40 I = 1,N
       XSTAR = X(I)
       X(I) = A(I,NP1)

C      CALCULATE NEW SOLUTION VALUE, X(I)

       DO 50 J = 1,N
       IF ( I .EQ. J) THEN
       GO TO 50
       ELSE
       X(I) = X(I)-A(I,J)*X(J)
       ENDIF
```

```
 50      CONTINUE

C        TEST X(I) FOR CONVERGENCE

         IF (ABS(XSTAR - X(I)) .LE. TOL) THEN
         GO TO 40
         else
         FLAG = 0
         ENDIF

 40      CONTINUE


         IF (FLAG .NE. 1) THEN
         GO TO 30
         ELSE

       WRITE(1,100) ITER
 100   FORMAT(/,10X,'PROCEDURE CONVERGED AFTER',2X,I2,2X,'ITERATIONS',/)

       WRITE(1,110)(X(I),I =1,N)
 110   FORMAT(/10X,'SOLUTION VECTOR X(1).....X(N) IS:',//,(15X,1PE14.6))

         WRITE (1, 120)
 120     FORMAT (5X, 70(1H-))



         GO TO 60
         ENDIF

 30      CONTINUE


 60      RETURN

C        ****************************************************************
C        NORMAL EXIT FROM THE LOOP MEANS NON CONVERGENT IN NITER
C        ITERATIONS PRINT MESSAGE AND RETURN TO THE MAIN PROGRAM.
C        ****************************************************************

         WRITE(1,130)TOL,NITER
 130     FORMAT(//,10X,'DID NOT MEET TOLERANCE OF',E14.6,'IN',I4,
     *   'ITERATIONS')

         WRITE(1,140)(X(I),I=1,N)
 140     FORMAT(/,10X,'CURRENT VECTOR X(1).....X(N) IS :',/(15X,1PE14.6))
         RETURN
         END
```

```
SOLUTION OF SIMULTANEOUS LINEAR EQUATIONS BY GAUSS-SEIDEL METHOD
**********************************************************************


     NUMBER OF LINEAR EQUATIONS:   4
     MAXIMUM ITERATIONS  15
     CONVERGING TOLERANCE:   .100000E-03


     THE COEFFICIENT MATRIX A(1,1)...A(N+1,N+1) IS:
----------------------------------------------------------------------

 1100.0000          .0000          .0000          .0000      1000.0000

 1000.0000     -1400.0000       100.0000          .0000          .0000

     .0000      1100.0000     -1240.0000       100.0000          .0000

     .0000          .0000      1100.0000     -1250.0000          .0000

----------------------------------------------------------------------


     THE STARTING VECTOR X(1)....X(N) IS:

            5.000000E-01

            5.000000E-01

            5.000000E-01

            5.000000E-01

     PROCEDURE CONVERGED AFTER   5  ITERATIONS


     SOLUTION VECTOR X(1).....X(N) IS:

            9.090909E-01
            6.968780E-01
            6.654189E-01
            5.855687E-01
----------------------------------------------------------------------
```

```
       PROGRAM PROG16
C
C     ***************************************************************
C     THIS PROGRAM EMPLOYS THE NEWTON-RAPHSON'S METHOD TO DETERMINE
C     THE ROOTS OF NONLINEAR EQUATIONS
C     ***************************************************************

      EXTERNAL FUN,FDERV

      OPEN (UNIT=1, FILE='PRN')

C     INPUT DATA FOR INITIAL GUESS OF THE ROOT

      DATA X/0.015/


      WRITE(1,100)
 100  FORMAT(15X,'NEWTON-RAPHSON METHOD FOR A NON-LINEAR EQUATION',
     *           /1H ,76(1H*))


      WRITE(1,110)X
 110  FORMAT(//,6X,'INITIAL GUESS OF THE ROOT:',F12.4)


      XTOL=1.E-4
      FTOL=1.E-5
      NLIM=50
      I=0
      CALL NEWT(FUN,FDERV,X,XTOL,FTOL,NLIM,I)

      CLOSE (UNIT=1)

      STOP
      END

C     ****************************************************************
C     THIS PROGRAM USES THE NEWTON-RAPHSON'S METHOD TO CALCULATE THE
C     ROOT OF NONLINEAR FUNCTIONS
C     ****************************************************************

      SUBROUTINE NEWT(FUN,FDERV,X,XTOL,FTOL,NLIM,I)
C
C     FUN   = FUNCTION THAT CALCULATES F(X)
C     FDERV = FUNCTION THAT CALCULATES THE DERIVATIVE OF FUN
C     X     = VALUE OF APPROXIMATE ROOT
C     XTOL,FTOL = TOLERANCE VALUES FOR X, F(X)
C     NLIM  = LIMIT TO NUMBER OF ITERATIONS
C     I     =0 SHOWS HOW ROUTINE IS TERMINATED
C     I     =1 MEETS TOLERANCE FOR X VALUES
C     I     =2   "        "       "  F(X)
C     I     =-1 NLIM IS EXCEEDED
C     ****************************************************************


      LOGICAL PRINT
      PRINT=.TRUE.
      IF (I .NE. 0) THEN
      PRINT=.FALSE.
```

```
      ELSE
      FX=FUN(X)
      ENDIF

      DO 10 J=1,NLIM
      DELTAX=FX/FDERV(X)
      X=X-DELTAX
      FX=FUN(X)
      FDX=FDERV(X)
      IF (.NOT. PRINT) THEN
      GO TO 20
      ELSE
      WRITE(1,140) J,X,FX
 140  FORMAT(//,1H0,3X,'AT ITERATION',I4,6X,'X=',E10.5,6X,
     *'F(X)=',E10.5)
      ENDIF
   20 IF (ABS(DELTAX) .LE. XTOL) THEN
      GO TO 30
      ELSEIF (ABS(FX) .LE. FTOL) THEN
      GO TO 40
      ELSE
      ENDIF
 10   CONTINUE


C     WHEN ITERATION IS COMPLETED, NLIM IS EXCEEDED

      I=-1
      WRITE(1,150)NLIM,X,FX
  150 FORMAT(//,1H0,3X,'TOLERANCE NOT MET AFTER',1X,I2,1X,
     *'ITERATIONS',1X,' THE FINAL ROOT:  X=',E10.5,2X,'F(X)=',E10.5)
      RETURN

C     THIS SECTION RETURNS AFTER MEETING XTOL

   30 I=1
      WRITE(1,160)J,X,FX
  160 FORMAT(//,1H0,3X,'TOLERANCE MET IN',1X,I2,1X,
     *'ITERATIONS',1X,'THE FINAL ROOT: X=',E10.5,2X,'F(X)=',E10.5)
      WRITE (1, 165)
 165  FORMAT (1H ,76(1H-))


      RETURN

C     THIS SECTION RETURNS AFTER MEETING F(X) TOLERANCE
   40 I=2
      WRITE(1,170)J,X,FX
 170  FORMAT(//,1H0,3X,'TOLERANCE MET IN',1X,I2,1X,
     *'ITERATIONS',1X,'THE FINAL ROOT: X=',E10.5,2X,'F(X)=',E10.5)
      WRITE (1, 175)
 175  FORMAT (1H ,76(1H-))

      RETURN
      END
C
C     ****************************************************************
C     THIS PROGRAM CALCULATES THE VALUE OF THE FUNCTION, FUN
C     ****************************************************************
```

```
      FUNCTION FUN(X)
C     The solution to F(X)=1/SQRT(X)+0.8686*ln{PR/3.7D+2.51/(RE*SQRT(X)}
C
      COMMON/COKER1/PR,D,RE

      DATA PR/.0018/,D/2.067/,RE/184000/

      FUN=1/(X**.5)+0.8686*ALOG((PR/(3.7*D))+(2.51/(RE*(X**.5))))
      RETURN
      END

C     ***************************************************************
C     THIS PROGRAM CALCULATES THE DERIVATIVE OF THE FUNCTION

      FUNCTION FDERV(X)
      COMMON/COKER1/PR,D,RE

      FDERV=-0.5/X**1.5-(4.03329/((RE*(X**1.5)*PR/D)+9.287*X))
      RETURN
      END
```

```
             NEWTON-RAPHSON METHOD FOR A NON-LINEAR EQUATION
**************************************************************************


     INITIAL GUESS OF THE ROOT:        .0150


   AT ITERATION   1      X=.19423E-01      F(X)=.22078E+00


   AT ITERATION   2      X=.20577E-01      F(X)=.93464E-02


   AT ITERATION   3      X=.20630E-01      F(X)=.18002E-04


   TOLERANCE MET IN  3 ITERATIONS THE FINAL ROOT: X=.20630E-01  F(X)=.18002E-04
--------------------------------------------------------------------------
```

```
        PROGRAM PROG17
C       ***************************************************************
C       THIS PROGRAM PERFORMS INTERPOLATION WITHIN A SET OF (X, Y)
C       PAIRS  TO GIVE THE Y VALUE CORRESPONDING TO A GIVEN X VALUE.
C       THE PROGRAM USES THE NEWTON-GREGORY FORWARD AND BACKWARD INTER-
C       POLATIONS AND STIRLING'S CENTRAL DIFFERENCE METHOD.
C
C       THE NUMBER OF DATA AND (X, Y) PAIRS ARE IN A DATA FILE:DATA17.DAT
C       THE RESULTS ARE PRINTED IN A UNIT NUMBER (UNIT=1) AND FILE NAME
C       IS ASSIGNED TO PRINT IN 'PRN'.
C
C       X    =   ARRAY OF VALUES OF THE INDEPENDENT VARIABLE
C       Y    =   ARRAY OF VALUES OF THE DEPENDENT VARIABLE
C       XR   =   THE X - VALUE FOR WHICH THE ESTIMATE OF Y IS REQUIRED
C       M    =   THE NUMBER OF INDEPENDENT VARIABLE TO BE INTERPOLATED
C       N    =   THE NUMBER OF POINTS
C       ****************************************************************


        DIMENSION X(1:90),Y(1:90,1:10),XR(1:40)
        OPEN (UNIT=3,FILE='DATA17.DAT',STATUS='OLD',ERR=18)
        OPEN (UNIT=1,FILE='PRN')
        E=0.000005

        READ(3,*,ERR=19)N
        K=(2*N)-1
        READ(3,*,ERR=19)(X(I),Y(I,1),I=1,K,2)
        GO TO 10
  18    WRITE(*,11)
  11    FORMAT(3X,'FILE DOES NOT EXIST')
        GO TO 30
  19    WRITE(*,22)
  22    FORMAT(3X,'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 30


 10     DO J=2,6
        N1=K-J
        DO I=J,K,2
        Y(I,J)=Y(I+1,J-1)-Y(I-1,J-1)
        IF (Y(I,J) .GT. E*2**(J-1)) THEN
        K1=J
        ELSE
        ENDIF
        END DO
        END DO
        WRITE(1,99)
 99     FORMAT(30X,'THE DIFFERENCE TABLE',/1H ,70(1H*))

        DO I1=1,3,2
        WRITE(1,100)X(I1),(Y(I1,J1),J1=1,I1,2)
        WRITE(1,110)(Y(I1+1,J1),J1=2,I1+1,2)
 100    FORMAT(1H ,8X,F8.1,2(8X,F8.4))
 110    FORMAT(1H ,32X,2(F8.4,8X))
        END DO

        DO I2=5,K-5,2
        WRITE(1,200)X(I2),(Y(I2,J2),J2=1,6,2)
```

```
        WRITE(1,250)(Y(I2+1,J2),J2=2,6,2)
 200    FORMAT(1H ,8X,F8.1,3(8X,F8.4))
 250    FORMAT(1H ,32X,3(F8.4,8X))
        END DO

        DO I3=K-4,K-1,2
        WRITE(1,300) X(I3),(Y(I3,J3),J3=1,K-I3+1,2)
        WRITE(1,350)(Y(I3+1,J3),J3=2,K-I3,2)
 300    FORMAT(1H ,8X,F8.1,3(8X,F8.4))
 350    FORMAT(1H ,32X,2(F8.4,8X))
        END DO

        WRITE(1,400) X(K),Y(K,1)
 400    FORMAT(1H ,8X,F8.1,8X,F8.4)

        WRITE(1,450) E
 450    FORMAT(//,10X,1H ,'ROUND-OFF ERROR:',E12.5,//)


C       READ THE NUMBER OF INDEPENDENT VARIABLES TO BE INTERPOLATED

        READ(3,*,ERR=19)M

        DO L=1,M

C       READ THE VALUE OF THE INDEPENDENT VARIABLE

        READ(3,*,ERR=19) XR(L)

        DO I=1,K-1,2
        IF (XR(L) .GT. X(I) .AND. XR(L) .LT. X(I+1)) THEN
        J=I
        ELSE
        END IF
        END DO

        RC=(XR(L)-X(J))/ABS(X(3)-X(1))
        R=(XR(L)-X(1))/ABS(X(3)-X(1))
        T=(XR(L)-X(K))/ABS(X(3)-X(1))

        CALL NFD(YF,Y,R)
        CALL NBD(YB,Y,T,K)
        CALL SCD(YC,Y,RC,J)

        WRITE(1,540)
        WRITE(1,550) XR(L),YF
        WRITE(1,600) XR(L),YB
        WRITE(1,650) XR(L),YC

 540    FORMAT(20X,1H ,'INTERPOLATED VALUE OF THE INDEPENDENT VARIABLE',
     *         /1H ,70(1H*))

 550  FORMAT(/,10X,'NEWTON FORWARD DIFF.',10X,'XR=',F8.2,10X,
     *'YF=',F8.4)
 600  FORMAT(/,10X,'NEWTON BACKWAD DIFF.',10X,'XR=',F8.2,10X,
     *'YB=',F8.4)
 650  FORMAT(/,10X,'STIRLING CENTRAL DIFF.',8X,'XR=',F8.2,10X,'YC=',
     *       F8.4)
        END DO
```

```
        WRITE (1, 700)
 700    FORMAT (1H ,70(1H-))

        CLOSE (UNIT=3,STATUS='KEEP')
        CLOSE (UNIT=1)

 30     STOP
        END
C
C       ***************************************************************
C       THIS PROGRAM PERFORMS THE NEWTON-GREGORY FORWARD INTERPOLATION
C       OF POLYNOMIALS
C       ***************************************************************

        SUBROUTINE NFD(B,C,D)
        DIMENSION C(1:90,1:10)
        B=C(1,1)+D*C(2,2)+(D*(D-1.)*C(3,3))/2.0
     1  +(D*(D-1.)*(D-2.)*C(4,4))/6.
        RETURN
        END

C       *****************************************************************
C       THIS PROGRAM PERFORMS THE NEWTON-GREGORY BACKWARD INTERPOLATION
C       OF POLYNOMIALS.
C       *****************************************************************

        SUBROUTINE NBD(F,G,H,J)
        DIMENSION G(1:90,1:10)
        F=G(J,1)+H*G(J-1,2)+(H*(H+1.)*G(J-2,3))/2.0
     1  +(H*(H+1.)*(H+2.)*G(J-3,4))/6.0
        RETURN
        END

C       *****************************************************************
C       THIS PROGRAM PERFORMS THE STIRLING'S CENTRAL DIFFERENCE
C       INTERPOLATION OF POLYNOMIALS.
C       *****************************************************************


        SUBROUTINE SCD(P,Q,S,J)
        DIMENSION Q(1:90,1:10)
        P=Q(J,1)+(S*((Q(J-1,2)+Q(J+1,2))/2.)/2.)+S*S*Q(J,3)
     1  +((S-1.)*S*(S-1.)*((Q(J-1,4)+Q(J+1,4))/2.)/6.)
        RETURN
        END
C       ****************************************************************
```

```
DATA17.DAT
--------------
7
200.0  0.5851
300.0  0.6059
400.0  0.6208
600.0  0.6457
800.0  0.6632
1000.0  0.6735
1200.0  0.6849
1
575.0
                             THE DIFFERENCE TABLE
**********************************************************************
           200.0           .5851
                                   .0208
           300.0           .6059          -.0059
                                   .0149           .0159
           400.0           .6208           .0100          -.0333
                                   .0249          -.0174           .0509
           600.0           .6457          -.0074           .0176
                                   .0175           .0002          -.0095
           800.0           .6632          -.0072           .0081
                                   .0103           .0083
          1000.0           .6735           .0011
                                   .0114
          1200.0           .6849

          ROUND-OFF ERROR:  .50000E-05

                    INTERPOLATED VALUE OF THE INDEPENDENT VARIABLE
**********************************************************************

         NEWTON FORWARD DIFF.          XR=  575.00          YF=   .6805

         NEWTON BACKWAD DIFF.          XR=  575.00          YB=   .4388

         STIRLING CENTRAL DIFF.        XR=  575.00          YC=   .6431
----------------------------------------------------------------------
```

```
        PROGRAM PROG18
C       *************************************************************
C       THIS PROGRAM CALCULATES THE AREA OF A FUNCTION DEFINED BY
C       THE UNIFORM SPACING OF THE INDEPENDENT X VALUES
C
C       FUN     =   ARRAY OF VALUES OF THE FUNCTION
C       N       =   NUMBER OF VALUES
C       H       =   THE UNIFORM SPACING BETWEEN X VALUES
C       AREA    =   THE ESTIMATED INTERVAL OF THE FUNCTION
C
C       **************************************************************


        DIMENSION F(1:100)

        OPEN (UNIT=3, FILE='DATA18.DAT', STATUS='OLD', ERR=18)
        OPEN (UNIT=1, FILE='PRN')


C       READ THE NUMBER OF VALUES AND THE UNIFORM SPACING
C       BETWEEN THE X- VALUES

        READ(3,*,ERR=19)N,H

        DO 10 I =1, N
        READ (3,*,ERR=19)F(I)

 10     CONTINUE

        WRITE(1,100)
 100    FORMAT(1H ,15X,'SIMPSON RULE TO CALCULATE THE INTEGRATION',\)
        WRITE(1,105)
 105    FORMAT(1X,'OF A FUNCTION',/5X,70(1H*))

        GO TO 20
 19     WRITE(*, 110)
 110    FORMAT(3X,'FILE DOES NOT EXIST')

        GO TO 999
 18     WRITE(*,120)
 120    FORMAT(3X,'ERROR MESSAGE IN THE DATA VALUE')

        GO TO 999


 20     CALL SIMPS (F, N, H, AREA)

        WRITE(1,130)AREA
 130    FORMAT(//, 20X,'AREA OF THE FUNCTION:',F10.4)

        WRITE (1, 140)
 140    FORMAT (5X,70(1H-))

        CLOSE (UNIT=3, STATUS='KEEP')
        CLOSE (UNIT=1)

 999    STOP
        END
```

```
C       **********************************************************
C       THIS PROGRAM PERFORMS SIMPSON'S RULE INTEGRATION OF A
C       FUNCTION DEFINED BY A TABLE OF EQUISPACED VALUES.
C       **********************************************************

        SUBROUTINE SIMPS(F, N, H, AREA)

        DIMENSION F(1:100)

        INTEGER N, NP, NH, NB, NE

C       DETERMINE WHETHER NUMBER OF PANELS IS EVEN
C       NUMBER OF PANELS IS N-1

        NP=N-1
        NH=NP/2
        NB=1
        AREA=1.0

        IF ((NP-2*NH) .NE. 0) THEN

C       NUMBER OF PANELS IS ODD.  THEREFORE USE SIMPSON'S 3/8 RULE
C       ON FIRST THREE AND 1/3 RULE ON THE REMAINING FUNCTION VALUES.
C

        AREA=3.0*H/8*(F(1)+3.0*F(2)+3.0*F(3)+F(4))
        NB=4
        ELSEIF (N .EQ. 4) THEN
        RETURN
        ENDIF


C       USE 1/3 RULE ADD TO FIRST, SECOND AND LAST VALUES.

        AREA=AREA+H/3.0*(F(NB)+4.0*F(NB+1)+F(N))
        NB=NB+2
        IF (NB .EQ. N) THEN
        RETURN
        ENDIF

        NE=N-2
        DO 30 I=NB, NE, 2
        AREA=AREA+H/3.0*(2.0*F(I)+4.0*F(I+1))

 30     CONTINUE
        RETURN
        END
```

```
DATA18.DAT
-----------
22  0.113
0.000
0.308
0.995
0.876
0.786
0.720
0.663
0.606
0.545
0.497
0.450
0.403
0.355
0.313
0.275
0.237
0.213
0.171
0.142
0.123
0.109
0.095
```

```
              SIMPSON RULE TO CALCULATE THE INTEGRATION OF A FUNCTION
    **********************************************************************

                  AREA OF THE FUNCTION:    1.0037
    ----------------------------------------------------------------------
```

```
      PROGRAM PROG19

C     ***********************************************************
C     THIS PROGRAM SOLVES A SYSTEM OF N FIRST ORDER DIFFENTIAL
C     EQUATIONS BY THE RUNGE-KUTTA FOURTH ORDER METHOD.
C     THE EQUATIONS ARE OF THE FORM DX1/DT = F1(X,T)
C     DX2/DT=F2(X,T), DX3/DT=F3(X,T), ETC.
C
C     DERIVS  =   A SUBROUTINE THAT CALCULATES VALUES OF THE
C                 N DERIVATIVES.  IT IS INVOKED BY THE STATEMENT
C                 CALL DERIVS (X, T, F, N)
C     TO      =   INITIAL VALUE OF THE INDEPENDENT VARIABLE.
C     H       =   THE STEP SIZE, THE INCREMENT TO TO.
C     XO      =   THE ARRAY THAT HOLDS THE INITIAL VALUES OF THE
C                 FUNCTIONS.
C     XEND    =   AN ARRAY THAT RETURNS THE FINAL VALUES OF THE
C                 FUNCTIONS.
C     XWRK    =   AN ARRAY USED TO HOLD INTERMEDIATE VALUES DURING
C                 CALCULATION.  IT MUST BE DIMENSIONED OF SIZE
C                 4 X N IN THE MAIN PROGRAM.
C     N       =   THE NUMBER OF EQUATIONS IN THE PROGRAM.
C     F       =   AN ARRAY THAT HOLDS VALUES OF THE DERIVATIVES.
C     TF      =   FINAL VALUE OF THE INDEPENDENT VARIABLE.
C     ************************************************************

      EXTERNAL DERIVS
      DIMENSION X0(1:4),F(1:4),XEND(1:4),XWRK(1:4,1:4)

      REAL K1, K2, K3, K4, K5
      COMMON/DATA1/X0
      COMMON/DATA2/K1,K2,K3,K4,K5
      COMMON/DATA3/TF

      DATA N,TF/4, 10.0/


      OPEN (UNIT=1, FILE='PRN')

      WRITE (1, 100)
 100  FORMAT (15X, 'RUNGE-KUTTA FOURTH ORDER METHOD FOR A SYSTEM OF')
      WRITE (1, 110)
 110  FORMAT (25X, 'ORDINARY DIFFERENTIAL EQUATIONS',/,5X, 74(1H*),//)

      WRITE (1, 120)
 120  FORMAT (18X,'TIME',3X,'CONC. CA',3X,'CONC. CB',3X,'CONC. CC',
     *         3X,'CONC. CD',/5X, 74(1H-),/)

      T0 = 0.0
      H = 0.5


      WRITE (1, 140) T0, (X0(I), I = 1, N)
 140  FORMAT (14X, F8.2, 5X, 4(F6.2, 5X))

5     CALL RKSYST (DERIVS, T0, H, X0, XEND, XWRK, F, N)
      T0 = T0 + H
      DO I = 1, N
      X0(I) = XEND(I)
      END DO
```

```
      WRITE (1, 150) TO, (XO(I), I = 1, N)
 150  FORMAT (14X, F8.2, 5X, 4(F6.2, 5X))

      IF (TO .LT. TF) THEN
      GO TO 5
      ELSE
      ENDIF

      WRITE (1, 160)
 160  FORMAT (5X, 74(1H-))


C     FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)


      CLOSE (UNIT = 1)

      STOP
      END
C
C     ***************************************************************
C     THIS PROGRAM SOLVES A SYSTEM OF N FIRST ORDER DIFFERENTIAL
C     EQUATIONS BY THE RUNGE-KUTTA FOURTH ORDER METHOD.
C
C     ***************************************************************

      SUBROUTINE RKSYST (DERIVS, TO, H, XO, XEND, XWRK, F, N)
      DIMENSION XO(1:N), XEND(1:N), XWRK(1:4,1:N), F(1:N)
      COMMON/DATA3/TF

C     CALCULATE THE FIRST ESTIMATE OF THE DATA X'S

      CALL DERIVS (XO, TO, F, N)
      DO I = 1, N
          XWRK(1,I) = H * F(I)
          XEND(I) = XO(I) + XWRK(1,I)/2.
      END DO

C     CALCULATE THE SECOND ESTIMATE , THE XEND VECTOR
C     HOLDS THE X-VALUES

      CALL DERIVS (XEND, TO+H/2.0, F, N)
      DO I = 1, N
          XWRK(2,I) = H * F(I)
          XEND(I)= XO(I) + XWRK(2,I)/2.
      END DO

C     CALCULATE THE THIRD ESTIMATE

      CALL DERIVS (XEND, TO+H/2.0, F, N)
      DO I = 1, N
      XWRK(3,I) = H * F(I)
      XEND(I) = XO(I) + XWRK(3,I)
      END DO

C     CALCULATE THE FOURTH ESTIMATE
```

```
        CALL DERIVS (XEND, TO+H, F, N)
        DO I = 1, N
        XWRK(4,I) = H * F(I)
        END DO

C       COMPUTE THE X VALUES AT THE END OF THE INTERVAL FROM A
C       WEIGHTED AVERAGE OF THE FOURTH ESTIMATES.

        DO I=1,N
        XEND(I)=X0(I)+(XWRK(1,I)+2.0*XWRK(2,I)+2.*XWRK(3,I)+
     +  XWRK(4,I))/6.
        END DO


        RETURN
        END


C       ****************************************************************
C       THIS PROGRAM DEFINES THE FUNCTIONS OF THE ORDINARY DIFFERENTIAL
C       EQUATIONS IN TERMS OF THE F'S AND THE X'S.
C       ****************************************************************


        SUBROUTINE DERIVS (X, T, F, N)
        DIMENSION X(1:N),F(1:N)
        COMMON/DATA2/K1,K2,K3,K4,K5
        REAL K1,K2,K3,K4,K5
        F(1)=K5*X(2)-K1*X(1)
        F(2)=K1*X(1)+K4*X(4)-(K2+K3+K5)*X(2)
        F(3)=K2*X(2)
        F(4)=K3*X(2)-K4*X(4)
        RETURN
        END

C       ****************************************************************
C       THIS STORES THE DATA FOR THE RATE CONSTANTS AND THE INITIAL
C       STARTING VALUES OF THE CONCENTRATIONS.
C       *****************************************************************

        BLOCK DATA
        DIMENSION X0(4)
        COMMON/DATA1/X0
        COMMON/DATA2/K1,K2,K3,K4,K5
        REAL K1,K2,K3,K4,K5
        DATA X0/9.9,0.0,0.0,0.5/
        DATA K1/0.4/,K2/0.16/,K3/0.13/,K4/0.08/,K5/0.10/
        END
```

CHAPTER 2

Physical Property of Liquids and Gases

INTRODUCTION

Physical property data of compounds are frequently required for pilot plant studies or for the design of large process plants. These data are not readily available except in some simulation design packages or in the largest libraries. The data can, of course, be obtained by conducting experiments to measure the properties of individual substances or of mixtures, which may exhibit nonideal behavior. However this is often time-consuming and expensive. Therefore engineers may resort to correlations and interpolations to obtain data of sufficient accuracy for design purposes. Thermodynamic data of this type is required in most calculations such as sizing vessels, process pipe lines, separation of multicomponents, gas absorption and chemical reactor design.

Many predictions and correlations of thermodynamic physical data have been published [1-3]. This chapter reviews physical property data for liquids and gases and presents computer programs to calculate these properties for a range of temperature and correlation constants. Appendix A provides tables of some selected physical property data.

Physical Property Data of Water

The programs described cover thermodynamic data of water over a range of temperature from 0°C to 350°C. These data are for density, viscosity, heat capacity, thermal conductivity, surface tension, latent heat of vaporization, and vapor pressure.

Density of Liquids

Saturated liquid densities at any temperature are based on the correlation [1]:

$$\rho_L = AB^{-(1-T_r)^{2/7}} \tag{2-1}$$

where ρ_L = saturated liquid density, g/cm^3.
A and B = correlation constants for a chemical compound.
T_r = reduced temperature, T/T_c.

Many methods [4,5,6] have been proposed to estimate specific volumes or densities of pure liquids. All are based on the law of corresponding states. They are complex algebraically and therefore require the aid of a computer when many calculations are involved. Appendix A1 gives tabulated values of the correlation constants A and B for some chemical compounds. Computer program PROG21 employs Equation 2-1 for estimating the density of liquids. Typical results for water are illustrated in Table 2-1. Figure 2-1 shows the density of water over the range from 0°C to a critical value of T_c = 374.2°C.

Viscosity of Liquids

The viscosity of a saturated liquid as a function of temperature can be expressed by,

$$\log \mu_L = A + \frac{B}{T} + CT + DT^2 \tag{2-2}$$

where μ_L = viscosity of saturated liquid, cP
A, B, C, and D = correlation constants
T = temperature, K

The viscosities of liquids decrease with temperature. Also, the variation is linear over a wide range of temperatures from the freezing point to the boiling point. This is expressed by the Andrade correlation [7],

$$\ln \mu_L = \ln A + \frac{B}{T} \tag{2-3}$$

Equation 2-3 is used to correlate the effect of temperature on liquid viscosity. However, it fails at low temperatures because liquids show a

(text continued on page 108)

Table 2-1
Computer Output of Physical Properties of Water

```
                         PHYSICAL PROPERTY DATA OF WATER
*****************************************************************************


                                         TEMPERATURE oC
                              1                .00
                              2              25.00
                              3              50.00
                              4             100.00
                              5             150.00
                              6             200.00
                              7             250.00
                              8             300.00
                              9             350.00
                             10             374.20
----------------------------------------------------------------------------


                         DENSITY OF WATER: OoC - 374.2oC
*****************************************************************************

                    TEMPERATURE oC          DENSITY g/cm.^3
----------------------------------------------------------------------------

          1               .0                1.267
          2             25.0                1.235
          3             50.0                1.203
          4            100.0                1.135
          5            150.0                1.062
          6            200.0                 .983
          7            250.0                 .893
          8            300.0                 .784
          9            350.0                 .627
         10            374.2                 .095
----------------------------------------------------------------------------


                         VISCOSITY OF WATER: OoC -   374.2oC
*****************************************************************************

                   TEMPERATURE oC          VISCOSITY  cP
----------------------------------------------------------------------------

          1               .0                1.732
          2             25.0                 .911
          3             50.0                 .561
          4            100.0                 .291
          5            150.0                 .192
          6            200.0                 .142
          7            250.0                 .109
          8            300.0                 .082
          9            350.0                 .058
         10            374.2                 .048
----------------------------------------------------------------------------


                         HEAT CAPACITY OF WATER: OoC - 350oC
*****************************************************************************
```

(continued)

Table 2-1
(continued)

	TEMPERATURE oc	HEAT CAPACITY cal/gm.oC
1	.0	.996
2	25.0	1.000
3	50.0	1.003
4	100.0	1.010
5	150.0	1.022
6	200.0	1.048
7	250.0	1.092
8	300.0	1.163
9	350.0	1.265

THERMAL CONDUCTIVITY OF WATER: 0oC - 350oC

	TEMPERATURE oC	THERMAL CONDUCTIVITY micro-cal/s.cm.K
1	.0	1375.736
2	25.0	1472.146
3	50.0	1549.540
4	100.0	1647.284
5	150.0	1668.968
6	200.0	1614.592
7	250.0	1484.156
8	300.0	1277.660
9	350.0	995.104

SURFACE TENSION OF WATER: 0oC - 374.2oC

	TEMPERATURE oC	SURFACE TENSION:dyne/cm.
1	.0	76.119
2	25.0	71.970
3	50.0	67.765
4	100.0	58.910
5	150.0	46.557
6	200.0	34.664
7	250.0	23.341
8	300.0	12.782
9	350.0	3.450
10	374.2	.000

VAPOR PRESSURE OF WATER: 0oC - 374.2 oC

	TEMPERATURE oC	VAPOR PRESSURE: mm Hg
1	.0	4.593

Table 2-1
(continued)

```
     2           25.0                 23.787
     3           50.0                 92.665
     4          100.0                761.613
     5          150.0               3578.623
     6          200.0              11679.780
     7          250.0              29846.610
     8          300.0              64535.430
     9          350.0             124430.400
    10          374.2             165952.400
-----------------------------------------------------------------------------

                 HEAT-OF-VAPORIZATION OF WATER:0oC-374.2 oC
*****************************************************************************

              TEMPERATURE oC           HEAT-OF-VAPORIZATION:cal/g
-----------------------------------------------------------------------------

     1             .0                606.263
     2           25.0                590.540
     3           50.0                574.104
     4          100.0                538.700
     5          150.0                499.026
     6          200.0                453.398
     7          250.0                398.701
     8          300.0                327.819
     9          350.0                214.156
    10          374.2                   .000
-----------------------------------------------------------------------------
```

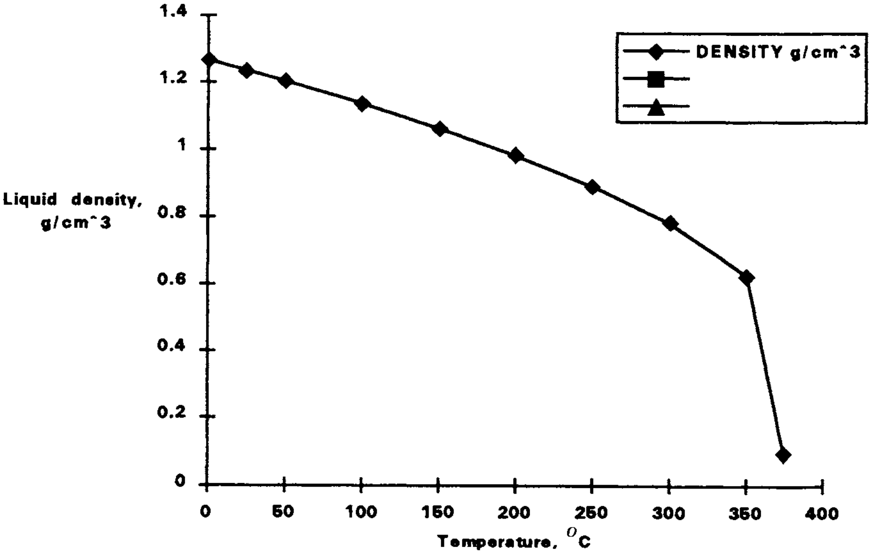

Figure 2-1. Liquid density of water as a function of temperature.

(text continued from page 104)

sharp increase in viscosity as the freezing point is approached. There are other methods in estimating liquid viscosities of compounds [2]. Figure 2-2 gives a plot of liquid viscosity of water from 0°C to its critical value of 374.2°C. Program Prog21 gives a routine for calculating the viscosity of liquids. Table 2-1 gives the viscosity of water as a function of temperature.

Heat Capacity of Liquids

Heat capacity data for liquids are relevant in process design of heat exchanger equipment and chemical reactors. For example, heat capacities are needed in the design of liquid-phase chemical reactors that involve energy input for heating liquid reactants to the reaction temperature. Alternatively, they are essential when sizing reboilers and condensers for distillation plant and when rating of heat exchangers in general.

Correlation constants for liquid heat capacity are expressed in a polynomial of the form:

$$C_p = A + BT + CT^2 + DT^3 \qquad (2\text{-}4)$$

where C_p = heat capacity of saturated liquid, cal/g°C

A, B, C , and D = correlation constants for a chemical compound

T = temperature, K

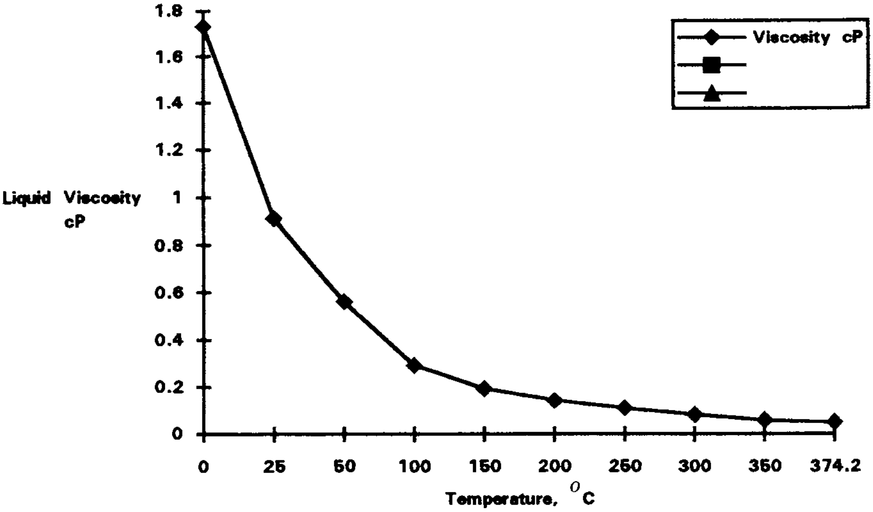

Figure 2-2. Liquid viscosity of water as a function of temperature.

Liquid heat capacities are not strongly dependent on temperatures, except at reduced temperature, ($T_r = T/T_c$), where $T_r = 0.7$ to 0.8. At high reduced temperatures, liquid heat capacities are large and strongly dependent on temperature. At the boiling point of most organic compounds, heat capacities are between 0.4 and 0.5 cal/g.K. However, in this temperature range, there is no effect of pressure [2]. The computer program PROG21 uses Equations 2-4 for estimating the heat capacity of liquids. Table 2-1 shows the heat capacity of water as a function of temperature. Figure 2-3 shows the heat capacity of water from 0°C to 350°C.

Thermal Conductivity of Liquids

Liquid thermal conductivities, k_L, are required in many chemical and process engineering applications where heat transfer is prevalent. They are required to evaluate the Nusselt number hd/k, the Prandtl number cμ/k, and in correlations to predict the idealized condensing film coefficient based upon laminar liquid flow over a cooled surface. The thermal conductivity of a saturated liquid is:

$$k_L = A + BT + CT^2 \tag{2-5}$$

where k_L = thermal conductivity of saturated liquid, microcal/s.cm.°C
A, B, and C = correlation constants
T = temperature, K

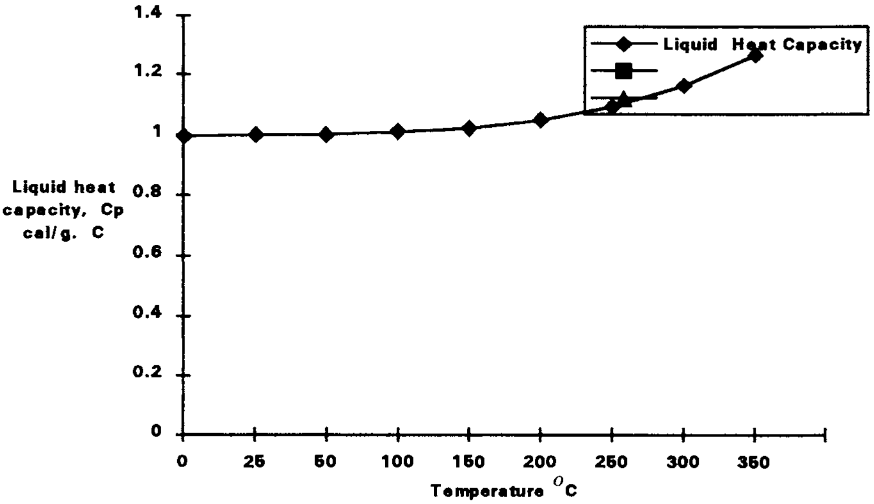

Figure 2-3. Liquid heat capacity of water as a function of temperature.

Values of k_L for most common organic liquids range between 250 and 400 μcal/cm.s.°C at temperatures below the normal boiling point. Water and other highly polar molecules have values that are two to three times larger. Except for water, aqueous solutions, and multihydroxy molecules, the thermal conductivity of most liquids decreases with temperature. Below or close to the normal boiling point, the decrease is nearly linear. Methods of computing k_L have been reviewed [2]. The computer program PROG21 gives a routine for calculating k_L of liquids, and Table 2-1 shows the results for water. Figure 2-4 is a plot of thermal conductivity of water from 0°C to 350°C.

Surface Tensions of Liquids

Surface tension data of liquids are important in many process design calculations for situations where these is a two-phase interface, e.g., two-phase flow, distillation, absorption and condensation. Surface tension can be expressed as:

$$\sigma = \sigma_1 \left[\frac{T_c - T}{T_c - T_1} \right]^R \qquad (2\text{-}6)$$

where σ_1 = surface tension at T_1°C, dynes/cm
T_c = critical temperature, K

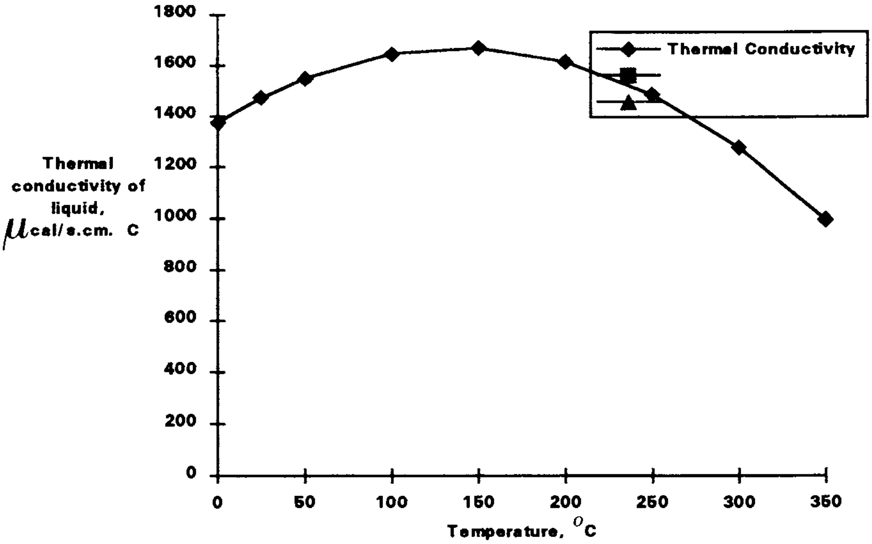

Figure 2-4. Thermal conductivity of water as a function of temperature.

T = temperature, K
R = correlation parameter

For water, the temperature range for which surface tension is valid is:

Temperature range 0°C to 100°C $\sigma_l = 71.97$
Temperature range 100°C to 374.2°C $\sigma_l = 58.91$
$T_l = 298.16$ K, R = 0.8105 for 0°C to 100°C
$T_l = 373.16$ K, R = 1.1690 for 100°C to 374.2°C.

The surface tension has been correlated with other physical parameters such as liquid compressibility, viscosity, molar fractions, and the refractive index. Rao *et al.* [8] developed a linear relationship between the surface tension at normal boiling point (log σ_b) and the reduced boiling point temperature (T_{br}). Hadden [9] presented a nomograph for hydrocarbons that enables rapid calculation of σ. For cryogenic liquids, Sprows and Prausnitz [10] introduced the equation

$$\sigma = \sigma_0(1 - T_r)^p \tag{2-7}$$

where σ = surface tension, dyne/cm

σ_0 and p were determined by a least-squares analysis of the measured data. The computer program PROG21 gives a routine for estimating the surface tension of liquids, and typical results for water are shown in Table 2-1. Figure 2-5 demonstrates the surface tension of water from 0°C to its critical value of 374.2°C. In general, the surface tension of a liquid in equilibrium with its own vapor decreases with temperature and becomes zero at the critical point. In the reduced temperature range 0.45 to 0.65, σ for most organic liquids range from 20 to 40 dyne/cm. For water, $\sigma = 71.97$ dyne/cm at 25°C.

Vapor Pressure

Vapor pressure data, P_v, of pure components are important in calculations relating to vapor-liquid phase equilibria, e.g., in the simplest case to predict the pressure in a closed vessel containing a specific liquid or mixture of liquids. P_v data are required for bubble point and most dew point computations. These values are used in flash calculations involving mass transfer operations. Clearly the design of pressure requirements for storage equipment requires knowledge of the vapor pressure of the components as does the design of appropriate pressure relief

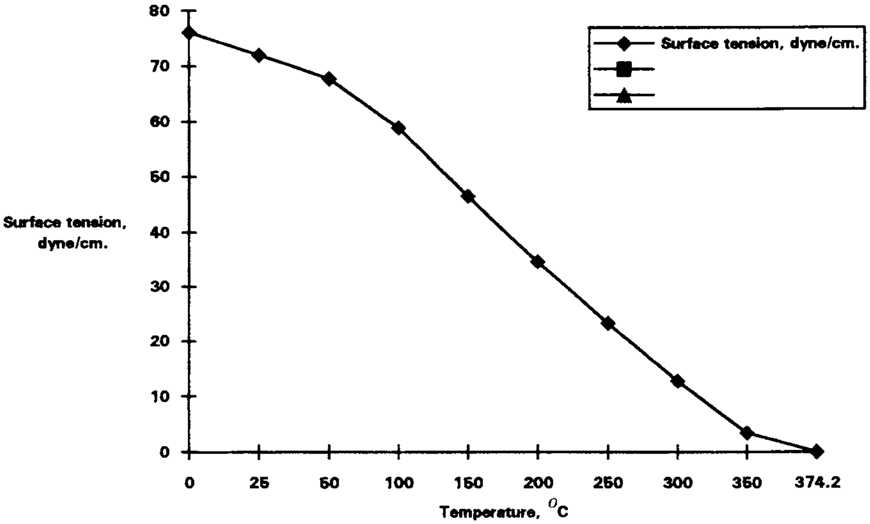

Figure 2-5. Surface tension of water as a function of temperature.

systems. The vapor pressure of the saturated liquid as a function of temperature is

$$\log P_v = A + \frac{B}{T} + C \log T + DT + ET^2 \qquad (2\text{-}8)$$

where P_v = vapor pressure of the saturated liquid, mm Hg
A, B, C, D, and E = correlation constants for the chemical compound

In the table of vapor pressure, there are values for the acentric factor ω, which is:

$$\omega = -\log P_r - 1.0 \text{ at } T_r = 0.7 \qquad (2\text{-}9)$$

where reduced pressure $P_r = P/P_c$
reduced temperature $T_r = T/T_c$

The acentric factor is used in thermodynamic correlations involving fugacity, compressibility factor, enthalpy, fugacity, and virial coefficients. The computer program PROG21 provides a routine for estimating the vapor pressure, and Table 2-1 shows P_v of water as a function of temperature. Figure 2-6 shows the vapor pressure of water as a function of temperature to its critical value of 374.2°C. For water, deviations of less

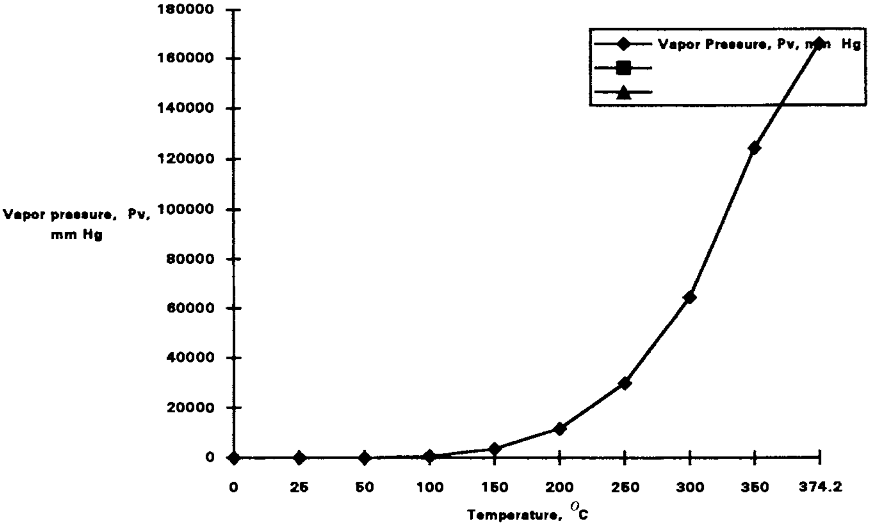

Figure 2-6. Vapor pressure of water as a function of temperature.

than 0.5% are experienced among the other methods. An equation often used to estimate the vapor pressure is the Antoine [11] equation.

$$\ln P_{vp} = A - \frac{B}{T + C} \qquad (2\text{-}10)$$

The constants A, B, and C for many compounds are in the data bank of some simulation design packages. Alternatively, these are found in texts such as Reid *et al* [2]. Equation 2-10 is only applicable for pressures with ranges from 10 to 1500 mmHg. Reid *et al* [2]. and Beaton and Hewitt [3] have discussed other methods in estimating vapor pressure of compounds but none appears to offer any specific advantage.

Enthaply of Vaporization

The enthalpy of vaporization, ΔH_v, is also termed the latent heat of vaporization. ΔH_v is the difference between the enthalpy of the saturated vapor and that of the saturated liquid at the same temperature. The enthalpy of vaporization data is used in process calculations such as the design of relief systems involving volatile compounds. In distillation, heat of vaporization values are needed to find the heat loads for the reboiler and condenser. Watson [12] has expressed a widely used correlation in calculating ΔH_v.

$$\Delta H_v = \Delta H_{v1}\left[\frac{T_c - T}{T_c - T_1}\right]^R \qquad (2\text{-}11)$$

where ΔH_v = heat of vaporization at any temperature cal/g
ΔH_{v1} = heat of vaporization at T_1, cal/g
T_c = temperature, K
R = characteristic constant for the chemical = 0.38

ΔH_v decreases with temperature and is zero at the critical point. The computer program PROG21 incorporates a routine for estimating ΔH_v, and Table 2-1 shows the results of water as a function of temperature. Figure 2-7 shows the heat of vaporization of water as a function of temperature. The shape of this plot agrees with most other enthalpy of vaporization data.

Heat Capacities of Gases

The heat capacity of gases is essential for some process engineering design, e.g., for air-cooled heat exchanger and for gas-phase chemical reactions. Here, in the latter case the heat capacities, C_p^0, for gases are required to determine the heat necessary to bring the chemical compound increase to the reaction temperature. C_p^0 is also used in the rating

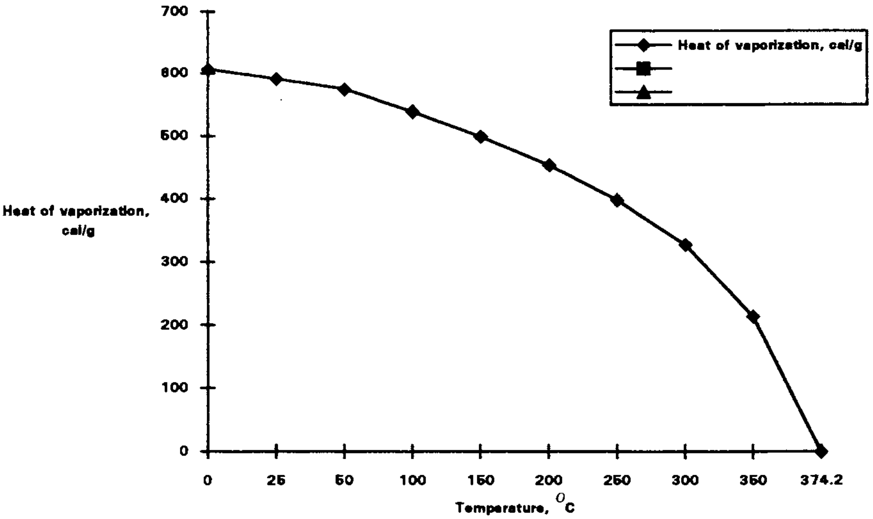

Figure 2-7. Heat of vaporization of water as a function of temperature.

of heat exchangers and energy balance computations. The heat capacity of a mixture of gases may be found from the heat capacities of the individual components contained in the mixtures.

The correlation for C_p^0 of the ideal gas at low pressure is a third-degree polynomial, which is a function of temperature.

$$C_p^0 = A + BT + CT^2 + DT^3 \tag{2-12}$$

where C_p^0 = heat capacity of ideal gas at low pressure, cal/gmol.K
A, B, C, and D = constants for the chemical compounds
T = temperature, K

The correlation coefficients A, B, C, and D can be determined using a least square fit of the experimental data, as discussed in Chapter 1. Huang and Daubert [13] published constants for a fourth-order polynomial for heat capacities of many hydrocarbons. Yuan and Mok [14] used an exponential temperature function to correlate C_p^0 with temperature and provided constants for many hydrocarbons and nonhydrocarbons. Tans [15] produced a nomograph that allows a rapid approximation of C_p^0 for paraffins. A compedium of C_p^0 as a function of temperature for several hundreds of organic compounds is given by Stull *et al.* [16] and in JANAF [17] tables. PROG22 provides a routine for estimating C_p^0 of gases, and Table 2-2 shows results of carbon dioxide. Figure 2-8 is a plot of C_p^0 with temperature for carbon dioxide.

Heats of Formation

Heats of formation, ΔH_f^0, for individual chemicals involved in chemical reactions are important to find the heat of reaction, ΔH_r^0, and associated heating and cooling requirements. If $\Delta H_r^0 < 0$, then the chemical reaction is exothermic and will require cooling. If $\Delta H_r^0 > 0$, the reaction is endothermic and heating is therefore required.

The correlation of ΔH_f^0 of the ideal gas at low temperature is based on a series expansion in temperature and is expressed as:

$$\Delta H_f^0 = A + BT + CT^2 \tag{2-13}$$

where ΔH_f^0 = heat of formation of ideal gas at low pressure, kcal/g–mol
A, B, and C = corellation constants
T = temperature, K

(text continued on page 118)

Table 2-2
Computer Output of Physical Properties of Gases

```
                         PHYSICAL PROPERTY DATA OF GASES
******************************************************************************

                                       TEMPERATURE RANGE (300 - 1500K)
-----------------------------------------------------------------------------
                              1          300.00
                              2          400.00
                              3          500.00
                              4          600.00
                              5          700.00
                              6          800.00
                              7          900.00
                              8         1000.00
                              9         1100.00
                             10         1200.00
                             11         1300.00
                             12         1400.00
                             13         1500.00
-----------------------------------------------------------------------------

                         HEAT OF FORMATION OF METHANE
******************************************************************************

                    TEMPERATURE K      HEAT OF FORMATION kcal/mol
-----------------------------------------------------------------------------

          1           300.0                   -17.962
          2           400.0                   -18.676
          3           500.0                   -19.320
          4           600.0                   -19.894
          5           700.0                   -20.398
          6           800.0                   -20.832
          7           900.0                   -21.196
          8          1000.0                   -21.490
          9          1100.0                   -21.714
         10          1200.0                   -21.868
         11          1300.0                   -21.952
         12          1400.0                   -21.966
         13          1500.0                   -21.910
-----------------------------------------------------------------------------

                         THE FREE ENERGY OF FORMATION OF ETHYLENE kcal/mol.
******************************************************************************

                   TEMPERATURE K      FREE ENERGY OF FORMATION:kcal/mol
-----------------------------------------------------------------------------

          1           300.0                    15.830
          2           400.0                    17.640
          3           500.0                    19.450
          4           600.0                    21.260
          5           700.0                    23.070
          6           800.0                    24.880
          7           900.0                    26.690
```

Table 2-2
(continued)

```
-----------------------------------------------------------------------------
        8          1000.0               28.500
        9          1100.0               30.310
       10          1200.0               32.120
       11          1300.0               33.930
       12          1400.0               35.740
       13          1500.0               37.550
-----------------------------------------------------------------------------


                         HEAT CAPACITY OF CARBON DIOXIDE
*****************************************************************************
                   TEMPERATURE K     HEAT CAPACITY cal/gm-mol.K
-----------------------------------------------------------------------------

        1               300.0            9.201
        2               400.0           10.134
        3               500.0           10.927
        4               600.0           11.594
        5               700.0           12.149
        6               800.0           12.607
        7               900.0           12.983
        8              1000.0           13.290
        9              1100.0           13.544
       10              1200.0           13.758
       11              1300.0           13.948
       12              1400.0           14.128
       13              1500.0           14.312
-----------------------------------------------------------------------------


                        THERMAL CONDUCTIVITY OF PROPANE:26.8oC-1026.8oC
*****************************************************************************
                   TEMPERATURE oC     THERMAL CONDUCTIVITY micro-cal/s.cm.K
-----------------------------------------------------------------------------

        1            26.8                 42.432
        2           126.8                 70.267
        3           226.8                103.678
        4           326.8                141.461
        5           426.8                182.412
        6           526.8                225.324
        7           626.8                268.995
        8           726.8                312.218
        9           826.8                353.789
       10           926.8                392.504
       11          1026.8                427.156
-----------------------------------------------------------------------------


                         THE VISCOSITY OF ETHANE: 26.8oC-1026.8oC
*****************************************************************************
                   TEMPERATURE oC     VISCOSITY cP.
-----------------------------------------------------------------------------

        1            26.8                   .009
        2           126.8                   .012
        3           226.8                   .015
        4           326.8                   .017
        5           426.8                   .019
        6           526.8                   .022
        7           626.8                   .024
        8           726.8                   .026
        9           826.8                   .028
       10           926.8                   .030
       11          1026.8                   .031
-----------------------------------------------------------------------------
```

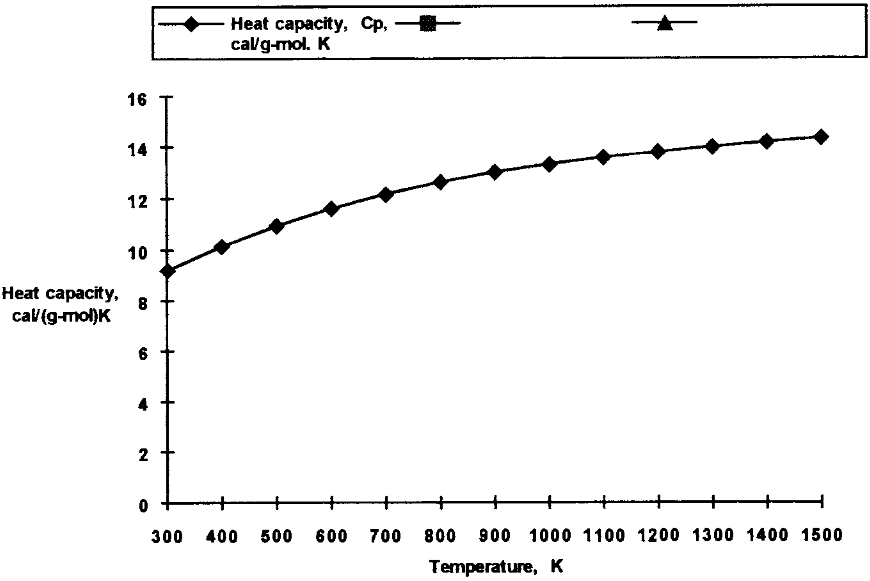

Figure 2-8. Heat capacity of carbon dioxide as a function of temperature.

(text continued from page 115)

Heats of formation are also found from measured heats of combustion, ΔH_c^0, or from an experimental enthalpy of reaction, ΔH_r^0. Domalski [18] reviewed values of $\Delta H^0_{f,298K}$ and $\Delta H^0_{c,298K}$ for several hundreds of organic compounds. The computer program PROG22 employs Equation 2-13 in a routine for estimating ΔH_f^0 as a function of temperature. Typical results for methane is presented in Table 2-2. Figure 2-9 shows a profile of ΔH_f^0 with temperature for methane between 298K and 1500K.

Free Energies of Formation

Few methods have been used to estimate the Gibbs free energy ΔG_f^0 directly. Often, ΔH_f^0 and the entropy of formation, ΔS_f^0, are determined separately. Equation 2-14 can be used to determine ΔG_f^0.

$$\Delta G_f^0 = \Delta H_f^0 - T\Delta S_f^0 \qquad (2\text{-}14)$$

ΔG_f^0 is often important in chemical reaction engineering. Values of ΔG_f^0 for individual chemicals are required to estimate the free energy of reaction, ΔG_r^0, and the corresponding chemical thermodynamic equilibrium for the reaction. Also, the following criteria are generally true for the feasibility of chemical reactions. A reaction is considered as promising, when

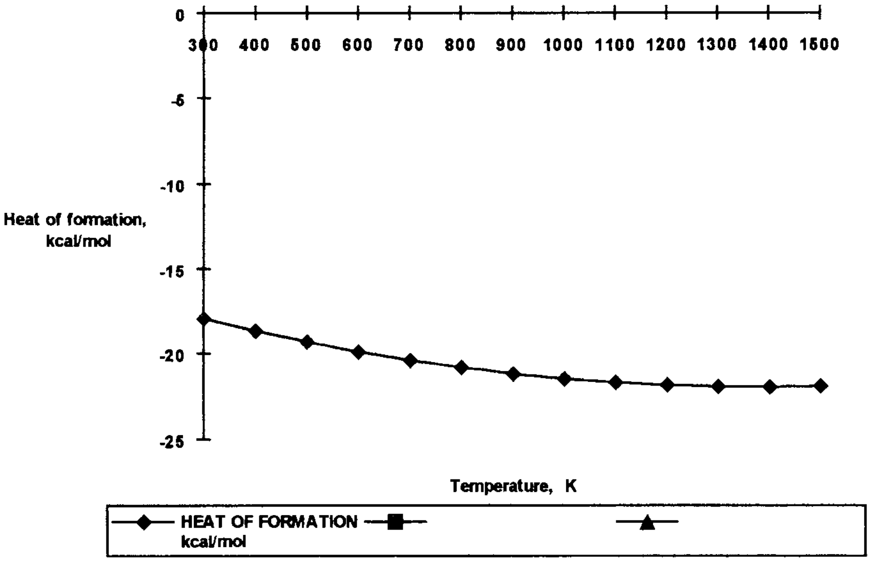

Figure 2-9. Heat of formation of methane as a function of temperature.

$\Delta G_r^0 < 0 \quad \text{kcal/gmol}$

It may possibly be promising, if

$0 < \Delta G_r^0 < 10 \quad \text{kcal/gmol}$

and not promising, if

$\Delta G_f^0 > 10 \quad \text{kcal/gmol}$

Correlation constants for Gibbs free energy of formation of the ideal gas at low pressure are based on a linear relationship in temperature as:

$$\Delta G_f^0 = A + BT \tag{2-15}$$

where ΔG_f^0 = free energy of formation of ideal gas at low pressure, kcal/gmol
A and B = correlation constants
T = temperature, K

A routine for calculating ΔG_f^0 is in PROG22, and typical results for ethylene are in Table 2-2. Figure 2-10 shows a plot of free energy for ethylene with temperature.

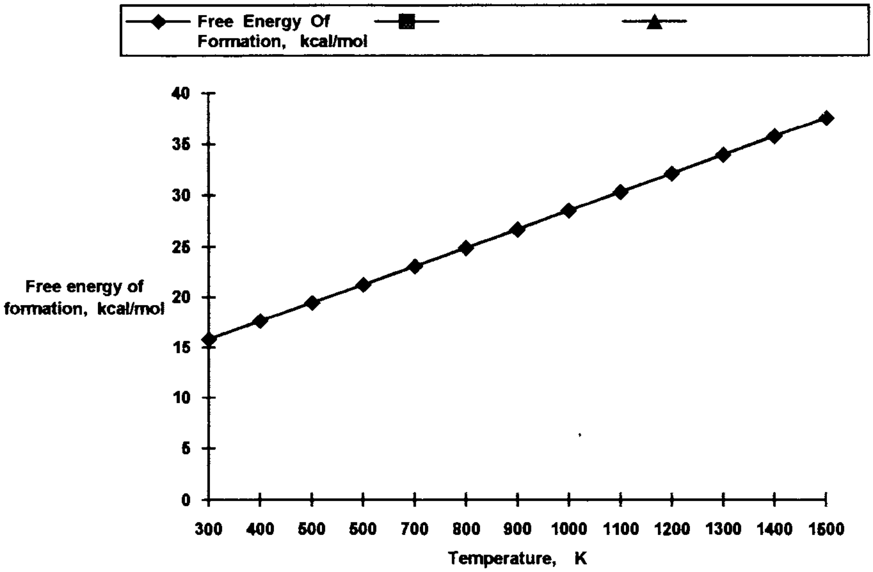

Figure 2-10. Free energy of formation of ethylene as a function of temperature.

Thermal Conductivity of Gases

The thermal conductivity, k_G of low pressure gases increases with temperature. In small temperature ranges, k_G, represents some form of linear relation. However, over wide temperature ranges, k_G increases significantly more rapidly with temperature than implied by a linear function. Gas thermal conductivity data are used, e.g., in the design of process equipment and unit operations involving heat transfer, such as the rating of heat exchangers and fluidized bed operations handling gases. Thermal conductivity of a gas can be correlated as a function of temperature as:

$$k_G + A + BT + CT^2 + DT^3 \tag{2-16}$$

where k_G = thermal conductivity of the gas at low pressure μcal/cm.s.K

A, B, C , and D = correlation constants

T = temperature, K

Figure 2-11 shows k_G of propane as a function of temperature. Reid *et al.* [2] have reviewed other methods for estimating k_G.

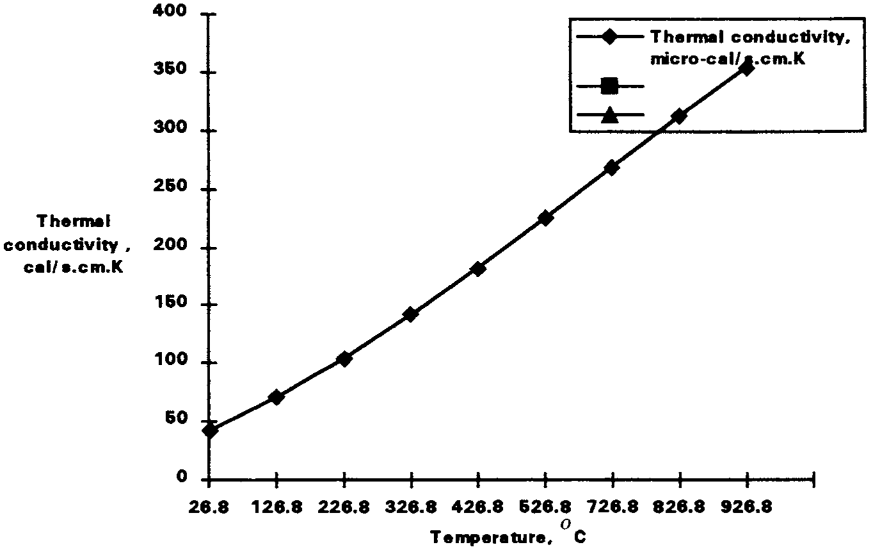

Figure 2-11. Thermal conductivity of propane as a function of temperature.

Viscosity of Gases

Gas phase viscosity data, μ_G, are used in the design of compressible fluid flow and unit operations. For example, the viscosity of a gas is required to determine the maximum permissible flow through a given process pipe size. Alternatively, the pressure loss of a given flowrate can be calculated. Viscosity data are needed for the design of process equipment involving heat, momentum, and mass transfer operations. The gas viscosity of mixtures is obtained from data for the individual components in the mixture.

The correlation for the viscosity of the gas at low pressure can be expressed as:

$$\mu_G = (A + BT + CT^2) \times (1 \times 10^{-4}) \tag{2-17}$$

where μ_G = viscosity of the gas at low pressure, cP
A, B, and C = correlation constants
T = temperature, K

The Herning-Zipperer [19] correlation for the calculation of gas mixture viscosity at low pressure is

$$\mu_m = \frac{\sum MF_i \mu_i (MW_i)^{0.5}}{\sum MF_i (MW_i)^{0.5}} \quad (2\text{-}18)$$

where μ_m = gas mixture viscosity, cP
MF_i = mole fraction of component i
μ_i = gas viscosity of component i
MW_i = molecular weight of component i

Reid *et al.* [2] have reviewed other correlation methods for determining μ_G at low pressure. The computer program PROG22 gives a subroutine for estimating gas viscosity and Figure 2-12 gives the viscosity of ethane as a function of temperature. Table 2-2 gives results of viscosity of ethane with temperature.

DIFFUSION COEFFICIENTS (DIFFUSIVITIES)

Diffusion coefficients are important in the design of mass transfer operations equipment, such as gas absorption, distillation and liquid-liquid extraction. Experimental data for the common systems can be found in the literature, but for most design work, the values will have to be estimated.

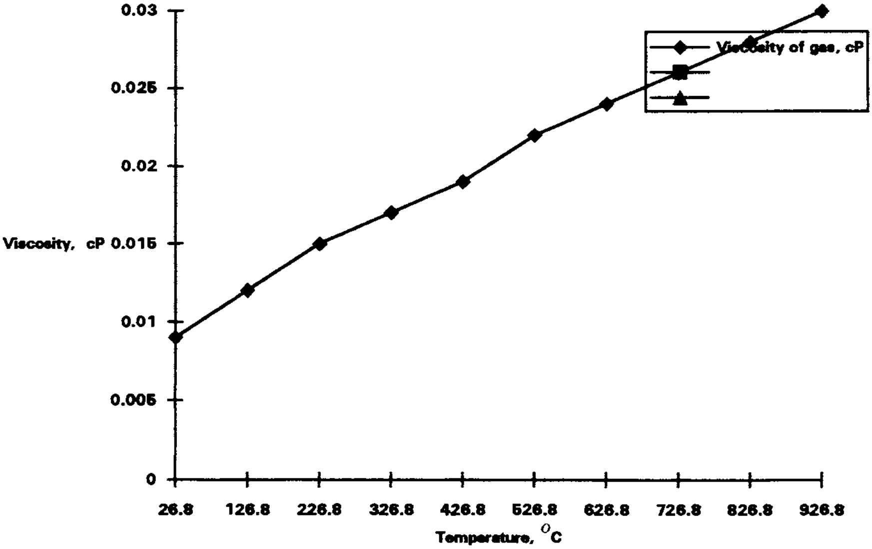

Figure 2-12. Viscosity of ethane as a function of temperature.

Liquid-Phase Diffusion Coefficients

Diffusion coefficients in liquid phases depend on concentration and are valid for dilute solutions, that is, solute concentrations no greater than 10%. Also, the lower the solute concentration, the more accurate the calculated coefficients. For a binary mixture of solute A in solvent B, the diffusion coefficient can be represented as D^0_{AB} for concentrations of A up to 5 or 10 mole percent [20]. A number of correlations have been proposed for predicting D^0_{AB} in dilute liquid solutions [21,22,23]. Here, the Wilke-Chang method is employed for estimating D^0_{AB}. This can be expressed as:

$$D^0_{AB} = \frac{7.4 \times 10^{-8} (\phi M_{wB})^{0.5} T}{\mu_B \bullet v_A^{0.6}} \tag{2-19}$$

where D^0_{AB} = Diffusion coefficient of solute A at very low concentrations in solvent B, cm^2/s

M_{wB} = molecular weight of solvent B

T = absolute temperature, K

μ_B = viscosity of solvent B, cP

v_A = molal volume of solute A at its normal boiling temperature, $cm^3/g\text{–}mol$

ϕ = association factor of solvent B, dimensionless
= 2.6 for water (some workers recommend 2.26)
= 1.9 for methanol
= 1.5 for ethanol
= 1.0 for unassociated solvents

The Le Bas additive volumes given by Reid *et al.* [2] can be used for the value of V_A, if no experimental data are available.

Gas-Phase Diffusion Coefficients

Diffusion coefficients for non-polar gases may be estimated from Chapman and Cowling [24], Wilke and Lee [25] and Fuller, Schettler, and Giddings [26]. Here, the Fuller, Schettler, and Giddings's method can be expressed as:

$$D^0_{AB} = \frac{10^{-3} T^{1.75} \left\{ \dfrac{M_{wA} + M_{wB}}{M_{wA} \bullet M_{wB}} \right\}^{0.5}}{P\left\{ \left(\sum v\right)_A^{1/3} + \left(\sum v\right)_B^{1/3} \right\}^2} \tag{2-20}$$

where D^0_{AB} = diffusion coefficient for a binary mixture of gases A and B, cm^2/s

M_{wA}, M_{wB} = molecular weights of A and B

V_A, V_B = atomic diffusion volumes

T = temperature, K

P = pressure, atmospheres

The summation, $\sum v$, of the diffusion volume coefficients for components A and B is shown in Table 2-3. The computer program PROG23

Table 2-3
Atomic Diffusion Volumes for Use in Calculating D_{AB} by the Correlation of Fuller-Schettler-Giddings

Atomic and Structural Diffusion-Volume Increments, v			
C	16.5	Cl*	19.5
H	1.98	S*	17.0
O	5.48	Aromatic ring	–20.2
N*	5.69	Heterocyclic ring	–20.2
Diffusion Volumes for Simple Molecules, $\sum v$			
H_2	7.07	CO	18.9
D_2	6.70	CO_2	26.9
He	2.88	N_2O	35.9
N_2	17.9	NH_3	14.9
O_2	16.6	H_2O	12.7
Air	20.1	$CCl_2F_2^*$	114.8
Ar	16.1	SF_6^*	69.7
Kr	22.8	Cl_2^*	37.7
Xe*	37.9	Br_2^*	67.2
		SO_2^*	41.1

**Based on a few data points*

calculates the liquid diffusion coefficient at varying molal volume of solute A, and the gas diffusion coefficient.

COMPRESSIBILITY Z-FACTOR OF NATURAL GASES

Many petroleum engineering and process design calculations dealing with natural gases require knowledge of deviation factors or compressibility Z factors. Experimental data from pressure-volume-temperature (P-V-T) measurements are seldom available. The Z-factors are available in charts [27] or tables as a function of pseudo-reduced temperatures T_r and pressures P_r. However, use of these charts is often time consuming and involves complex calculations.

Computer programs [28,29] for calculating the Z factors have been developed solely as a function of temperature and pressure of the gas. Furthermore, numerical methods and mathematical representations of the charts have been used to estimate the Z factors. Takacs [30] reviewed the various methods of estimating the Z-factors. Here, use is made of a modified form of the method developed by Awoseyin [31]. This method gives a compressibility factor to within 5% for natural hydrocarbon gases with specific gravities between 0.5 and 0.8 and for pressures up to 5000 psia. The Z factor can be expressed as:

$$Z = F_1 \left\{ \frac{1}{\left[1 + \frac{\left(A_6 . P . 10^{[1.785 S_g]} \right)}{T^{3.825}} \right]} + F_2 . F_3 \right\} + F_4 + F_5 \qquad (2\text{-}21)$$

where

$$F_1 = P(0.251 S_g - 0.15) - 0.202 S_g + 1.106 \qquad (2\text{-}22)$$

$$F_2 = 1.4 e^{\{-0.0054(T-460)\}} \qquad (2\text{-}23)$$

$$F_3 = A_1 P^5 + A_2 P^4 + A_3 P^3 + A_4 P^2 + A_5 P \qquad (2\text{-}24)$$

$$F_4 = \left\{ 0.154 - 0.152 S_g \right\} P^{(3.18 S_g - 1.0)} e^{(-0.5P)} - 0.02 \qquad (2\text{-}25)$$

$$F_5 = 0.35\left\{(0.6 - S_g)e^{[-1.039(P-1.8)^2]}\right\} \qquad (2\text{-}26)$$

The values of the constants A_1, A_2, A_3, A_4, A_5, and A_6 are:

$$A_1 = 0.001946$$

$$A_2 = -0.027635$$

$$A_3 = 0.136315$$

$$A_4 = -0.23849$$

$$A_5 = 0.105168$$

$$A_6 = 3.44 \times 10^8$$

The specific gravity, S_g, of natural gas can be calculated from its density or molecular weight. This is expressed as the ratio of the gas density at 60°F and 1 atmosphere (14.7psia), $\rho_{gas,60°F}$, to the density of air, $\rho_{air,60°F}$, under the same conditions.

$$S_g = \frac{\text{density of gas}}{\text{density of air}}$$

$$= \frac{\rho_{gas,60°F}}{\rho_{air,60°F}} \qquad (2\text{-}27)$$

Using the molecular weight of the gas, S_g, can be expressed as:

$$S_g = \frac{\text{molecular weight of gas}}{\text{molecular weight of air}}$$

$$= \frac{M_{w,\ gas}}{M_{w,\ air}} \qquad (2\text{-}28)$$

Appendix A2 shows the computer outputs of the Z-factor as a function of temperature, pressure and specific gravity. The computer program PROG24 calculates the compressibility Z-factor of natural gases as a function of specific gravity and temperature. Figure 2-13 gives a plot of the compressibility Z-factor of natural gases at 60°F as a function of pressure and specific gravity. Tables 2-1 to 2-25 in Appendix B give results of Z-factors at varying specific gravity and temperature.

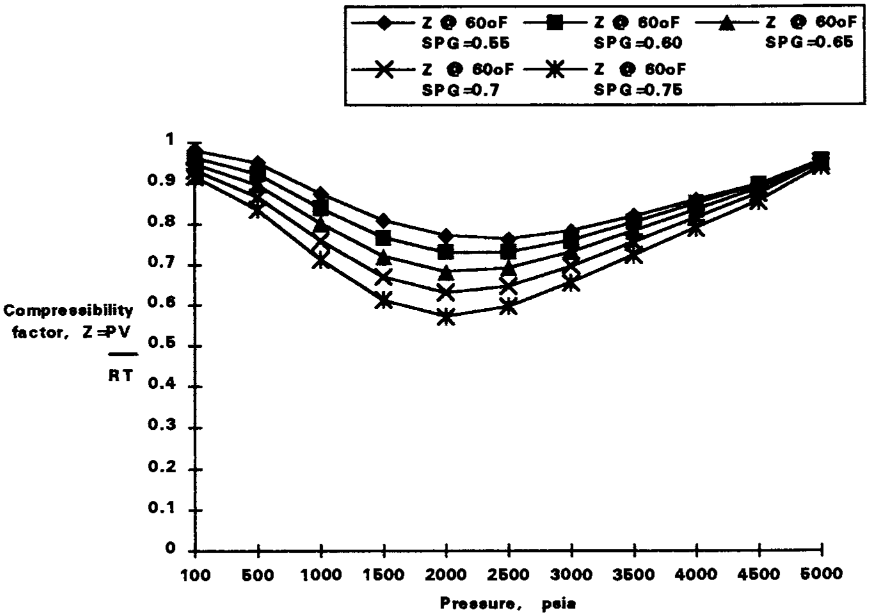

Figure 2-13. Compressibility factor of natural gases as a function of pressure and specific gravity.

PROBLEMS AND SOLUTIONS

Problem 2-1

Using the Wilke-Chang relation, determine the value of the infinite-dilution diffusion coefficient of propane in chlorobenzene at 0°C. $M_B = 112.56$ (chlorobenzene), $\mu = 1.05$ cP, $V_A = 74.5(\text{cm}^3/(\text{g}-\text{mol}))$ (propane), $T = 273.15\text{K}$ and $\phi = 1.0$.

Solution

The computer program PROG23 calculates the diffusion coefficient of propane in chlorobenzene at varying molal volume of solute A (propane). At $V_A = 74.5(\text{cm}^3/(\text{g}-\text{mol}))$, the computed value of the diffusion coefficient, $D^0_{AB} = 1.54 \times 10^{-5}(\text{cm}^2/\text{s})$.

Problem 2-2

Calculate the diffusion coefficient of allyl chloride (AC) in air at 25°C and 1 atmosphere. An experimental value is $0.0975\text{cm}^2/\text{s}$.

Solution

Using the correlation of Fuller-Schettler-Giddings, values of atomic diffusion volumes of $\sum v$ from Table 2-3 are:

$$\begin{aligned}\sum v(AC) &= 3(C) + 5(H) + Cl \\ &= 3(16.5) + 5(19.8) + 19.5 \\ &= 78.9\end{aligned}$$

$$\sum v(Air) = 20.1$$

Molecular weight of air, $M_{wA} = 29.0$
Molecular weight of allyl chloride, $M_{wB} = 76.53$

The computer program PROG23 determines the diffusion coefficient of the gas phase. The computed diffusion coefficient of allyl chloride is 0.0952cm^2/s. Table 2-4 shows the computer output of diffusion coefficients for the liquid and gas phases.

Table 2-4
Computer Output of Diffusion Coefficients for Liquid and Gas Phases Diffusion Coefficients for Liquids and Gases

```
                 DIFFUSION COEFFICIENTS FOR LIQUIDS AND GASES
*******************************************************************************

                  DIFFUSION COEFFICIENT OF LIQUID PHASE
------------------------------------------------------------------------------

                 MOLAL VOLUME OF            DIFFUSION COEFFICIENT
         NUMBER   SOLUTE A cm^3/g-mol           cm^2/s.
------------------------------------------------------------------------------
          1            10.00                     .5130E-04
          2            20.00                     .3385E-04
          3            40.00                     .2233E-04
          4            60.00                     .1751E-04
          5            74.50                     .1538E-04
          6            80.00                     .1473E-04
          7           100.00                     .1289E-04
          8           200.00                     .8502E-05
          9           400.00                     .5609E-05
         10           600.00                     .4398E-05
         11          1000.00                     .3237E-05
         12          2000.00                     .2136E-05
------------------------------------------------------------------------------

                  DIFFUSION COEFFICIENT OF GAS PHASE
------------------------------------------------------------------------------


                 DIFFUSION COEFFICIENT: .952273E-01   cm^2/s.
------------------------------------------------------------------------------
```

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```
        PROGRAM PROG21

C       *************************************************************
C       THIS PROGRAM CALCULATES THE PHYSICAL PROPERTIES OF WATER
C       AT A TEMPERATURE RANGE FROM 0oC TO 500oC.   THE CRITICAL
C       TEMPERATURE=374.12oC.
C
C       THE PROGRAM WILL CALCULATE THE FOLLOWING PHYSICAL PROPERTIES
C       1.  DENSITY                DEN      g/cm^3.
C       2.  VISCOSITY              VIS           cP
C       3.  HEAT CAPACITY          HC            cal/g.oC.
C       4.  THERMAL CONDUCTIVITY   THER         (micro-cal /s.cm.K)
C       5.  SURFACE TENSION        ST            dyne/cm.
C       6.  VAPOR PRESSURE         VP            mm Hg.
C       7.  HEATS OF VAPORIZATION  HV            cal/g
C       *************************************************************


        DIMENSION T(1:50), DEN(1:50), VIS(1:50), HC(1:50)
        DIMENSION THER(1:50), ST(1:50), TK(1:50), VP(1:50), HV(1:50)
        INTEGER N

C       OPEN FILE TO PRINT THE RESULTS

        OPEN (UNIT = 1, FILE = 'PRN')

C       INPUT THE NUMBER OF DATA AND THE VALUES OF THE TEMPERATURE
C       FOR WHICH THE PHYSICAL PROPERTIES ARE CALCULATED.

        DATA N /10/

        DATA T(1)/0.0/, T(2)/25.0/, T(3)/50.0/, T(4)/100.0/
        DATA T(5)/150.0/, T(6)/200.0/, T(7)/250.0/, T(8)/300.0/
        DATA T(9)/350.0/, T(10)/374.2/

        WRITE (1, 100)
 100    FORMAT (//, 1H , 25X, 'PHYSICAL PROPERTY DATA OF WATER',
     *          /1H ,78(1H*))

        WRITE (1, 110)
 110    FORMAT (//, 40X, 'TEMPERATURE oC')

        DO I = 1, N
        WRITE (1, 120) I, T(I)
 120    FORMAT (30X, I2, 10X, F8.2)
        END DO

        WRITE (1, 125)
 125    FORMAT (78(1H-))


C       CONVERT THE TEMPERATURE FROM DEGREE CENTIGRADE TO KELVIN.

        DO I = 1, N
        TK(I) = T(I) + 273.16
        END DO
```

```
        J = 1

 5      GO TO (11, 22, 33, 44, 55, 66, 77), J

C       CALL THE PROGRAM TO CALCULATE THE DENSITY OF WATER

 11     CALL PROG1 (T, DEN, N)

        WRITE (1, 130)
 130    FORMAT (//, 1H , 25X, 'DENSITY OF WATER: OoC - 374.2oC',
     *          /1H ,78(1H*))

        WRITE (1, 140)
 140    FORMAT (/,20X, ' TEMPERATURE oC', 10X, 'DENSITY g/cm.^3',
     *          /, 78(1H-),/)

        DO I = 1, N
        WRITE (1, 150) I, T(I), DEN(I)
 150    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 155)
 155    FORMAT (78(1H-))


        J = J + 1
        IF (J .EQ. 2) THEN
        GO TO 5
        ELSE
        GO TO  900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE WATER VISCOSITY

 22     CALL PROG2 (TK, VIS, N)

        WRITE (1, 160)
 160    FORMAT (//, 1H , 25X, 'VISCOSITY OF WATER: OoC -  374.2oC',
     *          /1H ,78(1H*))

        WRITE (1, 170)
 170    FORMAT (/, 20X, 'TEMPERATURE oC', 10X, 'VISCOSITY  cP',
     *          /, 78(1H-),/)

        DO I = 1, N
        WRITE (1, 180) I, T(I), VIS(I)
 180    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 185)
 185    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 3) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF
```

```
C       CALL THE PROGRAM TO CALCULATE HEAT CAPACITY OF WATER

 33     CALL PROG3 (TK, HC, N)

        WRITE (1, 190)
 190    FORMAT (//, 1H , 25X, 'HEAT CAPACITY OF WATER: 0oC - 350oC',
     *          /1H ,78(1H*))

        WRITE (1, 200)
 200    FORMAT (/, 20X,'TEMPERATURE oc',10X,'HEAT CAPACITY cal/gm.oC',
     *          /,78(1H-),/)

        DO I = 1, N-1
        WRITE (1,210) I, T(I), HC(I)
 210    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 215)
 215    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 4) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE THE THERMAL CONDUCTIVITY OF WATER

 44     CALL PROG4 (TK, THER, N)

        WRITE (1, 220)
 220    FORMAT (//, 25X, 'THERMAL CONDUCTIVITY OF WATER: 0oC - 350oC',
     *          /1H , 78(1H*))

        WRITE (1, 230)
 230    FORMAT (/, 20X, 'TEMPERATURE oC', 5X,'THERMAL CONDUCTIVITY',\)
        WRITE (1, 240)
 240    FORMAT (' micro-cal/s.cm.K', /, 78(1H-), /)

        DO I = 1, N-1
        WRITE (1, 250) I, T(I), THER(I)
 250    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 255)
 255    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 5) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE THE SURFACE TENSION OF
C       WATER (Page 219, Yaws et. al.)
```

```
 55     CALL PROG5 (TK, ST, N)

        WRITE (1, 260)
 260    FORMAT (//, 1H , 25X, 'SURFACE TENSION OF WATER: 0oC - 374.2oC',
     *          /1H , 78(1H*))

        WRITE (1, 270)
 270    FORMAT (/, 20X, 'TEMPERATURE oC',10X,'SURFACE TENSION:dyne/cm.',
     *          /, 78(1H-), /)

        DO I = 1, N
        WRITE (1, 280) I, T(I), ST(I)
 280    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 285)
 285    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 6) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE THE VAPOR PRESSURE OF
C       SATURATED LIQUIDS (PAGE 214 Yaws et. al.)


 66     CALL PROG6 (TK, VP, N)
        WRITE (1, 290)
 290    FORMAT(//, 1H , 25X, 'VAPOR PRESSURE OF WATER: 0oC - 374.2 oC',
     *         /1H , 78(1H*))

        WRITE (1, 300)
 300    FORMAT (/,20X,'TEMPERATURE  oC', 10X,'VAPOR PRESSURE: mm Hg',
     *          /, 78(1H-), /)

        DO I = 1, N
        WRITE (1, 310) I, T(I), VP(I)
 310    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 315)
 315    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 7) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE THE HEATS OF VAPORIZATION
C       (PAGE 204 , Yaws et. al.)
```

```
 77     CALL PROG7 (TK, HV, N)
        WRITE (1, 320)
 320    FORMAT(//, 1H ,25X,'HEAT-OF-VAPORIZATION OF WATER:0oC-374.2 oC',
     *         /1H , 78(1H*))

        WRITE (1, 330)
 330    FORMAT(//,20X,'TEMPERATURE oC',10X,'HEAT-OF-VAPORIZATION:cal/g',
     *         /, 78(1H-), /)

        DO I = 1, N
        WRITE (1, 340) I, T(I), HV(I)
 340    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 345)
 345    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 8) THEN
        GO TO 900
        ELSE
        ENDIF

 900    CONTINUE


C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR (12)

        CLOSE (UNIT = 1)
        STOP
        END

C       ***************************************************************
C       THIS PROGRAM CALCULATES THE DENSITY OF WATER FROM
C       "PHYSICAL PROPERTIES BY C.L. YAWS et. al. PAGE 222.
C       ****************************************************************

        SUBROUTINE PROG1 (T, DENL, N)
        DIMENSION T(1:50), DENL(1:50), TR(1:50), SUM(1:50)

        INTEGER N

C       CRITICAL TEMPERATURE : TC=374.2
C       CALCULATE THE REDUCED TEMPERATURE : TR=T/TC

        TC = 374.2
        DO I = 1, N
        TR(I) = T(I)/TC
        END DO

C       CORRELATION CONSTANTS OF WATER

        A = 0.3471
        B = 0.2740
C
C       CALCULATE THE DENSITY OF WATER

        DO 10 I = 1, N
```

```
      SUM(I) = (1.0 - TR(I))
      IF (SUM(I) .EQ. 0.0) THEN
      DENL(I) = A*B
      ELSE
      SUM(I) = SUM(I)**0.2857
      DENL(I) = A*(B**(-SUM(I)))
      ENDIF
 10   CONTINUE

      RETURN
      END

C     *************************************************************
C     THIS PROGRAM CALCULATES THE VISCOSITY OF WATER FROM
C     0oC TO 374.2oC PAGE 213, YAWS et. al.
C     *************************************************************

      SUBROUTINE PROG2 (TK, VIS1, N)
      DIMENSION TK(1:50), VIS1(1:50), VIS2(1:50)
      INTEGER N

C     CORRELATION CONSTANTS OF WATER

      A = -10.73
      B = 1828.0
      C = .01966
      D = -.00001466

C     CALCULATE THE VISCOSITY

      DO I = 1, N
      VIS2(I) = A + (B/TK(I)) + (C*TK(I)) + (D*TK(I)**2)
      VIS1(I) = 10**(VIS2(I))
      END DO

      RETURN
      END

C     ***************************************************************
C     THIS PROGRAM CALCULATES THE HEAT CAPACITY OF WATER FROM
C     0oC TO 350oC (PAGE 221 Yaws et. al.)
C     ***************************************************************

      SUBROUTINE PROG3 (TK, HC1, N)
      DIMENSION TK (1:50), HC1 (1:50)

C     CORRELATION CONSTANTS OF WATER

      A = 0.6741
      B = .002825
      C = -.000008371
      D = .000000008601

C     CALCULATE THE HEAT CAPACITY

      DO I = 1, N
      HC1(I) = A + (B*TK(I)) + (C*TK(I)**2) + (D*TK(I)**3)
      END DO

      RETURN
```

```
        END

C       ***************************************************************
C       THIS PROGRAM CALCULATES THE THERMAL CONDUCTIVITY OF WATER
C       ***************************************************************

        SUBROUTINE PROG4 (TK, THERM1, N)
        DIMENSION TK(1:50), THERM1(1:50)

        INTEGER N

C       CORRELATION CONSTANTS OF WATER

        A = -916.62
        B = 12.5473
        C = -.015212

C
C       CALCULATE THE THERMAL CONDUCTIVITY OF WATER

        DO I = 1, N - 1
        THERM1 (I) = A + (B*TK(I)) + (C*TK(I)**2)
        END DO

        RETURN
        END

C       ***************************************************************
C       THIS PROGRAM CALCULATES THE SURFACE TENSION OF WATER
C       FROM 0oC TO 374.2oC.
C       SURFACE TENSION ST=ST1*((TC-T)/(TC-T1))^N1
C       FOR 0 < T < 100oC, ST1=71.97, TC=374.2oC, T1=25.0oC.
C       FOR 100 < T < 374.2oC, ST1=58.91, TC=374.2oC, T1=100oC.
C       *****************************************************************

        SUBROUTINE PROG5 (TK, ST, N)
        DIMENSION TK(1:50), ST(1:50)
        REAL N1, N2

C       CALCULATE THE SURFACE TENSION BETWEEN 0oC AND 50oC.

        ST1 = 71.97
        TC = 374.2 + 273.16
        T1 = 25.0 + 273.16
        N1 = 0.8105

        DO I = 1, 3
        ST(I) = ST1 * ((TC-TK(I))/(TC-T1))**N1
        END DO

C       CALCULATE THE SURFACE TENSION BETWEEN 100oC AND 374.2oC.

        ST2 = 58.91
        T2 = 100.0 + 273.16
        N2 = 1.169

        DO I = 4, N
        ST(I) = ST2 * ((TC-TK(I))/(TC-T2))**N2
        END DO
```

```
      RETURN
      END

C     ***************************************************************
C     THIS PROGRAM CALCULATES THE VAPOR PRESSURE OF WATER FROM
C     0oC TO 374.2 oC.
C     ***************************************************************

      SUBROUTINE PROG6 (TK, VP1, N)
      DIMENSION TK (1:50), VP1 (1:50)

C
C     CORRELATION CONSTANTS OF WATER

      A = 16.373
      B = -2818.6
      C = -1.6908
      D = -0.0057546
      E = 0.0000040073

C
C     CALCULATE THE VAPOR PRESSURE

      DO I = 1, N
      VP1(I) = A + (B/TK(I))+(C*ALOG10(TK(I)))+(D*TK(I))+(E*TK(I)**2)
      VP1(I) = 10**VP1(I)
      END DO

      RETURN
      END

C     ******************************************************************
C     THIS PROGRAM CALCULATES THE HEAT OF VAPORIZATION OF WATER
C     FROM 0oC TO 374.2 oC.
C     ******************************************************************

      SUBROUTINE PROG7 (TK, HV1, N)
      DIMENSION TK(1:50), HV1(1:50)

C     CORRELATION CONSTANTS OF WATER

      THV = 538.7
      T1 = 100.0 + 273.16
      TC = 374.2 + 273.16
      R = 0.38


C     CALCULATE THE HEAT OF VAPORIZATION

      DO I = 1, N
      HV1(I) = THV*(((TC-TK(I))/(TC-T1))**R)
      END DO

      RETURN
      END
```

```
      PROGRAM PROG22

C
C     *************************************************************
C     THIS PROGRAM CALCULATES THE PHYSICAL PROPERTIES OF GASES
C     AT A TEMPERATURE RANGE FROM 300K TO 1500K FOR SOME GASES
C     AND 26.8oC TO 1026.8oC FOR OTHERS.
C
C     THE PROGRAM WILL CALCULATE THE FOLLOWING PHYSICAL PROPERTIES
C     1.  HEAT OF FORMATION          HF                kcal/mol.
C     2.  FREE ENERGY OF FORMATION   GF                kcal/mol
C     3.  HEAT CAPACITY              HC                cal/gm-mol K.
C     4.  THERMAL CONDUCTIVITY       THER             (micro-cal /s.cm.K)
C     5.  VISCOSITY                  VIS               cP.
C     *************************************************************


      DIMENSION T (1:50), HF (1:50), GF (1:50), HC (1:50)
      DIMENSION THER (1:50), VIS (1:50), TK (1:50)


      INTEGER N

C     OPEN FILE TO PRINT THE RESULTS.

      OPEN (UNIT = 1, FILE = 'PRN')

C     INPUT THE NUMBER OF DATA AND THE VALUES OF THE TEMPERATURE
C     FOR WHICH THE PHYSICAL PROPERTIES ARE CALCULATED.

      DATA N /13/

      DATA TK(1)/300.0/, TK(2)/400.0/, TK(3)/500.0/, TK(4)/600.0/
      DATA TK(5)/700.0/, TK(6)/800.0/, TK(7)/900.0/, TK(8)/1000.0/
      DATA TK(9)/1100.0/, TK(10)/1200.0/, TK(11)/1300.0/
      DATA TK(12)/1400.0/, TK(13)/1500.0/

      WRITE (1, 100)
 100  FORMAT (//, 1H , 25X, 'PHYSICAL PROPERTY DATA OF GASES',
     *        /1H ,78(1H*))
      WRITE (1, 110)
 110  FORMAT (//, 40X, 'TEMPERATURE RANGE (300 - 1500K)')

      WRITE (1, 115)
 115  FORMAT (78(1H-))

      DO I = 1, N
      WRITE (1, 120) I, TK(I)
 120  FORMAT (30X, I2, 10X, F8.2)
      END DO

      WRITE (1, 125)
 125  FORMAT (78(1H-))

      J = 1

 5    GO TO (11, 22, 33, 44, 55), J
```

```
C       CALL THE PROGRAM TO CALCULATE THE HEAT OF FORMATION OF A GAS

 11     CALL PROG1 (TK, HF, N)

        WRITE (1, 130)
 130    FORMAT (//, 1H , 25X, 'HEAT OF FORMATION OF METHANE',
     *          /1H , 78(1H*), /)

        WRITE (1, 140)
 140    FORMAT (20X,' TEMPERATURE K', 5X,'HEAT OF FORMATION kcal/mol',
     *         /, 78(1H-), /)

        DO I = 1, N
        WRITE (1, 150) I, TK(I), HF(I)
 150    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 155)
 155    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 2) THEN
        GO TO 5
        ELSE
        GO TO  900
        ENDIF


C       CALL THE PROGRAM TO CALCULATE THE FREE ENERGY OF FORMATION
C       OF A GAS

 22     CALL PROG2 (TK, GF, N)

        WRITE (1, 160)
 160    FORMAT (//, 1H , 25X, 'THE FREE ENERGY OF FORMATION OF',\)
        WRITE (1, 165)
 165    FORMAT(' ETHYLENE kcal/mol.', /1H ,78(1H*), /)

        WRITE (1, 170)
 170  FORMAT(20X,'TEMPERATURE K',5X,'FREE ENERGY OF FORMATION:kcal/mol')

        WRITE (1, 175)
 175    FORMAT (78(1H-), /)

        DO I = 1, N
        WRITE (1, 180) I, TK(I), GF(I)
 180    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 185)
 185    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 3) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE HEAT CAPACITY OF CARBON DIOXIDE
```

```
 33     CALL PROG3 (TK, HC, N)
        WRITE (1, 190)
 190    FORMAT (//, 1H , 25X, 'HEAT CAPACITY OF CARBON DIOXIDE',
     *          /1H ,78(1H*))

        WRITE (1, 200)
 200    FORMAT (20X,'TEMPERATURE K', 5X,'HEAT CAPACITY cal/gm-mol.K',
     *          /, 78(1H-), /)

        DO I = 1, N
        WRITE (1, 210) I, TK(I), HC(I)
 210    FORMAT (10X, I2, 15X, F6.1, 5X, F12.3)
        END DO

        WRITE (1, 215)
 215    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 4) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE THE THERMAL CONDUCTIVITY OF GASES


 44     CALL PROG4 (TK, THER, N)

        WRITE (1, 220)
 220    FORMAT(//,25X,'THERMAL CONDUCTIVITY OF PROPANE:26.8oC-1026.8oC',
     *          /1H , 78(1H*))

        WRITE (1, 230)
 230    FORMAT (20X,'TEMPERATURE oC', 5X,'THERMAL CONDUCTIVITY',\)
        WRITE (1, 235)
 235    FORMAT(' micro-cal/s.cm.K', /, 78(1H-), /)

        DO I = 1, N-2

        T(I) = TK(I) - 273.16
        WRITE (1, 240) I, T(I), THER(I)
 240    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 245)
 245    FORMAT (78(1H-))

        J = J + 1
        IF (J .EQ. 5) THEN
        GO TO 5
        ELSE
        GO TO 900
        ENDIF

C       CALL THE PROGRAM TO CALCULATE THE VISCOSITY OF ETHANE
```

```
 55     CALL PROG5 (TK, VIS, N)

        WRITE (1, 250)
 250    FORMAT (//, 1H ,25X, 'THE VISCOSITY OF ETHANE: 26.8oC-1026.8oC',
     *        /1H , 78(1H*))

        WRITE (1, 260)
 260    FORMAT (20X, 'TEMPERATURE oC', 5X, 'VISCOSITY cP.',
     *          /, 78(1H-), /)

        DO I = 1, N - 2
        T(I) = TK(I) - 273.16
        WRITE (1, 270) I, T(I), VIS(I)
 270    FORMAT (10X, I2, 10X, F6.1, 10X, F12.3)
        END DO

        WRITE (1, 275)
 275    FORMAT ( 78(1H-))

        J = J + 1
        IF (J .EQ. 6) THEN

        GO TO 900
        ELSE
        ENDIF
 900    CONTINUE

C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR (12)

        CLOSE (UNIT = 1)
        STOP
        END


C       ***************************************************************
C       THIS PROGRAM CALCULATES THE HEAT OF FORMATION OF METHANE
C       "PHYSICAL PROPERTIES BY C.L. YAWS et. al. PAGE 200
C       ***************************************************************

        SUBROUTINE PROG1 (TK, HF1, N)
        DIMENSION TK(1:50), HF1(1:50)

        INTEGER N

C       CORRELATION CONSTANTS OF METHANE

        A = -15.4
        B = -0.00959
        C = 0.0000035

C       CALCULATE THE HEAT OF FORMATION OF METHANE, kcal/mol.

        DO  I = 1, N
        HF1(I) = A + (B*TK(I))+(C*TK(I)**2)
        END DO

        RETURN
        END
```

```
C       ****************************************************************
C       THIS PROGRAM CALCULATES THE FREE ENERGY OF FORMATION OF
C       ETHYLENE  PAGE 202, YAWS et. al.
C       ****************************************************************

        SUBROUTINE PROG2 (TK, GF1, N)
        DIMENSION TK(1:50), GF1(1:50)

        INTEGER N

C       CORRELATION CONSTANTS OF ETHYLENE

        A = 10.4
        B = 0.0181

C       CALCULATE THE FREE ENERGY OF FORMATION

        DO I = 1, N
        GF1(I) = A + (B*TK(I))
        END DO

        RETURN
        END

C       ****************************************************************
C       THIS PROGRAM CALCULATES THE HEAT CAPACITY OF CARBON DIOXIDE
C       0oC-350oC (PAGE 198 Yaws et. al.)
C       ****************************************************************

        SUBROUTINE PROG3 (TK, HC1, N)
        DIMENSION TK(1:50), HC1(1:50)

C       CORRELATION CONSTANTS OF CARBON DIOXIDE

        A = 5.41
        B = 0.0154
        C = -0.00000994
        D = 0.00000000242

C       CALCULATE THE HEAT CAPACITY

        DO I = 1, N
        HC1(I) = A + (B*TK(I))+(C*TK(I)**2)+(D*TK(I)**3)
        END DO

        RETURN
        END

C       ****************************************************************
C       THIS PROGRAM CALCULATES THE THERMAL CONDUCTIVITY OF PROPANE
C       PAGE 208 Yaws et al.
C       ****************************************************************

        SUBROUTINE PROG4 (TK, THERM1, N)
        DIMENSION TK(1:50), THERM1(1:50)

        INTEGER N

C       CORRELATION CONSTANTS OF PROPANE
```

```
      A = 4.438
      B = -0.01122
      C = 0.0005198
      D = -0.0000002008

C     CALCULATE THE THERMAL CONDUCTIVITY OF PROPANE

      DO I = 1, N - 2
      THERM1(I) = A + (B*TK(I))+(C*TK(I)**2)+(D*TK(I)**3)
      END DO
      RETURN
      END

C     ****************************************************************
C     THIS PROGRAM CALCULATES THE VISCOSITY OF ETHANE FROM
C     0 - 1000 oC. PAGE 210 Yaws et al.
C     ****************************************************************

      SUBROUTINE PROG5 (TK, VIS1, N)
      DIMENSION TK(1:50), VIS1(1:50)

C     CORRELATION CONSTANTS OF ETHANE

      A = 5.576
      B = 0.3064
      C = -0.00005307

C     CALCULATE THE VISCOSITY

      DO I = 1, N-2
      VIS1(I) = (A + (B*TK(I))+(C*TK(I)**2))*0.0001
      END DO
      RETURN
      END
```

```
        PROGRAM PROG23


C       **************************************************************
C       THIS PROGRAM CALCULATES THE DIFFUSION COEFFICIENTS
C       FOR LIQUID AND GAS PHASES.
C       ------------------------------------------------------------
C       DIFFUSION COEFFICIENT FOR LIQUID PHASE

C       THE PROGRAM USES THE WILKE-CHANG METHOD TO CALCULATE THE
C       DIFFUSION COEFFICIENT OF A BINARY MIXTURE OF SOLUTE A IN
C       SOLVENT B.

C       DABL    =   DIFFUSION COEFFICIENT OF LIQUID PHASE cm^2/s.
C       MBL     =   MOLECULAR WEIGHT OF SOLVENT B.
C       TKL     =   ABSOLUTE TEMPERATURE, K
C       VISBL   =   VISCOSITY OF SOLVENT B, cP
C       VA      =   MOLAL VOLUME OF SOLUTE A AT ITS NORMAL BOILING
C                   TEMPERATURE, cm^3/g-mol.
C       FACTOR  =   ASSOCIATION FACTOR OF SOLVENT B, DIMENSIONLESS
C       --------------------------------------------------------------

C       DIFFUSION COEFFICIENT FOR GAS PHASE

C       THE PROGRAM USES THE FULLER, SCHETTLER AND GIDDLINGS METHOD

C       DABG    =   DIFFUSION COEFFICIENT OF GAS PHASE cm^2/s.
C       TKG     =   TEMPERATURE, KELVIN
C       MWA     =   MOLECULAR WEIGHT OF A.
C       MWB     =   MOLECULAR WEIGHT OF B
C       VAG     =   ATOMIC DIFFUSION VOLUME OF A
C       VBG     =   ATOMIC DIFFUSION VOLUME OF B
C       PRES    =   PRESSURE, ATMOSPHERE
C       **************************************************************

        DIMENSION VA (1:50), DABL(1:50), Y(1:50)
        REAL  MBL, MWA, MWB


C       OPEN FILE TO PRINT THE RESULTS.

        OPEN (UNIT = 1, FILE = 'PRN')

C       DATA FOR LIQUID PHASE DIFFUSION COEFFICIENT

        DATA VA(1)/10.0/, VA(2)/20.0/, VA(3)/40.0/, VA(4)/60.0/
        DATA VA(5)/74.5/, VA(6)/80.0/, VA(7)/100.0/, VA(8)/200.0/
        DATA VA(9)/400.0/, VA(10)/600.0/, VA(11)/1000.0/, VA(12)/2000.0/

        DATA TKL/273.15/, MBL/112.56/, VISBL/1.05/,  FACTOR/1.0/


C       DATA FOR GAS PHASE DIFFUSION COEFFICIENT

        DATA TKG/298.15/, MWA/29.0/, MWB/76.53/, VAG/20.1/, VBG/78.9/
        DATA PRES/1.0/

        WRITE (1, 100)
```

```
 100    FORMAT(//, 15X,'DIFFUSION COEFFICIENTS FOR LIQUIDS AND GASES',
     *         /1H , 78(1H*))


         J = 1

 5      GO TO (11, 22), J


C       CALL THE PROGRAM TO CALCULATE THE DIFFUSION COEFFICIENT OF
C       LIQUID PHASE


 11     WRITE (1, 110)
 110    FORMAT (//, 1H , 15X,'DIFFUSION COEFFICIENT OF LIQUID PHASE',
     *         /1H , 78(1H-))

        CALL PROG1 (DABL, TKL, MBL, VISBL, VA, FACTOR, Y)


        WRITE (1, 140)
 140    FORMAT (/, 20X, 'MOLAL VOLUME OF ', 10X, 'DIFFUSION COEFFICIENT',
     *          /, 10X, 'NUMBER',4X,'SOLUTE A cm^3/g-mol',10X,'cm^2/s.',
     *          /, 78(1H-))

        DO I = 1, 12

        WRITE (1, 150) I, VA(I), DABL(I)
 150    FORMAT (10X, I2, 10X, F10.2, 15X, E12.4)

        END DO

        WRITE (1, 160)
 160    FORMAT (78(1H-))


        J = J + 1
        IF (J .EQ. 2) THEN
        GO TO 5
        ELSE
        GO TO  900
        ENDIF


C       CALL THE PROGRAM TO CALCULATE THE DIFFUSION COEFFICIENT
C       OF A GAS PHASE

 22     WRITE (1, 10)
 10     FORMAT(//,1H ,15X,'DIFFUSION COEFFICIENT OF GAS PHASE',
     *         /1H , 78(1H-))

        CALL PROG2 (DABG, TKG, MWA, MWB, VAG, VBG, PRES)

        WRITE (1, 170) DABG
 170    FORMAT (//, 15X, 'DIFFUSION COEFFICIENT:', E12.6, 3X, 'cm^2/s.')

        J = J + 1
        IF (J .EQ. 2) THEN

        GO TO 900
```

```
        ELSE
        ENDIF
  900   CONTINUE

        WRITE (1, 180)
  180   FORMAT (78(1H-))


C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE (UNIT = 1)
        STOP
        END


C       ***************************************************************
C       THIS PROGRAM CALCULATES THE DIFFUSION COEFFICIENT OF THE
C       LIQUID PHASE USING THE WILKE-CHANG METHOD.
C       ***************************************************************

        SUBROUTINE PROG1 (DABL, TK, MB, VISB, VA, FACTOR, Y)

        DIMENSION VA(1:50), DABL(1:50), Y(1:50)
        REAL MB
C
        DO I = 1, 12

        SUM1 = (7.4*(FACTOR*MB)**0.5*TK)
        SUM2 = (VISB*VA(I)**0.6)
        DABL(I) = SUM1/SUM2
        DABL(I) = DABL(I)/(10**8)

        Y(I) = TK/(DABL(I)*VISB*10**7)
        END DO
        RETURN
        END

C       **************************************************************
C       THIS PROGRAM CALCULATES THE DIFFUSION COEFFICIENT OF THE
C       GAS PHASE USING THE FULLER, SCHETTLER AND GIDDINGS METHOD
C       **************************************************************

        SUBROUTINE PROG2 (DABG, TKG, MAG, MBG, VAG, VBG, PRES)
        REAL MAG, MBG

        SUM3 = ((MAG+MBG)/(MAG*MBG))**0.5
        SUM4 = (VAG**0.333+VBG**0.333)**2
        DABG = (TKG**1.75*0.001*SUM3)/(PRES*SUM4)
        RETURN
        END
```

```
      PROGRAM PROG24

C     THIS PROGRAM CALCULATES THE COMPRESSIBILITY FACTOR OF NATURAL
C     GAS AT A KNOWN SPECIFIC GRAVITY AND TEMPERATURE
C
C     **************************************************************
C     PP  =  NATURAL GAS PRESSURE, psia.
C     SPG =  GAS SPECIFIC GRAVITYL, dimensionless
C     TF  =  GAS TEMPERATURE, oF.
C     Z   =  GAS COMPRESSIBILITY FACTOR.
C     **************************************************************

C     OPEN FILE TO PRINT THE RESULTS.

      OPEN (UNIT=1, FILE='PRN')

      DATA TF /60.0/, SPG /0.550/

 9    WRITE (1, 100)

 100  FORMAT (20X,'COMPRESSIBILITY FACTOR OF NATURAL GAS',
     *          /1H, 78(1H*))

      WRITE (1, 105)
 105  FORMAT (10X, 'TEMPERATURE, oF', 10X, 'SPECIFIC GRAVITY')

      WRITE (1,110) TF, SPG
 110  FORMAT (10X, F6.0, 20X, F6.3,/)

      A1 = 0.001946
      A2 = -0.027635
      A3 = 0.136315
      A4 = -0.238489
      A5 = 0.105168
      A6 = 3.444*(10**8)
      T = TF + 460.0

      WRITE (1, 120)
 120  FORMAT (10X,'PRESSURE psia.',6X,'COMPRESSIBILITY FACTOR Z',
     *         /, 78(1H-))

      PP = 100.0

 10   P1 = PP/1000.0


C     WRITE THE EXPRESSIONS FOR F1, F2, F3, F4, F5

      F1 = P1*(0.251*SPG-0.150) - 0.202*SPG + 1.106
      F2 = 1.4*EXP(-0.0054*TF)
      F3 = (A1*P1**5) + (A2*P1**4) + (A3*P1**3) + (A4*P1**2) + A5*P1
      VAL1 = P1**(3.18*SPG-1.0)
      VAL2 = EXP(-0.5*P1)
      F4 = (VAL1*VAL2)*(0.154-0.152*SPG) - 0.02
      VAL3 = -1.039*((P1-1.8)**2)
      F5 = 0.35*(0.6-SPG)*EXP(VAL3)
      VAL4 = 1 + (A6*P1*10**(1.785*SPG))/(T**3.825)
      Z = F1*(1/VAL4+(F2*F3)) + F4 + F5
```

```
      WRITE (1, 130) PP, Z
 130  FORMAT (5X, F12.0, 15X, F12.5)

      PP = PP + 100.0

      IF (PP .GT. 5000.0) THEN
      GO TO 60
      ELSE
      GO TO 10
      ENDIF

C     PRINT THE RESULTS ON A NEW PAGE.

 60   WRITE (1, 140)
 140  FORMAT (78(1H-))

      WRITE (1, 150)
 150  FORMAT ('1')

      TF = TF + 10.0

      IF (TF .GT. 100.0) THEN
      GO TO 12
      ELSE
      GO TO 9
      ENDIF

 12   TF = TF - 50.0
      SPG = SPG + 0.05

      IF (SPG .GT. 0.8) THEN
      GO TO 70
      ELSE
      GO TO 9
      ENDIF

C     FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)

      CLOSE (UNIT = 1)
 70   STOP
      END
```

CHAPTER 3

Fluid Flow

INTRODUCTION

Transportation of fluids is important in the design of chemical process plants. In the chemical process industries (CPI), pipework and its accessories such as fittings, makeup 20% to 30% of the total design costs and 10% to 20% of the total plant investment. Maintenance requirements and energy usage in the shape of pressure drop (ΔP) in the fluids being pumped add to the cost. Also, these items escalate each year in line with inflation. As a result, sound pipe sizing practices can have a substantial influence on overall plant economics. It is the designer's responsibility to optimize the pressure drops in piping and equipment and to assess the most economical conditions of operations. Figures 3-1A and 3-1B illustrate piping layouts in a chemical plant.

The characteristics and complexity of flow pattern are such that most flows are described by a set of empirical or semi-empirical equations. These relate the pressure drop in the flow system as a function of flow rate, pipe geometry, and physical properties of the fluids. The aim in the design of fluid flow is to choose a line size and piping arrangement that achieve minimum capital and pumping costs. In addition, constraints on pressure drop and maximum allowable velocity in the process pipe should be maintained. These objectives require many trial and error computations, which can be performed well by a computer.

Flow of Fluids in Pipes

Pressure drop or head loss in a piping system is caused by fluid rising in elevation, friction, shaftwork (e.g., from a turbine) and turbulence due to sudden changes in direction or cross-sectional area. Figure 3-2

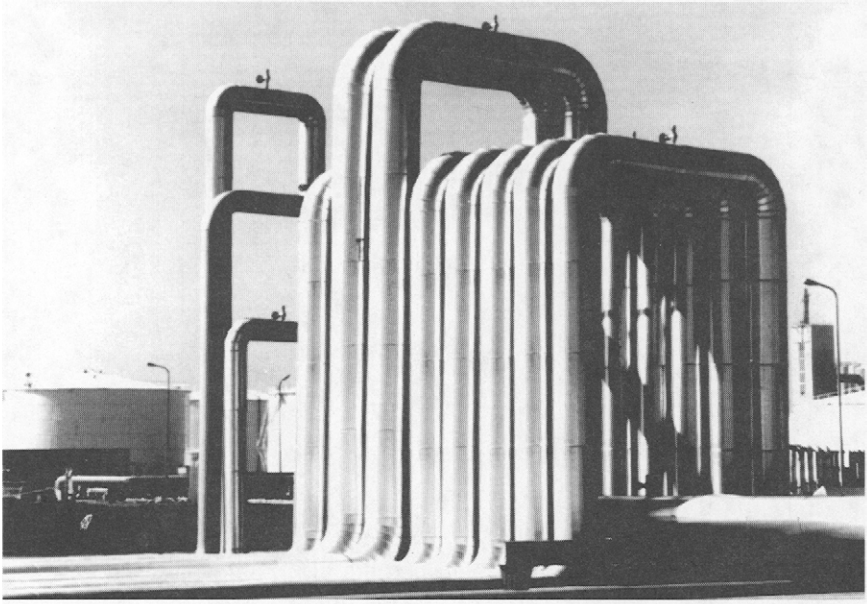


Figure 3-1A. Chemical plant piping layout.

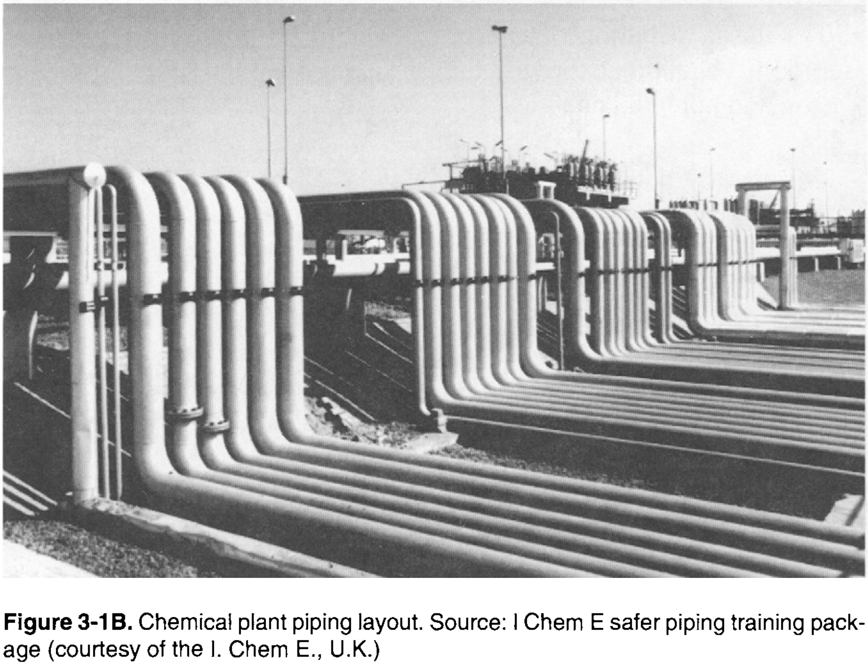
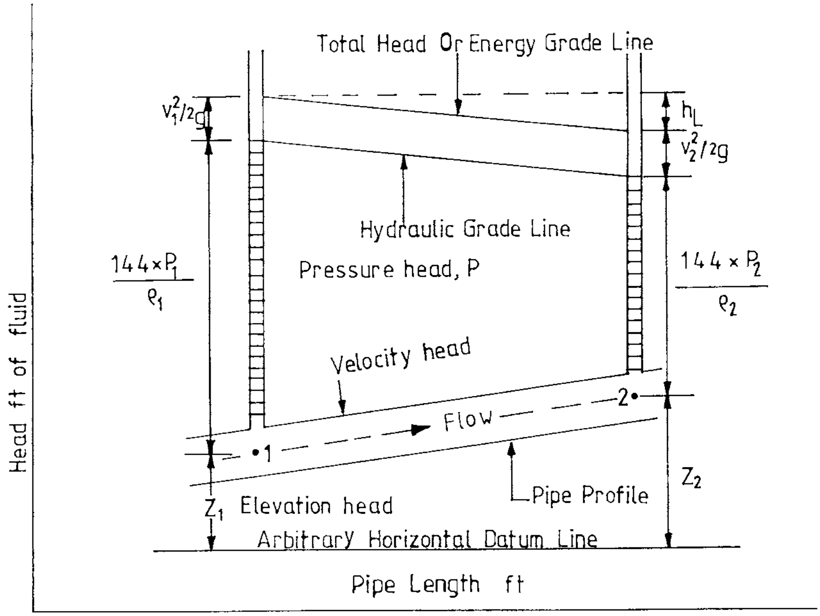


Figure 3-1B. Chemical plant piping layout. Source: I Chem E safer piping training package (courtesy of the I. Chem E., U.K.)



$$Z_1 + \frac{144 P_1}{\rho_1} + \frac{V_1^2}{2g} = Z_2 + \frac{144 P_2}{\rho_2} + \frac{V_2^2}{2g} + h_L$$

Figure 3-2. Distribution of fluid energy in a pipeline.

shows the distribution of energy between two points in a pipeline. Bernoulli's equation expresses the conservation of the sum of pressure, kinetic and potential energies.

$$\frac{1}{\rho}\int_1^2 dP + \frac{1}{g_c}\int_1^2 v\,dv + \int_1^2 dz = 0 \tag{3-1}$$

Integrating Equation 3-1 gives

$$\frac{1}{\rho}(P_2 - P_1) + \frac{v_2^2 - v_1^2}{2g_c} + (z_2 - z_1) = 0 \tag{3-2}$$

where P = pressure of fluid, lb_f/ft^2
ρ = density of fluid, lb_m/ft^3
V = velocity of fluid, ft/s
g_c = dimensional constant, $32.174(lb_m/lb_f)(ft/s^2)$
Z = elevation of fluid, ft
subscript 1 = condition at initial point
subscript 2 = condition at final point

The first, second, and third terms in Equation 3-2 represent pressure head, velocity head, and static differences respectively. Equation 3-2 is used for investigating energy distributions or determining pressure differentials between any two points in a pipeline. Incorporating the head loss due to friction, h_L, with constant pipe diameter, i.e., $V_1 = V_2$, Equation 3-2 becomes

$$\frac{1}{\rho}(P_2 - P_1) + (Z_2 - Z_1) = h_L \tag{3-3}$$

Equation 3-3 shows that the head loss, h_L, is generated at the expense of pressure head or static head difference. The static head difference can be either negative or positive. However, for a negative static head difference,

$$\Delta P > h_L + (Z_2 - Z_1) \tag{3-4}$$

In general, pressure loss due to flow is the same whether the pipe is horizontal, vertical, or inclined. The change in pressure due to the difference in head must be considered in the pressure drop calculation.

EQUIVALENT LENGTH OF VARIOUS FITTINGS AND VALVES

The effects of bends and fittings, such as elbow, valves, tees, and reduction or enlargement of pipes are determined empirically through a fictituous equivalent length of straight pipe having the same diameter and they would develop the same pressure drop. The equivalent pipe length is the most convenient method for determining the overall ΔP in a pipe. The drawback to this approach is that, for a given fitting the equivalent length is not constant but depends on the Reynolds number, the pipe roughness, the pipe size, and the geometry of the fitting. The equivalent length is added to the length of actual straight pipe to give the total length of pipe.

$$L_{Total} = L_{st} + L_{eq} \tag{3-5}$$

where L_{Total} = total length of pipe, ft
L_{st} = length of straight pipe, ft
L_{eq} = equivalent length of pipe, ft

The pressure drop equation can be expressed as:

$$\Delta P = \left(f_D \frac{L}{D} + \sum K \right) \rho \frac{v^2}{2g_c} \tag{3-6}$$

and the head loss equation can be expressed as:

$$\Delta H = \left(f_D \frac{L}{D} + \sum K \right) \frac{v^2}{2g_c} \tag{3-7}$$

where D = internal diameter of pipe, ft
f_D = Darcy friction factor
K = Excess head loss
L = pipe length, ft

Excess Head Loss

K is a dimensionless factor defined as the excess head loss in a pipe fitting, and expressed in velocity heads. The velocity head is the amount of kinetic energy contained in a stream or the amount of potential energy required to accelerate a fluid to its flowing velocity. Most published K values apply to fully developed turbulent flow because at high Reynolds number, K is found to be independent of Reynolds number. However, the two-K technique includes a correction factor for low Reynolds number. Hooper [1] gives a detailed analysis of his method compared to others [2,3], and has shown that the two-K method is the most suitable for any pipe size. In general, the two-K method is independent of the roughness of the fittings, but it is a function of Reynolds number and of the exact geometry of the fitting. The method can be expressed as:

$$K = \frac{K_1}{N_{Re}} + K_\infty \left(1 + \frac{1}{d} \right) \tag{3-8}$$

where K_1 = K for fitting at $N_{Re} = 1$
K_∞ = K for a large fitting at $N_{Re} = \infty$
d = internal diameter of attached pipe, inch

The conversion between equivalent pipe length and the resistance coefficient, K, can be expressed as:

$$K = f_D \frac{L_{eq}}{D} \tag{3-9}$$

Table 3-1 lists values of K_1 and K_∞ for the two-K method.

Table 3-1
Velocity Head Factors of Pipe Fittings

		Fitting Type		K_1	K_∞
Elbows	90°	Standard (R/D = 1), screwed		800	0.40
		Standard (R/D = 1), flanged/welded		800	0.25
		Long-radius (R/D = 1.5, all types		800	0.20
		Mitered elbows (R/D = 1.5)	1 Weld (90° angle)	1000	1.15
			2 Weld (45° angles)	800	0.35
			3 Weld (30° angles)	800	0.30
			4 Weld (22 1/2° angles)	800	0.27
			5 Weld (18° angles)	800	0.25
	45°	Standard (R/ D = 1), all types		500	0.20
		Long-radius (R/D = 1.5), all types		500	0.15
		Mitered, 1 weld, 45° angle		500	0.25
		Mitered, 2 weld, 22 1/2° angles		500	0.15
	180°	Standard (R/D = 1), screwed		1000	0.60
		Standard (R/D = 1), flanged/welded		1000	0.35
		Long radius (R/D = 1.5) all types		1000	0.30
Tees	Used as elbow	Standard, screwed		500	0.70
		Long-radius, screwed		800	0.40
		Standard, flanged or welded		800	0.80
		Stub-in-type branch		1000	1.00
	Run-through tee	Screwed		200	0.10
		Flanged or welded		150	0.05
		Stub-in-type branch		100	0.00
Valves	Gate, ball, plug	Full line size, $\beta = 1.0$		300	0.10
		Reduced trim, $\beta = 0.9$		500	0.15
		Reduced trim, $\beta = 0.8$		1000	0.25
	Globe, standard			1500	4.00
	Globe, angle or Y-type			1000	2.00
	Diaphragm, dam type			1000	2.00
	Butterfly			800	0.25
	Check	Lift		2000	10.00
		Swing		1500	1.50
		Tilting-disk		1000	0.50

Note: Use R/D = 1.5 values for R/D = 5 pipe bends, 45° to 180°. Use appropriate tee values for flow through crosses.

Source: Hooper [1]

Pipe Reduction and Enlargement

The velocity head is $v^2/2g_c$. For any velocity profile the true velocity represents the integral of the local velocity head across the pipe diameter. It is found by dividing the volumetric flow rate by the cross-sectional area of the pipe and multiplying by a correction factor. For laminar flow this factor is 2; for turbulent flow the factor depends on both the Reynolds number and the pipe roughness and $(1 + 0.8f_D)$ [4]. Therefore, when the pipe size changes, the velocity head also changes. Because the velocity is inversely proportional to the flow area and thus to the diameter squared, K is inversely proportional to the velocity squared.

$$K_2 = K_1\left(\frac{D_2}{D_1}\right)^4 \tag{3-10}$$

Although the potential energy provides the flowing fluid with kinetic energy at the pipe entrance, the kinetic energy is later recovered. This indicates that the measured pipe pressure will be lower than the calculated pressure by one velocity head. If the kinetic energy is not recovered at the pipe exit, the exit counts as a loss of one velocity head. Table 3-2 shows how K varies with changes in pipe size.

PRESSURE DROP CALCULATIONS FOR SINGLE-PHASE INCOMPRESSIBLE FLUIDS

The pressure drop of flowing fluids can be calculated from the Darcy friction factor:

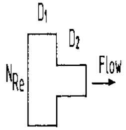
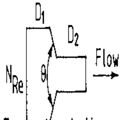
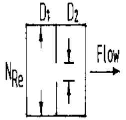
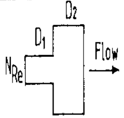
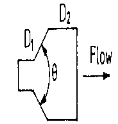
$$\frac{\Delta P}{L} = \frac{f_D}{D} \bullet \frac{\rho V^2}{2g_c} \tag{3-11}$$

where f_D = Darcy friction factor
ρ = density of fluid, lb_m/ft^3
V = velocity of fluid in the pipe, ft/s
g_c = dimensional constant, $32.174(lb_m/lb_f)(ft/s^2)$
L = length of pipe, ft

Friction Factor

The friction factor is related to the Reynolds number by a set of correlations and depends on whether the flow regime is laminar, transitional, or turbulent. The Reynolds number is:

Table 3-2
Excess Head Loss 'K' Correlation for Fitting Caused by a Change in Pipe Size

TYPE	FITTING	INLET N_{Re}	K – BASED ON INLET VELOCITY HEAD
1	 Square reduction	$N_{Re} \leq 2500$	$K = \left[1.2 + \frac{160}{N_{Re}}\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]$
		$N_{Re} > 2500$	$K = \left[0.6 + 0.48 f_D\right]\left(\frac{D_1}{D_2}\right)^2\left[\left(\frac{D_1}{D_2}\right)^2 - 1\right]$
2	 Tapered reduction	All	Multiply K from Type 1 by $\sqrt{\sin(\theta/2)}$ For $45^\circ < \theta < 180^\circ$ or $\left[1.6\sin(\theta/2)\right]$ For $0^\circ < \theta < 45^\circ$
3	 Thin, sharp orifice	$N_{Re} \leq 2500$	$K = \left[2.7 + \left(\frac{D_2}{D_1}\right)^2\left(\frac{120}{N_{Re}} - 1\right)\right]\left[1 - \left(\frac{D_2}{D_1}\right)^2\right]\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]$
		$N_{Re} > 2500$	$K = \left[2.7 - (D_2/D_1)^2(4000/N_{Re})\right]\left[1 - (D_2/D_1)^2\right]\left[(D_1/D_2)^4 - 1\right]$
4	 Square expansion	$N_{Re} \leq 4000$	$K = 2\left[1 - \left(\frac{D_1}{D_2}\right)^4\right]$
		N_{Re} 4000	$K = \left[1 + 0.8 f_D\right]\left\{\left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^2\right\}$
5	 Tapered expansion	All	If θ > 45°, use K from Type 4, otherwise multiply K from Type 4 by $\left[2.6\sin\left(\frac{\theta}{2}\right)\right]$

$$N_{Re} = \frac{\rho V D}{\mu} = 50.6\frac{Q\rho}{d\mu} = 6.31\frac{W}{d\mu} \tag{3-12}$$

where Q = volumetric flowrate, gals/min
W = Mass flow rate, lb/h
μ = fluid viscosity, cP

For laminar flow with $N_{Re} \leq 2000$

$$f_D = \frac{64}{N_{Re}} \tag{3-13}$$

The Darcy friction factor is four times the Fanning friction factor, f_F, i.e., $f_D = 4f_F$. For fully developed turbulent flow regime in smooth and rough pipes, the Colebrook [5] equation or the Chen [6] equation can be used.

The Colebrook equation is expressed as:

$$\frac{1}{\sqrt{f_D}} = -0.8686\ln\left\{\frac{\varepsilon}{3.7D} + \frac{2.51}{N_{Re}\sqrt{f_D}}\right\} \tag{3-14}$$

Equation 3-14 is implicit in f_D, as it cannot be rearranged to derive f_D directly and thus requires an iterative solution. Here, the Chen equation is used for calculating f_D, (i.e, $f_D = 4f_C$). The Chen equation is explicit and easier to use than Equation 3-14). This can be expressed as:

$$\frac{1}{\sqrt{f_C}} = -4 \log\left\{\frac{\varepsilon}{3.7D} - \frac{5.02}{N_{Re}} \log A\right\} \tag{3-15}$$

where

$$A = \frac{\varepsilon/D}{3.7} + \left(\frac{6.7}{N_{Re}}\right)^{0.9}$$

and

ε = pipe roughness, ft

A detailed review of other explicit equations is given by Gregory and Fogarasi [7]. Different piping materials are often used in the chemical process industries, and at a high Reynolds number, the friction factor is affected by the roughness of the surface. This is measured as the ratio ε/D of projections on the surface to the diameter of the pipe. Glass and plastic pipe essentially have $\varepsilon = 0$. Values of ε are shown in Table 3-3.

The Overall Pressure Drop

Designers involved in sizing process piping often apply trial and error procedure. The designer first selects a pipe size and then calculates the

Table 3-3
Values of Absolute Pipe Roughness

Pipe Material	ε, ft
Riveted steel	0.003-0.03
Concrete	0.001-0.01
Wood stave	0.0006-0.003
Cast iron	0.00085
Galvanized iron	0.0005
Asphalted cast iron	0.0005
Commercial steel or wrought iron	0.00015
Drawn tubing	0.000005

Reynolds number, friction factor, and coefficient of resistance. The pressure drop per 100 feet of pipe is then computed. For a given volumetric rate and physical properties of a single-phase fluid, ΔP_{100} for laminar and turbulent flows is:

laminar flow

$$\Delta P_{100} = 0.0273 \frac{\mu Q}{d^4}, \quad \text{psi / 100ft} \tag{3-16}$$

turbulent flow

$$\Delta P_{100} = 0.0216 f_D \frac{\rho Q^2}{d^5}, \quad \text{psi / 100ft} \tag{3-17}$$

Alternatively, for a given mass flow rate and physical properties of a single-phase fluid, ΔP_{100} for laminar and turbulent flows respectively is:

laminar flow

$$\Delta P_{100} = 0.0034 \frac{\mu W}{d^4 \rho}, \quad \text{psi / 100ft} \tag{3-18}$$

turbulent flow

$$\Delta P_{100} = 0.000336 f_D \frac{W^2}{d^5 \rho}, \quad \text{psi / 100ft} \tag{3-19}$$

Multiplying Equations 3-16, 3-17, 3-18, and 3-19 by the total length between two points and adding the pipe elevation yields the overall pressure drop.

$$\Delta P = \Delta P \bullet \frac{L_{\text{Total}}}{100} + \frac{\rho \Delta Z}{144}, \quad \text{psi} \tag{3-20}$$

Equation 3-20 is valid for compressible isothermal fluids of shorter lines where pressure drops are no more than 10% of the upstream pressure. In general, pipe size for a given flow rate is often selected on the assumption that the overall pressure drop is close to or less than the available pressure difference between two points in the line.

Nomenclature

A = pipe cross-sectional area, ft^2

d = internal pipe diameter, inch

D = internal pipe diameter, ft
f_C = Chen friction factor
f_p = Darcy friction factor
g_c = dimensional constant 32.174 ($lb_m/lb_f \bullet ft/s^2$)
h_L = head loss, ft
K = excess head loss for a fitting, velocity heads
K_1 = K for fitting at $N_{Re} = 1$, velocity heads
K_∞ = K for very large fitting at $N_{Re} = \infty$, velocity heads
L_{eq} = equivalent length of pipe, ft
L_{st} = actual length of pipe, ft
L_{Total} = total length of pipe, ft
n = number of fittings
N_{Re} = Reynolds number
ΔP_{100} = pressure drop per 100 ft of pipe, psi/100 ft
ΔP = overall pressure drop of pipe, psi
ρ = fluid density, lb/ft^3
ε = absolute roughness of pipe wall, ft
μ = fluid viscosity, cP

COMPRESSIBLE FLUID FLOW IN PIPES

The flow of compressible fluids (e.g., gases and vapors) through pipelines and other restrictions is often affected by changing conditions of pressure, temperature, and physical properties. The densities of gases and vapors vary with temperature and pressure. During isothermal flow, i.e., constant temperature (PV = constant) density varies with pressure. Conversely, in adiabatic flow, i.e., no heat loss (PV^k = constant), a decrease in temperature occurs when pressure decreases, resulting in a density increase. At high pressures and temperatures, the compressibility factor can be less than unity, which results in an increase in the fluid density.

The condition of high ΔP in compressible flow frequently occurs in venting systems, vacuum distillation equipment, and long pipelines [8]. Some design situations involve vapor flows at very high velocities resulting in $\Delta P > 10\%$ of the upstream pressure. Such cases are vapor expanding through a valve, high speed vapor flows in narrow pipes, and vapors flowing in process lines under vacuum conditions. In many cases, ΔP is critical and requires accurate analysis and design. For instance, the inlet pipe ΔP of a safety relief valve should not exceed 3% of the relief valve set pressure (guage) at its relieving capacity for stable operation. This limit is to prevent the rapid opening and closing of the valve, a phenomenom known as chattering, resulting in lowered fluid capacity and subsequent damage of the value seating surfaces. Conversely, the tailpipe or ventline of a relief valve should be designed in such a way that ΔP < 10% of the relieving pressure, i.e., set pressure + over pressure in gauge. Figure 3-3 shows a typical tail pipe and relief valve connected to a heat exchanger.

Maximum Flow and Pressure Drop

Determining the maximum fluid flow rate or pressure drop for process design often has the dominant influence on density. As pressure decreases due to piping and component resistance, the gas expands and its velocity increases. A limit is reached when the gas or velocity cannot exceed the sonic or critical velocity. Even if the downstream pressure is lower than the pressure required to reach sonic velocity, the flow rate will still not increase above that evaluated at the critical velocity. Therefore, for a given ΔP, the mass discharge rate through a pipeline is greater for an adiabatic condition (i.e., insulated pipes, where heat transfer is

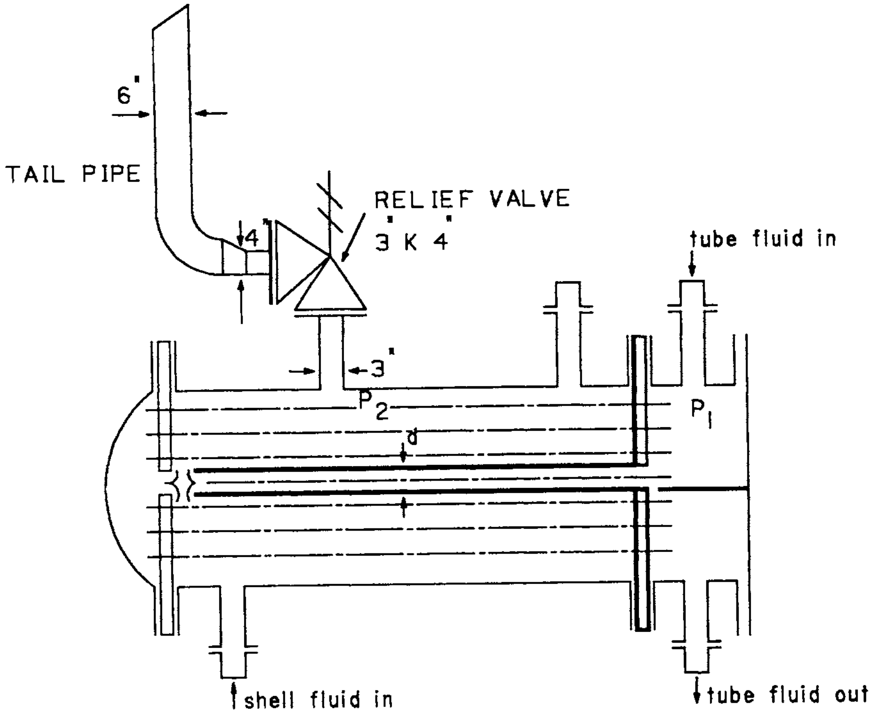


Figure 3-3. Fluid flow through a heat exchanger, relief valve, and tail pipe.

nil) than the rate for an isothermal condition by as much as 20%. There is, however, no difference if the pipeline is more than 1,000 pipe diameters long [10]. In practice, the actual flows are between the two conditions, and the inflow rates are often below 20% even for lines less than 1,000 pipe diameters.

Critical or Sonic Flow and the Mach Number

The flow rate of a compressible fluid in a pipe with a given upstream pressure will approach a certain maximum rate that it cannot exceed even with reduced downstream pressure. The maximum velocity is limited by the velocity of propagation of a pressure wave that travels at the speed of sound in the fluid. The maximum velocity that a compressible fluid can attain in a pipe is known as the sonic velocity, V_s, and can be expressed as:

$$V_s = 223\left(\frac{kT}{M_W}\right)^{0.5}, \quad \text{ft/s}$$

$$= 68.1\left(\frac{kP_1}{\rho_1}\right)^{0.5}, \quad \text{ft/s} \qquad (3\text{-}21)$$

With a high velocity vapor flow, the possibility of attaining critical or sonic flow conditions in a process pipe should be investigated. These occur whenever the resulting pressure drop approaches the following values of ΔP as a percentage of the upstream pressure [11]:

1. saturated steam, $\Delta P = 42\%$
2. diatomic gases, (e.g., H_2, N_2, O_2), $\Delta P = 47\%$
3. triatomic and higher molecular weight gases including hydrocarbon vapors and superheated steam, $\Delta P = 45\%$. Vapor flow at or near this maximum velocity should be avoided because a critical pressure, P_c, is attained at the sonic velocity and any ΔP beyond P_c will translate into shock waves and critical turbulence instead of being converted into useful kinetic energy.

In the case of a high pressure header, the flow may be sonic at the exit. Therefore, it is often necessary to check that the outlet pressure of each pipe segment is not critical. If P_c is less than terminal P_2, the flow is subcritical. If however, P_c is greater than P_2, then the flow is critical.

Although, it may be impractical to keep the flow in high pressure subheaders below sonic, Mak [12] suggests that the main flare header should not be sized for critical flow at the outlet of the flare stack. This would obviate the undesirable noise and vibration resulting from sonic flow. Crocker's [13] equation for critical pressure can be expressed as:

$$P_c = \frac{G}{11400d^2}\left(\frac{RT}{k(k+1)}\right)^{0.5}, \quad \text{psia} \tag{3-22}$$

where R = (1544/29•SpGr), molar gas constant
SpGr = molecular weight of the gas ÷ molecular weight of air

The upstream fluid velocity is:

$$V = \frac{0.0509G}{d^2\rho_1}, \quad \text{ft/s} \tag{3-23}$$

A recommended compressible fluid velocity for trouble-free operation is $V \le 0.6V_s$. The design criteria for compressible fluid process lines (e.g., carbon steel) are shown in Table 3-4.

The Mach Number

The Mach number, M, is the velocity of the gas divided by the velocity of the sound in the gas and can be expressed as:

$$M = \frac{V}{V_s} \tag{3-24}$$

The exit Mach number for compressible isothermal fluid has been shown to be $M \neq 1$, but $1/\sqrt{k}$, where k is the ratio of the fluid specific heat capacities at constant pressure to that at constant volume. Table 3-5 shows the k values for some common gases. The following cases are such:

1. for $M < 1/\sqrt{k}$, the flow is subsonic
2. for $M = 1/\sqrt{k}$, the flow is sonic
3. for $M > 1/\sqrt{k}$, the flow is supersonic

Case 3 is produced under certain operating conditions in the throttling process (e.g., a reduction in the flow cross-sectional area). Kirkpatrick [14] indicates that there is a maximum length for which continuous flow is applied for an isothermal condition, and this corresponds to

Table 3-4
Recommended Fluid Velocity and Maximum ΔP for Carbon Steel Vapor Lines

Type of Service	Recommended Velocity ft/sec.	Maximum ΔP psi/100 ft.
1. General Recommendation		
Fluid pressure psig		
Subatmospheric		0.18
$0 < P \leq 50$		0.15
$50 < P \leq 150$		0.30
$150 < P \leq 200$		0.35
$200 < P \leq 500$		1.0
$P > 500$		2.0
2. Tower Overhead		
Pressure ($P > 50$ psia)	40-50	0.2-0.5
Atmospheric	60-100	
Vacuum ($P < 10$ psia)		0.05-0.1
3. Compressor Piping Suction	75-200	0.5
4. Compressor Piping Discharge	100-250	1.0
Gas lines with battery limits.		0.5
Refrigerant Suction lines	15-35	
Refrigerant Discharge lines	35-60	
Steam lines		
1. General Recommendation		
Maximum: Saturated	200	
Superheated	250	
Steam pressure in psig.		
0–50	167	0.25
50–150	117	0.40
150–300		1.0
>300		1.5
2. High pressure Steam Lines		
short ($L < 600$ ft)		1.0
Long ($L > 600$ ft)		0.5
3. Exhaust Steam lines		0.5
($P >$ atmosphere)		0.5
Leads to Exhaust Header		1.5
4. Relief valve discharge	$0.5V_s$	
Relief valve, Entry point at silencer	V_S	

Table 3-5
Approximate k values for some common gases (68°F, 14.7 psia)

Gas	Chemical Formula or Symbol	Approximate Molecular Weight	$k(C_p/C_v)$
Acetylene (Ethyne)	C_2H_2	26.0	1.30
Air	—	29.0	1.40
Ammonia	NH_3	17.0	1.32
Argon	A	39.9	1.67
Butane	C_4H_{10}	58.1	1.11
Carbon Dioxide	CO_2	44.0	1.30
Carobon Monoxide	CO	28.0	1.40
Chlorine	$C1_2$	70.9	1.33
Ethane	C_2H_6	30.0	1.22
Ethylene	C_2H_4	28.0	1.22
Helium	He	4.0	1.66
Hydrogen Chloride	HC1	36.5	1.41
Hydrogen	H_2	2.0	1.41
Methane	CH_4	16.0	1.32
Methyl Chloride	CH_3C1	50.5	1.20
Natural Gas	—	19.5	1.27
Nitric Oxide	NO	30.0	1.40
Nitrogen	N_2	28.0	1.41
Nitrous Oxide	N_2O	44.0	1.31
Oxygen	O_2	32.0	1.40
Propane	C_3H_8	44.1	1.15
Propylene (Propene)	C_3H_6	42.1	1.14
Sulfur Dioxide	SO_2	64.1	1.26

$M = 1/\sqrt{k}$. The limitation for isothermal flow, however, is the heat transfer required to maintain a constant temperature. Therefore, when $M < 1/\sqrt{k}$, heat must be added to the stream to maintain constant temperature. For $M < \sqrt{k}$, heat must be rejected from the stream. Depending on the ratio of specific heats, either condition could occur with subsonic flow. Therefore, to maintain isothermal flow during heat transfer, high temperatures require high Mach numbers and low temperatures require low Mach numbers.

Mathematical Model of Compressible Isothermal Flow

The derivations of the maximum flow rate and pressure drop of compressible isothermal flow are based on the following assumptions:

1. isothermal compressible fluid
2. no mechanical work done on or by the system
3. the gas obeys the perfect gas laws
4. a constant friction factor along the pipe
5. steady state flow or discharge unchanged with time

Figure 3-4 illustrates the distribution of fluid energy with work done by the pump and heat added to the system. Table 3-6 gives friction factors for clean commercial steel pipes with flow in zones of complete turbulence.

Flow Rate Through Pipeline

Bernoulli's equation for the steady flow of a fluid can be expressed as:

$$\int_1^2 \frac{dP}{\rho} + \frac{V^2}{2g_c\alpha} + \frac{g}{g_c}\Delta Z + h_L + \delta W_s = 0 \tag{3-25}$$

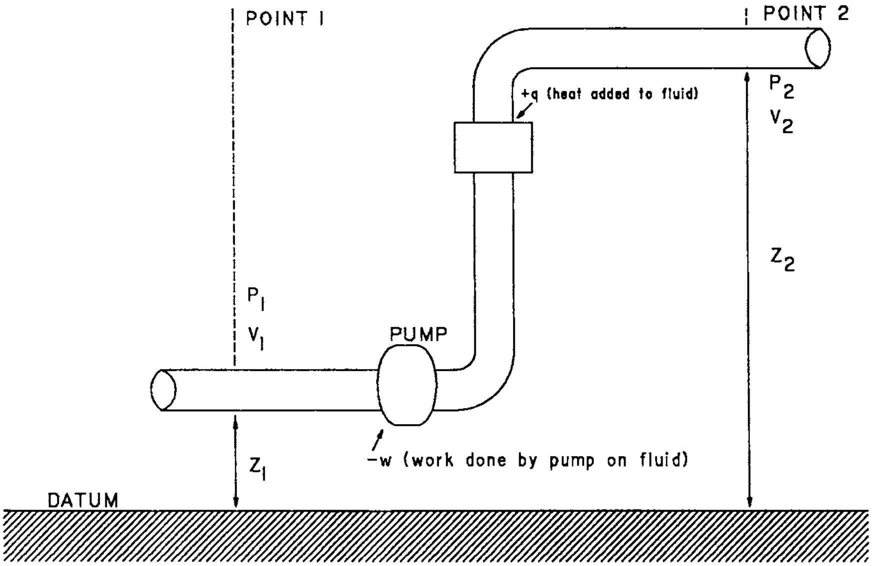


Figure 3-4. Energy aspects of a single-stream piping system.

Table 3-6
Friction Factors for Total Turbulence in New Commerical Steel Pipes

Nominal Size (inch)	Friction Factor (f)
1	0.023
1.5	0.0205
2	0.0195
3	0.0178
4	0.0165
5	0.016
6	0.0152
8	0.0142
10	0.0136
12	0.0132
14	0.0125
16	0.0122
18	0.12
20	0.0118
24	0.0116

where α (the dimensionless velocity distribution) = 1 for turbulent or plug flow. Assuming no shaft work is done (i.e., $\delta W_s = 0$), then Equation 3-25 becomes

$$\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2g_c\alpha} + \frac{g}{g_c}(Z_2 - Z_1) + h_L = 0 \quad . \qquad (3\text{-}26)$$

For expanding gas flow, $V_2 \neq V_1$; with horizontal pipe, $Z_2 = Z_1$. Hence, the differential form of Bernoulli's equation can be expressed as

$$-\frac{dP}{\rho} = \frac{1}{g_c} VdV + h_L \qquad (3\text{-}27)$$

where ρ is constant and the velocity head is

$$h_L = K\frac{V^2}{2g_c} \qquad (3\text{-}28)$$

The mass flow rate through the pipe is $G = \rho VA$ or

$$\frac{G}{A} = \rho V = \text{constant} \tag{3-29}$$

Because both density and velocity change along the pipeline, Equation 3-29 can be expressed in differential form as:

$$\rho dv + Vd\rho = 0 \tag{3-30}$$

In expanding gas flow, the pressure and density ratio are constant:

$$\frac{P}{\rho} = \frac{dP}{d\rho} \tag{3-31}$$

and, with respect to initial condition, P_1 and ρ_1,

$$\frac{P}{\rho} = \frac{dP}{d\rho} = \frac{P_1}{\rho_1} \tag{3-32}$$

From Equation 3-30

$$dV = -\frac{V}{\rho} d\rho \tag{3-33}$$

and

$$\frac{dP}{P} = \frac{d\rho}{\rho} \tag{3-34}$$

Therefore

$$\frac{1}{\rho} = \frac{1}{P}\left(\frac{dP}{d\rho}\right) = \frac{1}{P}\left(\frac{P_1}{\rho_1}\right) \tag{3-35}$$

Substituting Equation 3-34 into Equation 3-33

$$dV = -\frac{V}{\rho}\left(\frac{dP}{P}\right)\rho \tag{3-36}$$

Therefore

$$dV = -V\left(\frac{dP}{P}\right) \tag{3-37}$$

Substituting Equation 3-37 into Equation 3-27

$$-\frac{dP}{\rho} = \frac{1}{g_c} V\left(-V\frac{dP}{P}\right) + \frac{KV^2}{2g_c} \tag{3-38}$$

$$-\frac{dP}{\rho} = -\frac{1}{g_c} V^2\left(\frac{dP}{P}\right) + \frac{KV^2}{2g_c} \tag{3-39}$$

Therefore,

$$-dP = \frac{V^2}{g_c}\rho\left(\frac{K}{2} - \frac{dP}{P}\right) \tag{3-40}$$

From the mass flow rate, G = ρVA

$$V = \frac{G}{\rho A} \tag{3-41}$$

Substituting Equation 3-41 into Equation 3-40

$$-dP = \frac{G^2}{g_c A^2 \rho^2} \bullet \rho\left(\frac{K}{2} - \frac{dP}{P}\right) \tag{3-42}$$

In terms of the initial conditions of pressure and density, i.e., substituting Equation 3-35 into Equation 3-42

$$-dP = \left(\frac{G}{A}\right)^2 \frac{1}{g_c}\left\{\frac{1}{P}\left(\frac{P_1}{\rho_1}\right)\right\}\left[\frac{K}{2} - \frac{dP}{P}\right] \tag{3-43}$$

Integrating Equation 3-43 gives:

$$-2\int_1^2 PdP = \left(\frac{G}{A}\right)^2 \left(\frac{P_1}{\rho_1}\right)\frac{1}{g_c}\left\{K - 2\int_1^2 \frac{dP}{P}\right\} \tag{3-44}$$

which is

$$P_1^2 - P_2^2 = \left(\frac{G}{A}\right)^2 \frac{P_1}{\rho}\left(\frac{1}{g_c}\right)\left\{K + 2\ln\frac{P_1}{P_2}\right\} \tag{3-45}$$

Therefore, for maximum flow rate through the pipe,

$$G = \left[\left(\frac{A^2\rho_1 g_c}{K_{TOTAL} + 2\ln\frac{P_1}{P_2}}\right)\left(\frac{P_1^2 - P_2^2}{P_1}\right)\right]^{0.5} \tag{3-46}$$

where K_{TOTAL} is the total velocity head due to friction, fittings, and valves:

$$K_{TOTAL} = f_D\frac{L}{D} + \sum K_f \quad \text{(pipe fittings + valves)}$$

ΣK_f (pipe fittings + valves) is the sum of the pressure loss coefficient for all the fittings and valves in the line. Expressing the maximum fluid rate in pounds per hour, Equation 3-46 becomes

$$G = 1335.6d^2\left[\left(\frac{\rho_1}{K_{TOTAL} + 2\ln\frac{P_1}{P_2}}\right)\left(\frac{P_1^2 - P_2^2}{P_1}\right)\right]^{0.5} \tag{3-47}$$

Pipeline Pressure Drop

If ΔP due to velocity acceleration is relatively small compared with the frictional drop, then $\ln(P_1/P_2)$ may be neglected. Therefore Equation 3-47 becomes

$$G = 1335.6d^2\left[\frac{\rho_1}{K_{TOTAL}}\left(\frac{P_1^2 - P_2^2}{P_1}\right)\right]^{0.5} \tag{3-48}$$

Putting $C = 1335.6d^2$

$$\frac{G^2}{C^2} = \frac{\rho_1}{K_{TOTAL}} \bullet \frac{P_1^2 - P_1^2}{P_1} \tag{3-49}$$

i.e.,

$$P_1^2 - P_2^2 = \frac{P_1 G^2 K_{TOTAL}}{\rho_1 C^2}$$

$$P_2 = \left[P_1^2 - \frac{P_1 G^2 K_{TOTAL}}{\rho_1 C^2}\right]^{0.5} \tag{3-50}$$

Therefore, the pressure drop

$$\Delta P \cong P_1 - P_2$$

i.e.,

$$\Delta P \cong P_1 - \left[P_1^2 \, \frac{P_1 G^2 K_{TOTAL}}{\rho_1 C^2} \right]^{0.5}, \quad \text{psi} \tag{3-51}$$

Nomenclature

A = pipe cross-sectional area, ft^2
d = pipe internal diameter, inch
D = pipe internal diameter, ft
f_C = Chen friction factor
f_D = Darcy friction factor
g = acceleration due to gravity ($32 ft/s^2$)
g_c = conversion factor $\left(32.174(lb_m/lb_f) \bullet (ft/s^2)\right)$
G = fluid flow rate lb/h
k = ratio of specific heat capacities (C_p/C_v)
K = resistance coefficient due to pipe fittings plus valves
K_f = resistance coefficient due friction pipe fittings + valves
K_{Total} = total resistance coefficient
L_{st} = length of straight pipe, ft
M_w = molecular weight of fluid (lb/lb.mol)
M = Mach number
N_{Re} = Fluid Reynolds number ($6.31G/d\mu$)
P_1 = inlet fluid pressure, psia
P_2 = outlet fluid pressure, psia
P_c = critical pressure, psia
R = molar gas constant ($1544/29 \times SpGr.$)
$SpGr$ = molecular weight of gas ÷ molecular weight of air
T = fluid temperature, °F
V = fluid velocity, ft/s
V_s = fluid sonic or critical velocity, ft/s
Z = compressibility factor
α = correction factor (1 for turbulent or plug flow)
ρ = fluid density, (lb_m/ft^3)($PM_w/10.73ZRT$)
μ = fluid viscosity, cP
ε = absolute pipe roughness, ft (0.00015 ft for carbon steel)
Δ = difference

Subscripts

1 = upstream point in pipe
2 = downstream point in pipe

TWO-PHASE FLOW IN PROCESS PIPING

Two-phase flow often presents design and operational problems not associated with liquid or gas flow. For example, several different flow patterns may exist along the pipeline. Frictional pressure losses are more difficult to estimate, and in the case of a cross-country pipeline, a terrain profile is necessary to predict pressure drops due to elevation changes. The downstream end of a pipeline often requires a separator to separate the liquid and vapor phases, and a slug catcher may be required to remove liquid slugs.

Static pressure losses in gas-liquid flow differ from those in single-phase flow because an interface can be either smooth or rough, depending on the flow pattern. Two-phase pressure losses may be up to a factor of 10 higher than those in single-phase flow. In the former, the two phases tend to separate and the liquid lags behind. Most published correlations for two-phase pressure drop are empirical, and therefore, limited by the range of data for which they were derived [15,16,17]. If two-phase situations are not detected, pressure drop problems may develop that can prevent systems from operating.

Flow Patterns

In determining the type of flow in a process pipeline, designers refer to a diagram similar to Figure 3-5, which is known as the Baker map. Figure 3-6 shows the types of flow regimes that can exist in a horizontal

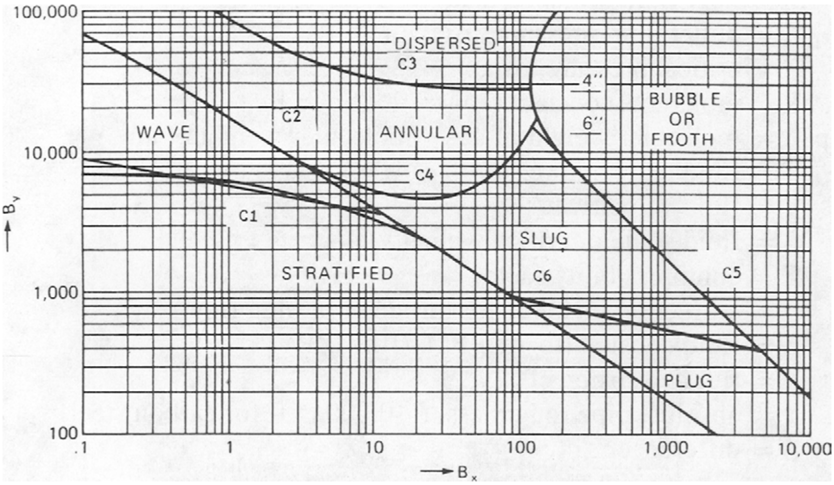


Figure 3-5. Baker parameters for two-phase flow regimes with modified boundaries. Source: Baker [15].

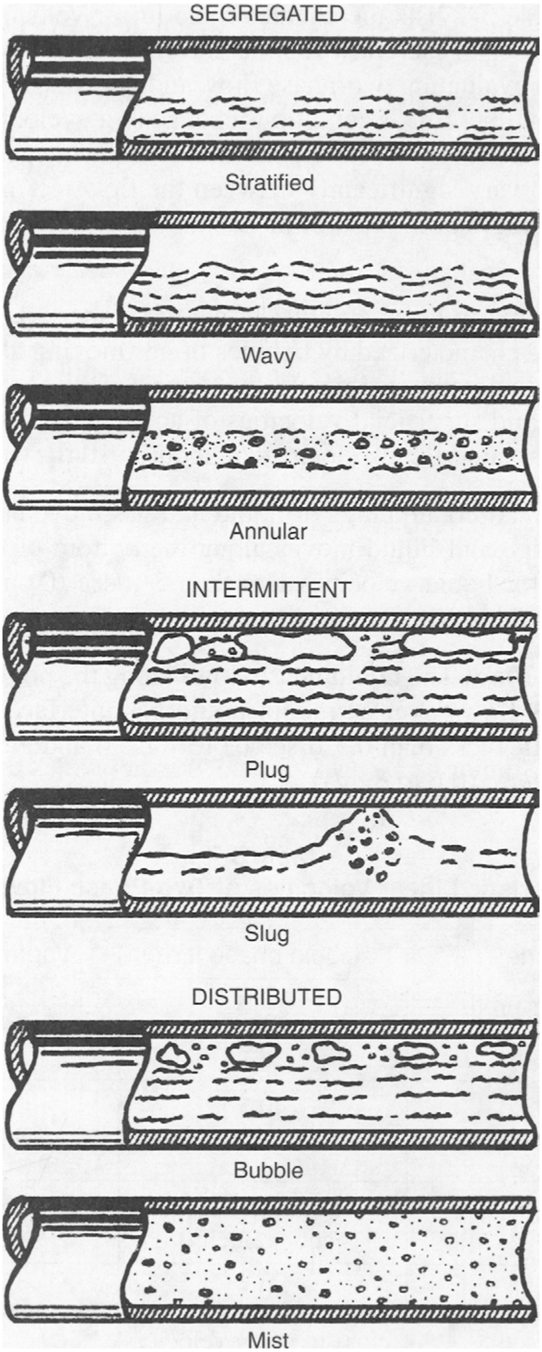


Figure 3-6. Flow regimes in horizontal two-phase flow.

pipe, and Table 3-7 lists the characteristic linear velocities of the gas and liquid phases in each flow regime. Seven types of flow patterns are considered in evaluating two-phase flow, and only one type can exist in a pipeline at a time. But as conditions change (e.g., velocity, roughness, and elevation), the type of flow pattern may also change. The pressure drop can also vary significantly between the flow regimes. The seven types of flow regimes in order of increasing gas rate at a constant liquid flow rate are:

Bubble or Froth Flow. Bubbles of gas are dispersed throughout the liquid and are characterized by bubbles of gas moving along the upper part of the pipe at approximately the same velocity as the liquid. It occurs for liquid superficial velocities of about 5–15 ft/sec (1.5 to 4.5 m/sec) and gas superficial velocities of about 1–10 ft/s (0.3 to 3 m/sec).

Plug Flow. Alternate plugs of liquid and gas move along the upper part of the pipe and liquid moves along the bottom of the pipe. Plug flow occurs for liquid velocities less than 2 ft/sec (0.6m/sec) and gas velocities less than about 3 ft/sec (0.9 m/sec).

Stratified Flow. The liquid phase flows along the bottom of the pipe while the gas flows over a smooth liquid-gas interface. It occurs for liquid velocities less than 0.5 ft/sec (0.15 m/sec) and gas velocities of about 2–10 ft/sec (0.6 to 3 m/s).

Table 3-7
Characteristic Linear Velocities of Two-Phase Flow Regimes

Regime	Liquid phase ft/s	Vapor phase ft/s
Bubble or Froth	5–15	0.5–2
Plug	2	<4
Stratified	<0.5	0.5–10
Wave	<1.0	>15
Slug	15 (but less than vapor velocity)	3–50
Annular	<0.5	>20
Dispersed, Spray or Mist	close to vapor velocity	>200

Wave Flow. Wave flow is similar to stratified flow except that the gas is moving at a higher velocity and the gas-liquid interface is distributed by waves moving in the direction of flow. It occurs for liquid velocities less than 1 ft/sec (0.3 m/sec) and gas velocities from about 15 ft/sec. (4.5 m/sec).

Slug Flow. This pattern occurs when waves are picked up periodically by the more rapidly moving gas. These form frothy slugs that move along the pipeline at a much higher velocity than the average liquid velocity. This type of flow causes severe and, in most cases, dangerous vibrations in equipment because of the high velocity slugs against fittings.

Annular Flow. In annular flow, liquid forms around the inside wall of the pipe and gas flows at a high velocity through the central core. It occurs for gas velocities greater than 20 ft/sec (6 m/sec).

Dispersed, Spray, or Mist Flow. Here, all of the liquid is entrained as fine droplets by the gas phase. Dispersed flow occurs for gas velocities greater than 200 ft/sec (60 m/sec).

Flow Regimes

Establishing the flow regime involves determining the Baker parameters B_x and B_y from the two-phase system's characteristics and physical properties. The Baker parameters can be expressed as:

$$B_x = 531\left(\frac{W_L}{W_G}\right)\left\{\frac{(\rho_L\rho_G)^{0.5}}{\rho_L^{2/3}}\right\}\left(\frac{\mu_L^{1/3}}{\sigma_L}\right) \tag{3-52}$$

$$B_y = 2.16\left(\frac{W_G}{A}\right)\frac{1}{(\rho_L\rho_G)^{0.5}} \tag{3-53}$$

B_x depends on the weight ratio and the physical properties of the liquid and vapor phases. It is independent of pipe size; therefore, it remains constant once calculated from the characteristics of the liquid and vapor, and its position on the Baker map changes only if the liquid-vapor proportion changes. B_y depends on the vapor-phase flow rate, the vapor and liquid densities, and pipe sizes. The practical significance of the pipe size, however, is the effect on the frictional losses. The point B_x, B_y determines the flow regime for the calculated liquid-vapor ratio and the liquid's and vapor's physical properties. With increasing vapor content, B_x, B_y moves up and to the left on the map.

The boundaries of the various flow pattern regions depend on the mass velocity of the gas phase. These boundaries are represented by analytical equations developed by Coker [18]. These equations are used as the basis for determining the prevailing regime for any given flow rates and physical properties of the liquid and vapor. The mathematical models representing the boundaries of the flow regimes are:

$$C_1: \ln B_y = 9.774459 - 0.6548(\ln B_x) \quad (3\text{-}54)$$

$$C_2: \ln B_y = 8.67694 - 0.1901(\ln B_x) \quad (3\text{-}55)$$

$$C_3: \ln B_y = 11.3976 - 0.6084(\ln B_x) + 0.0779(\ln B_x)^2 \quad (3\text{-}56)$$

$$C_4: \ln B_y = 10.7448 - 1.6265(\ln B_x) + 0.2839(\ln B_x)^2 \quad (3\text{-}57)$$

$$C_5: \ln B_y = 14.569802 - 1.0173(\ln B_x) \quad (3\text{-}58)$$

$$C_6: \ln B_y = 7.8206 - 0.2189(\ln B_x) \quad (3\text{-}59)$$

Pressure Drop

Various studies have been conducted in predicting the two-phase frictional pressure losses in pipes. The Lockhart-Martinelli correlations [19] shown in Figure 3-7 are employed. The basis of the correlations is that the two-phase pressure drop is equal to the single-phase pressure drop of either phase multiplied by a factor that is derived from the single-phase pressure drops of the two-phases. The total pressure drop is based on the vapor-phase pressure drop. The pressure drop computation is based on the following assumptions:

1. The two-phase flow is isothermal and turbulent in both liquid and vapor phases.
2. The pressure loss is less than 10% of the absolute upstream pressure.

The two-phase pressure drop can be expressed as:

$$\frac{\Delta PT}{100\,\text{ft}} = \frac{\Delta PG}{100\,\text{ft}} \bullet YG \quad (3\text{-}60)$$

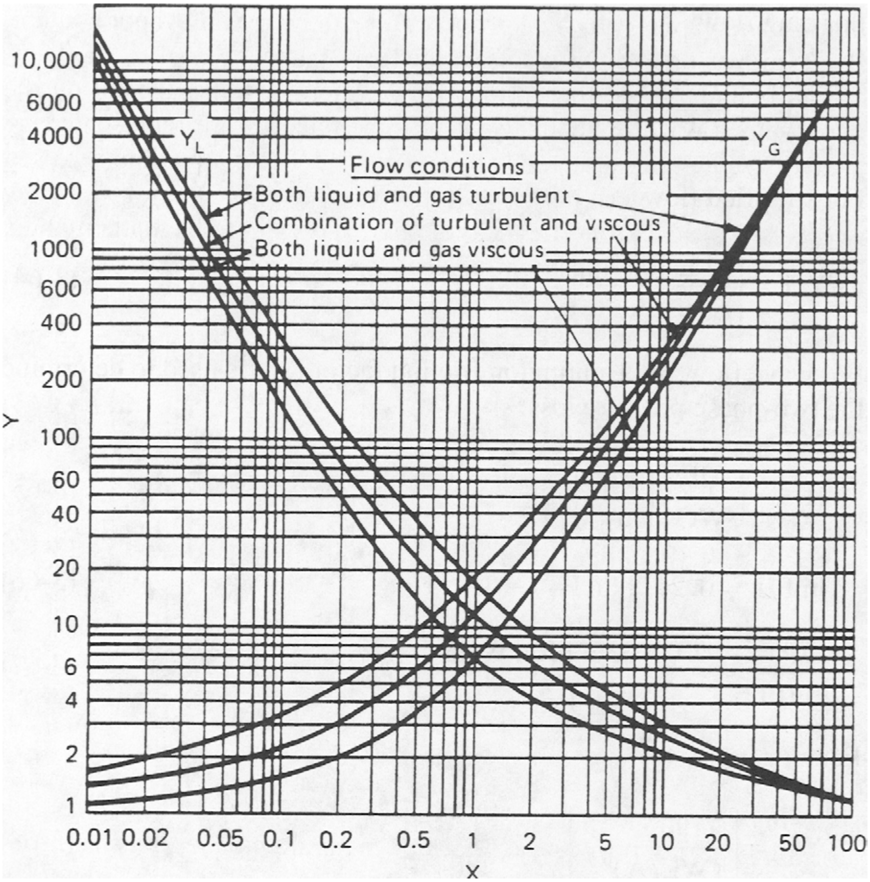


Figure 3-7. Lockhart-Martinelli pressure drop correlation. Source: Lockhart and Martinelli [19].

where YG is the two-phase flow modulus. YG is a function of the Lockhart-Martinelli two-phase flow modulus X, which is defined as:

$$X = \left(\frac{\Delta PL}{\Delta PG}\right)^{0.5} \tag{3-61}$$

$$YG = f(x)$$

The value of YG for the different flow regimes is determined as follows:

For bubble or froth flow

$$YG = \left[\frac{14.2X^{0.75}}{(WL/A)^{0.1}}\right]^2 \tag{3-62}$$

For plug flow

$$YG = \left[\frac{27.315X^{0.855}}{(WL/A)^{0.17}}\right]^2 \tag{3-63}$$

For stratified flow

$$YG = \left[\frac{15,400X}{(WL/A)^{0.8}}\right]^2 \tag{3-64}$$

For wave flow, the Huntington friction factor [20] is used to determine the two-phase pressure loss:

$$H_X = \left(\frac{HL}{WG}\right)\left(\frac{\mu_L}{\mu_G}\right) \tag{3-65}$$

$$\ln FH = 0.2111 \ln(H_x) - 3.993 \tag{3-66}$$

$$\frac{\Delta PT}{100 ft} = \frac{0.000336(FH)(WG)^2}{d^5 \rho_G} \tag{3-67}$$

For slug

$$YG = \left[\frac{1190X^{0.815}}{(WL/A)^{0.5}}\right]^2 \tag{3-68}$$

For annular flow

$$YG = (aX^b)^2 \tag{3-69}$$

$a = 4.8 - 0.3125d$

$b = 0.343 - 0.021d$

d = pipe inside diameter, inch

d = 10 for 12 inch and larger sizes

For dispersed or spray flow

$$YG = \left\{\exp\left[C_0 + C_1(\ln X) + C_2(\ln X)^2 + C_3(\ln X)^3\right]\right\}^2 \tag{3-70}$$

$$C_0 = 1.4659$$

$$C_1 = 0.49138$$

$$C_2 = 0.04887$$

$$C_3 = -0.000349$$

Once the two-phase flow modulus (YG) for the particular flow regime has been calculated, Equation 3-60 can be used to calculate ΔPT/100ft, the two-phase, straight-pipe pressure drop. The pressure drop of liquid or gas flowing alone in a straight pipe can be expressed as:

$$\frac{\Delta PT}{100\,ft} = \frac{0.000336 f_D W_x^2}{d^5 \rho_G}, \quad psi/100ft \tag{3-71}$$

Equation 3-71 can be modified for calculating the overall pressure drop of the two-phase flow for the total length of pipe plus fittings, L from Equation 3-5, based on the gas-phase pressure drop.

$$\Delta PT_{overall} = \frac{0.000336 \bullet f_D \bullet WG^2 \bullet YG \bullet L}{100 d^5 \rho_G}, \quad psi \tag{3-72}$$

The velocity of the two-phase fluid is

$$V = \frac{0.0509}{d^2}\left[\frac{WG}{\rho_G} + \frac{WL}{\rho_L}\right] \tag{3-73}$$

Erosion-Corrosion

Depending on the flow regime, the liquid in a two-phase flow system can be accelerated to velocities approaching or exceeding the vapor velocity. In some cases, these velocities are higher than what would be desirable for process piping. Such high velocities lead to a phenomenon known as erosion-corrosion, where the corrosion rate of a material is accelerated by an erosive material or force (in this case, the high-velocity liquid).

An index [21] based on velocity head can indicate whether erosion-corrosion may become significant at a particular velocity. It can be used to determine the range of mixture densities and velocities below which erosion-corrosion should not occur.

This index is:

$$\rho_M U_M^2 \leq 10,000 \tag{3-74}$$

where the mixture density is:

$$\rho_M = \frac{WL + WG}{\left(\frac{WL}{\rho_L} + \frac{WG}{\rho_G}\right)} \tag{3-75}$$

and the mixture velocity is:

$$U_M = U_G + U_L$$

$$= \left(\frac{WG}{3600\rho_G A} + \frac{WL}{3600\rho_L A}\right) \tag{3-76}$$

Nomenclature

A = inside cross-sectional area of pipe, ft^2
B_x, B_y = Baker parameters for determining for regime
d = pipe inside diameter, inch
D = pipe inside diameter, ft
f_C = Chen friction factor
f_D = Darcy friction factor
f_F = Fanning friction factor
FH = Huntington friction factor
H_x = Huntington flow factor
ID = internal diameter of pipe, inch
K = excess head loss for a fitting, velocity heads
K_1 = K for fitting at $N_{Re} = 1$ velocity heads
K_∞ = K for large fittings at $N_{Re} = \infty$ velocity heads
L = total fitting equivalent pipe length plus straight pipe length, ft
L_{eq} = equivalent length of pipe due to fittings, ft
L_{st} = straight pipe length, ft
L_{Total} = total length of pipe, ft
MW = molecular weight
N_{Re} = Reynolds number
N_{ReL} = liquid Reynolds number
N_{ReG} = gas Reynolds number
$\Delta PL/100ft$ = pressure drop of liquid if flowing alone in the pipe (psi/100 ft)

$\Delta PG/100ft$ = pressure drop of gas if flowing alone in the pipe (psi/100 ft)
$\Delta PT/100ft$ = pressure drop of the two-phase mixture in straight pipe (psi/100 ft)
$\Delta PT_{overall}$ = overall pressure drop of the two-phase mixture for the total length plus fittings, psi
U_L = liquid velocity, ft/s
U_G = gas velocity, ft/s
U_M = velocity of the two-phase mixture, ft/s
V = velocity of fluid in a pipe, ft/s
WL = liquid flow rate, lb/h
WG = gas flow rate, lb/h
W_x = flow rate of either liquid or gas, lb/h
X = Lockhart-Martinelli two-phase flow modulus $(\Delta PL/\Delta PG)^{0.5}$
Y_G = two-phase flow modulus
ε = absolute roughness of pipe wall, ft (0.00015 ft for carbon steel)
ρ_L = liquid density, lb/ft^3
ρ_G = gas density, lb/ft^3
ρ_M = density of liquid-gas mixture, lb/ft^3
μ_x = viscosity of liquid or gas, cP
μ_L = liquid viscosity, cP
μ_G = gas viscosity, cP
σ_L = surface tension of liquid (dyne/cm)

VAPOR-LIQUID TWO-PHASE VERTICAL DOWNFLOW

An understanding of two-phase flow is necessary for sound piping design because almost all chemical process plants encounter two-phase flow conditions. Two-phase vertical downflow presents its own problems in horizontal flow. In a vertical flow, large vapor bubbles, known as slug flow, are formed in the liquid stream. This flow regime is associated with pipe vibration and pressure pulsation. With bubbles greater than 1 inch in diameter and the liquid viscosity less than 100 cP, slug flow region can be represented by dimensionless numbers for liquid and vapor phases respectively (Froude numbers $(N_{Fr})_L$ and $(N_{Fr})_G$). These are related by the ratio of inertial to gravitational force and are expressed as:

$$(N_{Fr})_L = \frac{VL}{(gD)^{0.5}}\left(\frac{\rho_L}{\rho_L - \rho_G}\right)^{0.5} \qquad (3\text{-}77)$$

$$(N_{Fr})_G = \frac{VG}{(gD)^{0.5}}\left(\frac{\rho_L}{\rho_L - \rho_G}\right)^{0.5} \qquad (3\text{-}78)$$

The velocities VG and VL are superficial velocities based on the total pipe cross section. These Froude numbers exhibit several features in the range $0 < (N_{Fr})_L$ and $(N_{Fr})_G < 2$.

Simpson [3] illustrates the values of $(N_{Fr})_L$ and $(N_{Fr})_G$ with water flowing at an increased rate from the top of an empty vertical pipe. As the flow rate further increases to the value $(N_{Fr})_L = 2$, the pipe floods and the total cross section is filled with water. If the pipe outlet is further submerged in water and the procedure is repeated, long bubbles will be trapped in the pipe below $(N_{Fr})_L = 0.31$. However, above $(N_{Fr})_L = 0.31$, the bubbles will be swept downward and out of the pipe.

If large long bubbles are trapped in a pipe (d ≥1 inch) in vertically down flowing liquid having a viscosity less than 100 cP and the Froude number for liquid phase, $(N_{Fr})_L \le 0.3$, the bubbles will rise. At higher Froude numbers, the bubbles will be swept downward and out of the pipe. A continuous supply of vapor causes the Froude number in the range $0.31 \le (N_{Fr})_L < 1$ to produce pressure pulsations and vibration. These anomalies are detrimental to the pipe and must be avoided. If the Froude number is greater than 1.0, the frictional force offsets the effect of gravity, and thus requires no pressure gradient in the vertical downflow liquid. This latter condition depends on the Reynolds number and pipe roughness.

The Equations

The following equations will calculate Froude numbers for both the liquid and gas phases. The computer program will print out a message indicating whether the vertical pipe is self-venting, whether pulsating flow occurs, or whether no pressure gradient is required.

$$D = \frac{d}{12}, \quad \text{ft} \qquad (3\text{-}79)$$

$$\text{Area} = \frac{\pi D^2}{4}, \quad \text{ft} \qquad (3\text{-}80)$$

$$VL = \frac{WL}{3600 \bullet \rho_L \bullet \text{Area}}, \quad \text{ft/s} \qquad (3\text{-}81)$$

$$VG = \frac{WG}{3600 \bullet \rho_G \bullet \text{Area}}, \quad \text{ft/s} \tag{3-82}$$

$$FRNL = \frac{VL}{(gD)^{0.5}}\left[\frac{\rho_L}{\rho_L - \rho_G}\right]^{0.5} \tag{3-83}$$

$$FRNG = \frac{VG}{(gD)^{0.5}}\left[\frac{\rho_G}{\rho_L - \rho_G}\right]^{0.5} \tag{3-84}$$

The Algorithm

If FRNL < 0.31, vertical pipe is SELF-VENTING

else

0.3 ≤ FRNL < 1.0, PULSE FLOW, and may result in pipe vibration

FRNL > 1.0, NO PRESSURE GRADIENT

Nomenclature

Area = inside cross-sectional area of pipe, ft^2
d = inside diameter of pipe, inch
D = inside diameter of pipe, ft
FRNL, $(N_{Fr})_L$ = Froude number of liquid phase, dimensionless
FRNG, $(N_{Fr})_G$ = Froude number of vapor phase, dimensionless
g = gravitational constant, 32.2 ft/s^2
VL = liquid velocity, ft/s
VG = vapor velocity, ft/s
WL = liquid flowrate, lb/h
WG = vapor flowrate, lb/h
ρ_L = liquid density, lb/ft^3
ρ_G = vapor densit, lb/ft^3

LINE SIZES FOR FLASHING STEAM CONDENSATE

When a liquid is flowing near its saturation point (i.e., the equilibrium or boiling point) in a pipe line, decreased pressure will cause vaporization. The higher the pressure difference, the greater the vaporization resulting in flashing of the liquid. Steam condensate lines cause a two-phase flow condition, with hot condensate flowing to a lower pressure through short and long lines. For small lengths with low pressure drops, and the outlet end being a few pounds per square inch of the inlet, the flash will be assumed as a small percentage. Consequently, the line can be sized as an all liquid line. However, caution must be exercised because 5% flashing can develop an important impact on the pressure drop of the system [22].

Sizing of flashing steam condensate return lines requires techniques that calculate pressure drop of two-phase flow correlations. Many correlations have been presented in the literature [15,16,19,23]. Most flow patterns for steam condensate headers fall within the annular or dispersed region on the Baker map. Sometimes, they can fall within the slug flow region; however, the flashed steam in steam condensate lines is less than 30% by weight.

Ruskin [24] developed a method for calculating pressure drop of flashing condensate. Ruskin's method gave pressure drops comparable to those computed by the two-phase flow with good agreement with experimental data. The method employed here is based on a similar technique given by Ruskin. The pressure drop for flashing steam uses the average density of the resulting liquid-vapor mixture after flashing. In addition, the friction factor used is valid for complete turbulent flows in both commercial steel and wrought iron pipe. The pressure drop assumes that the vapor-liquid mixture throughout the condensate line is represented by mixture conditions near the end of the line. This assumption is valid because most condensate lines are sized for low pressure drop, with flashing occurring at the steam trap or valve close to the pipe entrance. If the condensate line is sized for a higher pressure drop, an iterative method must be used. For this case, the computations start at the end of the pipeline and proceed to the steam trap.

The method employed determines the following:

1. the amount of condensate flashed for any given condensate header from 15 to 140 psia. Initial steam pressure may vary from 40 to 165 psia.
2. the return condensate header temperature.
3. the pressure drop (psi/100 ft) of the steam condensate mixture in the return header.
4. the velocity of the steam condensate mixture and gives a warning message if the velocity is greater than 5000 ft/min, because this may present problems to the piping system.

The Equations

The following equations are used to determine the pressure drop for flashed condensate mixture [20].

$$\text{WFRFL} = B(\ln P_c)^2 - A \qquad (3\text{-}85)$$

where

$$A = 0.00671(\ln P_h)^{2.27} \qquad (3\text{-}86)$$

$$B = e^x \bullet 10^{-4} + 0.0088 \qquad (3\text{-}87)$$

and

$$X = 6.122 - \left(\frac{16.919}{\ln P_h}\right) \qquad (3\text{-}88)$$

$$\text{WG} = \text{WFRFL} \bullet W \qquad (3\text{-}89)$$

$$\text{WL} = W - \text{WG} \qquad (3\text{-}90)$$

$$\text{TFL} = 115.68(P_h)^{0.226} \qquad (3\text{-}91)$$

$$\rho_G = 0.0029 P_h^{0.938} \qquad (3\text{-}92)$$

$$\rho_L = 60.827 - 0.078 P_h + 0.00048 P_h^2 - 0.0000013 P_h^3 \qquad (3\text{-}93)$$

$$\rho_M = \frac{\text{WG} + \text{WL}}{\left(\dfrac{\text{WG}}{\rho_G} + \dfrac{\text{WL}}{\rho_L}\right)} \qquad (3\text{-}94)$$

For turbulent flow

$$f = \frac{0.25}{\left[-\log\left(\dfrac{0.000486}{d}\right)\right]^2} \qquad (3\text{-}95)$$

where d = pipe diameter, inch

Pressure drop

$$\Delta \text{PT} = \frac{0.000336 f \bullet W^2}{d^5 \bullet \rho_M} \qquad (3\text{-}96)$$

$$V = \frac{3.054}{d^2}\left[\frac{\text{WG}}{\rho_G} + \frac{\text{WL}}{\rho_L}\right] \qquad (3\text{-}97)$$

If $V \geq 5000$ ft/min, print a warning message as condensate may cause deterioration of the process pipeline.

Nomenclature

d = internal pipe diameter, inch
f = friction factor, dimensionless
P_c = steam condensate pressure before flashing, psia
P_h = flashed condensate header pressure, psia
V = velocity of flashed condensate mixture, ft/min
W = total flow of mixture in condensate header, lb/h
WG = flashed steam flow rate, lb/h
WL = flashed condensate liquid flow rate, lb/h
WFRFL = weight fraction of condensate flashed to vapor
TFL = temperature of flashed condensate, °F
ΔPT = pressure drop of flashed condensate mixture, psi/100 ft
ρ_G = flashed steam density, lb/ft^3
ρ_L = flashed condensate liquid density, lb/ft^3
ρ_M = density of mixture (flashed condensate/steam), lb/ft^3

FLOW THROUGH PACKED BEDS

Flow of fluids through packed beds of granular particles occurs frequently in chemical processes. Examples are flow through a fixed-bed catalytic reactor, flow through a filter cake, and flow through an absorption or adsorption column. An understanding of flow through packed beds is also important in the study of sedimentation and fluidization.

An essential factor that influences the design and operation of a dynamic catalytic or adsorption system is the energy loss (pressure drop). Factors determining the energy loss are many and investigators have made simplifying assumptions or analogies so that they could use some of the general equations. These equations represent the forces exerted by the fluids in motion (molecular, viscous, kinetic, static, etc.) to arrive at a useful expression correlating these factor.

Ergun [25] developed a useful pressure drop equation caused by simultaneous kinetic and viscous energy losses and applicable to all types of flow. Ergun's equation relates the pressure drop per unit of bed depth to dryer or reactor system characteristics, such as, velocity, fluid gravity, viscosity, particle size, shape, surface of the granular solids and void fraction. The original Ergun equation is:

$$\frac{\Delta P}{L} g_c = \frac{150(1-\varepsilon)^2}{\varepsilon^3} \bullet \frac{\mu V}{D_p^2} + \frac{1.75(1-\varepsilon)}{\varepsilon^3} \bullet \frac{GV}{D_p} \qquad (3\text{-}98)$$

where ΔP = pressure drop
L = unit depth of packed bed
g_c = dimensional constant $32.174(lb_m/lb_f)(ft/s^2)$
μ = viscosity of fluid, lb/ft.h
V = superficial fluid velocity, ft/s
D_p = effective particle diameter, ft
ε = void fraction of bed
ρ = fluid density, lb/ft^3

Equation 3-98 gives the total energy loss in fixed beds as the sum of viscous energy loss (the first term on the right side of the equation) and the kinetic or turbulent energy loss (the second term on the right side of the equation). For gas systems, approximately 80% of the energy loss is dependent on turbulence and can be represented by the second term of Equation 3-98. In liquid systems, the viscous term is the major factor.

The Equation

The original Ergun equation of the total energy loss can be rearranged as follows:

$$\Delta PT = \frac{BL}{144} \bullet \frac{1-\varepsilon}{\varepsilon^3} \bullet \frac{G^2}{D_P g_c \rho}\left[\frac{150(2.419\mu)(1-\varepsilon)}{D_P G} + 1.75\right] \qquad (3\text{-}99)$$

$$\varepsilon = \text{fraction void volume of bed, ft}^3,$$

$$\text{void/ft}^3 \text{ of packed tower volume}$$

$$= \frac{\text{volume of void}}{\text{volume of bed}}$$

$$= \frac{\left[\left(\dfrac{\text{mass of bed}}{\rho_{\text{bed}}}\right) - \left(\dfrac{\text{mass of bed}}{\rho_{\text{catalyst}}}\right)\right]}{\dfrac{\text{mass of bed}}{\rho_{\text{bed}}}}$$

$$= \frac{\rho_c - \rho_b}{\rho_c} \tag{3-100}$$

ρ_c = density of catalyst, lb/ft^3

ρ_b = density of the packed bed, lb/ft^3

$$\rho = \frac{M_w P}{10.73ZT} \tag{3-101}$$

$$D_p = \frac{6(1-\varepsilon)}{S} \tag{3-102}$$

$$S = \frac{(1-\varepsilon)}{V_p} \bullet A_p \tag{3-103}$$

For cylindrical particles

$$V_p = \frac{1}{1728}\left[PD^2 \bullet \frac{\pi}{4} \bullet PL\right] \tag{3-104}$$

$$A_p = \frac{1}{144}\left[\frac{\pi \bullet PD^2}{2} + \pi \bullet PD \bullet PL\right] \tag{3-105}$$

Reynolds number

$$N_{Re} = \frac{GD_p}{2.419\mu(1-\varepsilon)} \tag{3-106}$$

Friction factor
For laminar flow with $N_{Re} < 1$

$$f_p = \frac{150}{N_{Re}} \tag{3-107}$$

For intermediate Reynolds number

$$f_p = \frac{150}{N_{Re}} + 1.75 \tag{3-108}$$

For completely turbulent flow, it is assumed that f_p approaches a constant value for all packed beds with the same relative roughness. The constant is found by experiment to be 1.75 [26].

Nomenclature

A = cross-sectional area of bed, ft^2
A_p = area of particles, ft^2
BL = bed length, ft
D_p = effective particle diameter, ft
f_p = friction factor
g_c = gravitational constant = $4.17 \times 10^8 \left((lb_m/lb_f) \bullet (ft/h^2)\right)$
G = superficial mass velocity = W/A, $lb/h.ft^2$
MW = molecular weight of fluid
N_{Re} = Reynolds number, dimensionless
P = fluid pressure, psia
PD = particle diameter, inch
PL = particle length, inch
S = packed bed surface area, ft^2/ft^3 bed
T = fluid temperature, °R
V_p = volume of particles, ft^3
W = fluid flow rate, lb/h
Z = compressibility factor
ΔPT = total pressure drop in packed bed, lb/in^2
ε = fraction voids in packed bed
ρ = density of fluid at flowing conditions, lb/ft^3
μ = fluid viscosity, cP (1cP = 2.419lb/ft h)

SCREEN HANDLING

The code in this book makes use of a suite of subroutines for screen handling that have been developed from those given by Ward and Bromhead [27,28].

In principle, a number of subroutines are invoked by my code, and these in turn invoke other, lower level subroutines. The top level subroutines are called:

GETTXT
GETINT
GETFLO

and

MENU

GETTXT is perhaps the simplest of these. It uses **ANSI** control sequences to locate the cursor on the screen, to highlight a box for text entry, and through assembly-language-coded calls to an **MS DOS** function, intercepts individual keypresses and builds them into a text string in the text entry box.

The low level functions that use the **ANSI** codes are coded into

GOTOXY	Cursor location	(FORTRAN)
REVID	Turn reversed video effect on	(ASM)
NORMAL	Restore normal video (no attributes)	(ASM)
SHWTXT	Display string	(FORTRAN)

From these further calls to assembly language routines that call **DOS** functions are made. These routines are:

GETCHR	Get character from keyboard buffer
SHWBYT	Display character string

Analogous routines to **GETTXT** are provided for inputting INTEGER and FLOATING POINT (REAL) variables, and they are called **GETINT** and **GETFLO**. In principle, they are identical to **GETTXT**, but they perform the additional tasks of intercepting invalid keypresses (e.g., no alphabetic characters are permitted nor can the decimal point be duplicated, etc.) and converting from a text string into a valid number format. A routine **BEEP** is provided to send ASCII 07 (BEL) to the screen, which drives the PC's internal speaker.

The subroutine **MENU** displays a list of mnemonics on the screen at predefined locations. In my code, these mnemonics are usually in a vertical stack, and they are all accompanied by a line of explanatory text per mnemonic. Use of the cursor keys causes a highlighted bar to step through the mnemonics. Pressing the RETURN key selects the option equivalent to the currently selected mnemonic.

In addition to the GETxxx subroutines, I sometimes need to display text or numbers at predefined locations on the screen. The **GOTOXY** and **SHWTXT** calls are put together in **DISTXT, DISINT,** and **DISFLO** (DIS implying DISplay). Some other routines which are used to create special effects are

BORDER
COLORS

BORDER permits me to draw rectangular boxes on the screen using the extended character set line-drawing characters (both single and double). **COLORS** uses the **ANSI** codes to set foreground and background colors. The advantage of using the ANSI screen control system is that it makes many of the jobs involved in screen control simple for the **FORTRAN** programmer, but at a cost: the computer on which the software is run must have **ANSI.SYS** loaded. Under DOS 5 or DOS 6, **ANSI.SYS** can be loaded "high," which prevents it from taking up valuable conventional **DOS** memory. There are various "enhanced **ANSI.SYS**" utilities which are public domain or shareware, including FANSI and NANSI. Another useful utility is ANSI.COM (PC Magazine, Ziff Davies Publishing), which has the advantage of being unloadable if the user wishes to reclaim the small amount of memory that it consumes.

Title Screen and Keyboard Utilities

```
;
CSSANDK   SEGMENT   PUBLIC     PARA 'CODE'
                    ASSUME CS:CSSANDK
;
PUBLIC    CLS
CLS       PROC      FAR
          PUSH      DS
          MOV       AH, 9
          MOV       DH, SEG CLRSTRG
          MOV       DS, DX
          MOV       DX, OFFSET CLSRTRG
          INT       21H
          POP       DS
CLRSTRG   DB        1BH,'[2J$'
CLS       ENDP

          PUBLIC    REVID
REVID     PROC      FAR
          PUSH      DS
          MOV       AH, 9
          MOV       DX, SEG REVSTR
          MOV       DS, DX
          MOV       DX, OFFSET REVSTR
          INT       21H
```

```
          POP       DS
          RET
REVSTR    DB        1BH,'[7m$'
REVID     ENDP

          PUBLIC    NORMAL
NORMAL    PROC      FAR
          PUSH      DS
          MOV       AH, 9
          MOV       DX, SEG NORSTR
          MOV       DS, DX
          MOV       DX, OFFSET NORSTR
          INT       21H
          POP       DS
          RET
NORSTR    DB        1BH,'[0m$'
NORMAL    ENDP

          PUBLIC    SHWBYT
SHWBYT    PROC      FAR
          PUSH      BP
          MOV       AH, 09H
          MOV       BP, SP
          LDS       DX, [BP+6]
          INT       21H
          POP       BP
          RET       04H
SHWBYT    ENDP

          PUBLIC    GETCHR
GETCHR    PROC      FAR
          PUSH      BP
          MOV       AH, 08H
          INT       21H
          MOV       BP, SP
          LES       BX, DWORD PTR[BP+6]
          XOR       AH, AH; this zeroes AH
          MOV       ES:[BX], AX; better than MOV
          POP       BP
          RET       04H
GETCHR    ENDP
```

```
         PUBLIC KBCLEAR
KBCLEAR  PROC       FAR
         PUSH       BP
         MOV        BP, SP
WHILE:
         MOV        AH, 0BH
         INT        21H
         OR         AL, AL
         JZ         SHORT RETURN
         MOV        AH, 08H
         INT        21H
         JMP        SHORT WHILE
RETURN:
         POP        BP
         RET
KBCLEAR  ENDP

         PUBLIC     CURSOF
CURSOF   PROC       FAR
         PUSH       BP
         MOV        CX, 2000H
         MOV        AH, 1
         INT        10H
         POP        BP
         RET
CURSOF   ENDP

         PUBLIC     CURSBLK
CURSBLK  PROC       FAR
         PUSH       BP
         MOV        CX, 0007H
         MOV        AH, 1
         INT        10H
         POP        BP
         RET
CURSBLK  ENDP

         PUBLIC     CURSON
CURSON   PROC       FAR
         PUSH       BP
         MOV        CX, 0607H
```

```
         MOV      AH, 1
         INT      10H
         POP      BP
         RET
CURSON   ENDP
;
CSSANDK  ENDS
;
         END
```

Fortran Subroutines

```
      SUBROUTINE CLS
      WRITE(*,100) CHAR(27)//'[2J'
100   FORMAT(A4/)
      RETURN
      END

      SUBROUTINE REVID
      WRITE(*,100) CHAR(27)//'[7m'
100   FORMAT(A4/)
      RETURN
      END

      SUBROUTINE NORMAL
      WRITE(*,100) CHAR(27)//'[0m'
100   FORMAT(A4/)
      RETURN
      END

      SUBROUTINE SHWBYT (STR, NSTR)
      CHARACTER*(*) STR
      WRITE(*,100) STR(1:NSTR)
100   FORMAT(A/)
      RETURN
      END
```

PROBLEMS AND SOLUTIONS

Problem 3-1

A piping isometric (Figure 3-8) shows a 6-inch (Schedule 40) line with six 90°LR elbows and two flow-through tees. The actual length of

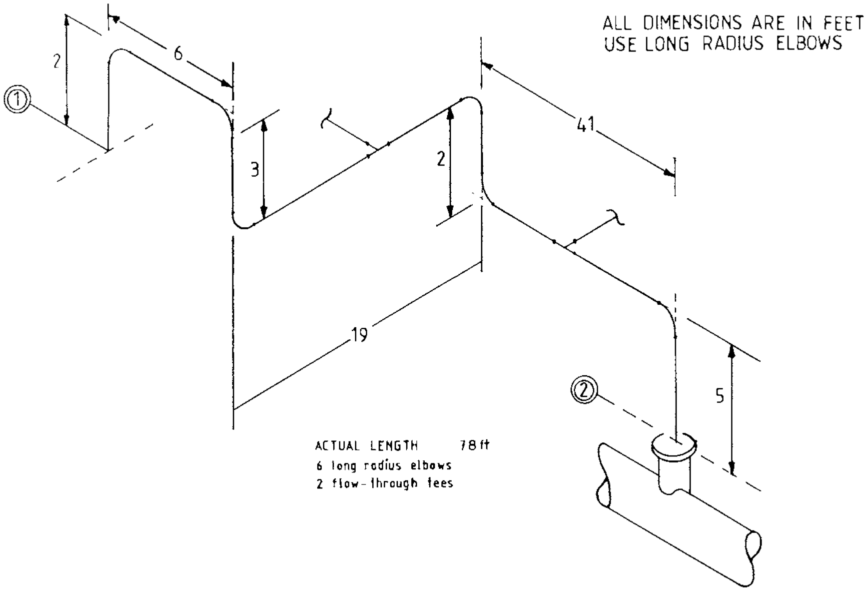


Figure 3-8. Piping isometric layout.

pipe is 78 ft. The fluid flow is 75,000 lb/h and its physical properties are viscosity μ = 1.25 cP, density ρ = 64.30 lb/ft^3, and pipe roughness ε = 0.00015 ft. Calculate the equivalent length of pipe fittings, total length of the pipe, velocity head, head loss, and the overall pressure drop.

Solution

The computer program PROG31 is a subroutine in the screen handling suites of programs used to calculate the parameters for the 6-inch (Schedule 40) pipe. The software program **PIPECAL** is run to determine the total length of the pipe (i.e., the sum of the straight length of the pipe and the equivalent length due to pipe fittings), the head loss, the pressure drop per 100 ft of pipe, and the overall pressure drop. Table 3-8 gives the computer output from the screen handling software program. The equivalent length due to pipe fittings is 38.3 ft, the total pipe length is 116.3 ft, the excess head loss is 0.196 ft, the pressure drop per 100 ft of the pipe is 0.075 psi, and the overall pressure drop is 0.088 psi.

Table 3-8
Computer Output From the Screen Handling Programs

```
        PRESSURE DROP CALCULATION OF AN INCOMPRESSIBLE FLUID IN A PIPE LINE
*****************************************************************************
        PIPE INTERNAL DIAMETER, inch:                           6.065
        MASS FLOW RATE, lb/h:                                    75000.00
        VOLUMETRIC FLOW RATE, gal/min.:                            145.44
        FLUID VISCOSITY, cP:                                       1.2500
        FLUID DENSITY, lb/ft.^3:                                  64.3000
        FLUID VELOCITY, ft/sec.:                                1.614
        VELOCITY HEAD LOSS DUE TO FITTINGS:                    1.5960
        EQUIVALENT LENGTH OF PIPE, ft:                        38.3099
        ACTUAL LENGTH OF PIPE, ft:                            78.0000
        TOTAL LENGTH OF PIPE, ft.:                           116.3099
        REYNOLDS NUMBER:                                           62424.
        PIPE ROUGNESS, ft.:                                   .000150
        DARCY FRICTION FACTOR:                                  .0211
        EXCESS HEAD LOSS, ft:                                   .1961
        PIPE PRESSURE DROP/100 ft, psi/100ft:                   .0754
        OVERALL PRESSURE DROP OF PIPE, psi:                     .0877
-----------------------------------------------------------------------------
```

Running Pipecal

The computer program **PIPECAL**, as well as the other programs described in the screen handling, has been compiled to calculate the equivalent length due to pipe fittings, the total length of the pipe, velocity head, the head loss, the pressure drop per 100 ft of pipe, and the overall pressure drop for any given pipe size, fluid flow rate, and its physical properties. To run the program from either the floppy diskette or a hard drive, type after the A or C:\> prompt from the command line, PIPECAL.EXE (or PIPECAL) followed by a return key.

For example, A or C:\>PIPECAL.EXE (or PIPECAL)

A title is displayed and the user then presses any key from the PC console to continue. Once the screen is cleared, a list of eight options is displayed as follows:

1. **OPEN**	Open a pre-existing file
2. **CREATE**	Create a new data file
3. **SAVE**	Save the data file you just edited
4. **CALCS**	Start calculating
5. **PRT RES**	Print the result file
6. **SAVE RES**	Save the result file
7. **FINISH**	Next problem?
8 **QUIT**	Exit to DOS

PIPECAL is user-friendly and the procedure in running the program is as follows:

1. Create a data file (option 2). Assign the value zero to any fitting type that is not included in the calculation. Press a return key or a downward arrow key to continue.
2. Calculate the input data (option 4).
3. Print the results onto a printer (option 5). The results are also viewed on the screen.
4. Quit the program by typing N (option 8) to return to DOS (Disk Operating System).
5. Press **FINISH** (Option 7) before opening or creating a datafile.

Options 1, 3, 6, and 7 can be further used after the datafile has been created.

Before using the software **(PIPECAL)**, you must have **ANSI.SYS** installed as a device driver in the **CONFIG.SYS** file. If for example, **ANSI.SYS** is located in the directory **C:\DOS**, the following line must be a part of **CONFIG.SYS**

```
DEVICE=C:\DOS\ANSI.SYS
```

Problem 3-2

Calculate the overall pressure drop between points 1 and 2 for a 6-inch (Schedule 40, ID=6.065 inch) line for kerosene. Liquid conditions are: flow rate $Q_{60} = 900$ gpm, density at 60°F, $\rho = 51$ lb/ft^3, and temperature, t = 321°F. Figure 3-8 shows an isometric layout of the pipeline with fittings.

Specific gravity at 60°F, $S_{60} = 51/62.37 = 0.82$
Specific gravity at t = 321°F, $S_{321} = 0.72$
Density at t = 321°F, $\rho = 62.37\ (0.72) = 44.9$ lb/ft^3
Expansion factor, $E = S_{60}/S_{321} = 0.82/0.72 = 1.14$
Flow rate at t = 321°F, $Q = Q_{60}.\ E = 900(1.14) = 1026$ gpm
Viscosity, $\mu = 0.3$ cP
Actual length of pipe = 78 ft.

Solution

The computer program PROG32 evaluates the pressure drop for any incompressible fluid per 100 ft of pipe and the overall pressure drop between two points for any given pipe size. The program PROG32 calculates the equivalent length of pipe due to fittings. This is added to the straight length of pipe to give the total length. Table 3-9 gives the input data and computer output for the 6-inch pipe size. The pressure drop per 100 ft of pipe is 1.93 psi, and the overall pressure drop is 3.4 psi.

Table 3-9
Input Data and Computer Output for an Incompressible Fluid in a Pipe Line

```
DATA32.DAT
-------------------------
6.065    78.0  1026.0  0.0
44.9     0.3   0.0     3.0
0.00015
```

```
     PRESSURE DROP CALCULATION OF AN INCOMPRESSIBLE FLUID IN A PIPE LINE
******************************************************************************
    PIPE INTERNAL DIAMETER, inch:                                   6.065
    MASS FLOW RATE, lb/h.:                                      369263.30
    VOLUMETRIC FLOW RATE, gal/min.:                                1026.00
    FLUID VISCOSITY, cP:                                           .3000
    FLUID DENSITY, lb/ft^3:                                       44.900
    FLUID VELOCITY, ft/sec.:                                      11.380
    VELOCITY HEAD LOSS DUE TO FITTINGS:                            3.000
    EQUIVALENT LENGTH OF PIPE, ft.:                               97.919
    ACTUAL LENGTH OF PIPE, ft.:                                   78.000
    TOTAL LENGTH OF PIPE, ft.:                                   175.919
    REYNOLDS NUMBER:                                              1281127.
    PIPE ROUGHNESS, ft.:                                         .000150
    DARCY FRICTION FACTOR:                                         .0155
    EXCESS HEAD LOSS, ft.:                                        10.867
    PIPE PRESSURE DROP /100ft., psi/100ft:                        1.9264
    OVERALL PRESSURE DROP OF PIPE, psi:                           3.3889
-----------------------------------------------------------------------------
```

Problem 3-3
Maximum Compressible Fluid Flow

Calculate the maximum flow rate of natural gas through a ruptured exchanger tube assuming a complete break near the tube sheet as shown in Figure 3-3. The data are:

- exchanger tubes = 3/4 inch, Schedule 160
- internal diameter, d inch = 0.614
- tube length, Lst, ft = 20
- pipe friction factor for complete turbulence, f = 0.026
- compressibility factor, Z = 0.9
- gas temperature, °F = 100
- molecular weight, $M_w = 19.5$
- pressure in exchanger tubes, P_1(psig) = 1110 psig (1124.7 psia)
- relief valve set pressure on the shell side, P_2(psig) = 400 psig (414.7 psia)
- ratio of specific heat capacities, k = 1.27
- fluid viscosity, μ, cP = 0.012
- resistance coefficient due to fittings and valves, K = 2.026

Solution

The computer program PROG33 determines the maximum flow rate for any compressible fluid, having a design specification that is ΔP > 10% of the upstream pressure or compressible fluids at high velocities. The program calculates the maximum fluid flow rate for a given pipe size, length of pipe, and the fluid's physical properties. Table 3-10 shows the input data and computer output for the maximum flow rate of natural gas in the 0.614-inch pipe. The computed maximum flow rate of natural gas through the 0.614-inch pipe is 8397 lb/hr. The Mach number at the pipe inlet is 0.2074. At critical condition, the Mach number is 0.8874. The critical pressure of the compressible fluid is 242.3 psia, with a sonic velocity of 1346.7 ft/sec. The compressible fluid flow pattern through the pipe is **SUBSONIC**.

Table 3-10
Input Data and Computer Output for Maximum Compressible Fluid in a Pipe Line

```
DATA33.DAT
----------------------------
0.614   20.0    0.026
2.026   0.9     100.0   19.5
1124.7  414.7   1.27    0.012
```

```
         COMPRESSIBLE FLUID FLOW CALCULATIONS IN A PIPE LINE
****************************************************************************
    PIPE INTERNAL DIAMETER, inch:                               .614
    STRAIGHT LENGTH OF PIPE, ft.:                             20.000
    MAXIMUM FLUID FLOWRATE, lb/h.:                             8396.90
    FLUID DENSITY, lb/ft^3:                                    4.059
    PIPE FRICTION FACTOR:                                      .0260
    FLUID COMPRESSIBILITY FACTOR:                              .9000
    FLUID TEMPERATURE, oF:                                   100.000
    FLUID MOLECULAR WEIGHT, Mw:                               19.500
    RATIO OF SPECIFIC HEAT CAPACITIES, Cp/Cv:                  1.270
    FLUID VISCOSITY, cP:                                       .0120
    RESISTANCE COEFF. DUE TO FRICTIONAL LOSS:                 10.163
    RESISTANCE COEFF. DUE TO FITTINGS + VALVES:                2.026
    TOTAL RESISTANCE COEFFICIENT:                             12.189
    INLET FLUID PRESSURE, psia:                              1124.700
    OUTLET FLUID PRESSURE, psia:                              414.700
    PRESSURE DROP, psi:                                       710.000
    FLUID VELOCITY, ft/sec.:                                  279.289
    FLUID SONIC VELOCITY, ft/sec.:                           1346.739
    MACH MUMBER AT INLET:                                      .2074
    MACH NUMBER AT CRITICAL CONDITION:                         .8874
    REYNOLDS NUMBER:                                        86293830.
    CRITICAL PRESSURE, psia:                                  242.305
    FLUID FLOW IS:                                          SUBSONIC
----------------------------------------------------------------------------
```

Problem 3-4
Compressible Fluid Pressure Drop

What is the overall pressure drop for natural gas flowing at 27,000 lb/hr through a 6-inch Schedule 40 tail pipe to a header during relieving condition as shown in Figure 3-3? Relief valve set pressure, $P_1 = 400$ psig, during relieving condition is

$$P_1 = P_1 + 10\% \text{ accumulation } + 14.7$$

$$= 454.7 \text{ psia}$$

The data are:

- pipe internal diameter, d inch = 6.065
- tail pipe length, ft = 10
- gas flow rate, lb/h = 27000
- gas viscosity, μ, cP = 0.012
- gas compressibility factor, Z=0.9
- gas temperature, °F = 100
- molecular weight of gas, $M_w = 19.5$
- ratio of specific heat capacities k=1.27
- gas inlet pressure, psia, 454.7
- pipe roughness, $\varepsilon = 0.00015$ ft
- resistance coefficient due to fittings and valves, K, 2.013
- pipe line resistance: 1 × 90°LR elbows
  1 × entrance loss
  1 × exit loss
  4.026 inch pipe reduction

Solution

The computer program PROG34 determines the overall pressure drop for the 6-inch tail pipe having a relieving rate of 27,000 lb/hr. Table 3-11 illustrates both the input data and computer output. The Mach number at inlet condition is 0.0169, and at the critical condition is 0.8874. The critical pressure is 7.985 psia and the overall pressure drop is 0.213 psi. The compressible fluid flow pattern through the pipe is **SUBSONIC**.

Problem 3-5

Calculate the pressure drop of a 5 mile length in a 6-inch (Schedule 40, ID=6.065 inch) pipe, for a 5000 bpd rate of salt water ($\gamma_w = 1.07$), having a gas flowing at 6 mmscfd of 0.65 specific gravity at a temperature of 110°F.

Table 3-11
Input Data and Computer Output for Compressible Fluid Flow Pressure Drop

```
DATA34.DAT
--------------------------------
6.065     10.0   27000.0  2.013
0.012     0.9    100.0    19.5
0.00015   1.27   454.7
```

```
         COMPRESSIBLE FLUID FLOW CALCULATIONS IN A PIPE LINE
*****************************************************************************
    PIPE INTERNAL DIAMETER, inch:                                   6.065
    STRAIGHT LENGTH OF PIPE, ft.:                                  10.000
    FLUID FLOWRATE, lb/h.:                                         27000.00
    FLUID DENSITY, lb/ft^3:                                         1.641
    FLUID VISCOSITY, cP:                                            .0120
    PIPE ROUGHNESS, ft.:                                             .000
    FLUID COMPRESSIBILITY FACTOR:                                   .9000
    FLUID TEMPERATURE, oF:                                        100.000
    FLUID MOLECULAR WEIGHT, Mw:                                    19.500
    RATIO OF SPECIFIC HEAT CAPACITIES, Cp/Cv:                       1.270
    RESISTANCE COEFF. DUE TO FRICTIONAL LOSS:                        .301
    RESISTANCE COEFF. DUE TO FITTINGS + VALVES:                     2.013
    TOTAL RESISTANCE COEFFICIENT:                                   2.314
    INLET FLUID PRESSURE, psia:                                    454.700
    OUTLET FLUID PRESSURE, psia:                                   454.487
    PRESSURE DROP, psi:                                               .213
    FLUID VELOCITY, ft/sec.:                                        22.766
    FLUID SONIC VELOCITY, ft/sec.:                                1346.739
    MACH MUMBER AT INLET:                                           .0169
    MACH NUMBER AT CRITICAL CONDITION:                              .8874
    DARCY FRICTION FACTOR:                                          .0152
    REYNOLDS NUMBER:                                               2340890.
    CRITICAL PRESSURE, psia:                                        7.985
    FLUID VISCOSITY, cP:                                            .0120
    FLUID FLOW IS:                                               SUBSONIC
-----------------------------------------------------------------------------
```

Physical properties are:

	Liquid	Gas
Flow rate W, lb/h	77956	12434
Density ρ, lb/ft^3	66.7	2.98
Viscosity μ, cP	1.0	0.02
Surface tension σ, dyne/cm	70.0	

Pipe length 5 miles = 26,400 ft.

Solution

The computer program PROG35 calculates the flow regime and the pressure drops for liquid and vapor phases. From the two-phase flow modulus, the overall pressure drop for the 6-inch pipe is calculated. Table 3-12 gives the input data and computer output of the two-phase

Table 3-12
Input Data and Computer Output for Two-Phase Fluid Flow in a Pipe Line

```
DATA35.DAT
---------------------------------
6.065   26400.0   77956.0   1.0
66.7    70.0      12434.0   0.02
2.98    0.00015   0.0


         TWO-PHASE PRESSURE LOSS CALCULATION IN A PIPE LINE
*****************************************************************************
    PIPE INTERNAL DIAMETER, inch:                                  6.065
    EQUIVALENT LENGTH OF PIPE, ft.:                                 .000
    ACTUAL LENGTH OF PIPE, ft.:                                26400.000
    TOTAL LENGTH OF PIPE, ft.:                                 26400.000
    LIQUID FLOWRATE, lb/hr.:                                      77956.000
    LIQUID REYNOLDS NUMBER:                                          81105.
    LIQUID FRICTION FACTOR:                                       .0201
    PRESSURE DROP OF LIQUID,  psi/100ft.:                         .0818
    GAS FLOW RATE, lb/hr.:                                        12434.000
    GAS REYNOLDS NUMBER:                                            646814.
    GAS FRICTION FACTOR:                                          .0159
    PRESSURE DROP OF GAS, psi/100ft.:                             .0367
    FLOW REGIME IS:                                            ANNULAR
    LOCKHART-MARTINELLI TWO PHASE FLOW MODULUS:                   1.4920
    VELOCITY OF FLUID IN PIPE, ft./sec.:                          7.391
    BAKER PARAMETER IN THE LIQUID PHASE:                              40.768
    BAKER PARAMETER IN THE GAS PHASE:                               9495.209
    TWO-PHASE FLOW MODULUS:                                     10.0264
    PRESSURE DROP OF TWO-PHASE MIXTURE, psi/100ft:                .3684
    OVERALL PRESSURE DROP OF THE TWO-PHASE MIXTURE, psi:        97.2478
    INDEX       926.  IS LESS THAN 10000  PIPE EROSION IS UNLIKELY
-----------------------------------------------------------------------------
```

flow. The Lockhart-Martinelli two-phase flow modulus is 1.49. The Baker parameter in the liquid phase is 40.8, and the Baker parameter in the gas phase is 9495.2. These results indicate that the flow regime is **ANNULAR** (and can be observed from the Baker's plot, Figure 3-5). The two-phase modulus is 10.03 and the pressure drop of the two-phase mixture per 100 ft of pipe is 0.368 psi/100ft. The overall pressure drop of the two-phase mixture is 97.25 psi. In addition, the pipe is unlikely to encounter any corrosion-erosion because the computed index of 926 is less than 10,000.

Problem 3-6

Calculate the Froude numbers and flow conditions for the 2-, 4- and 6-inch (Schedule 40) vertical pipes having the following liquid and vapor flow rates and densities.

WL = 6930 lb/h	WG = 1444 lb/h
$\rho_L = 61.8$ lb/ft^3	$\rho_G = 0.135$ lb/ft^3

Solution

The computer program PROG36 calculates the Froude numbers for the liquid and vapor phases. In addition, PROG36 will determine whether the pipe is self venting or whether pulsation flow is encountered. Table 3-13 shows the results for the 2-, 4-, and 6-inch (Schedule 40) pipes. Table 3-14 gives a typical input data and computer output for the 2-inch (Schedule 40) pipe.

Problem 3-7

Determine the pressure drop for the 4-, 6-, and 8-inch (Schedule 40) condensate headers under the following conditions:

flow = 10,000 lb/h
steam condensate pressure = 114.7 psia
header pressure = 14.7 psia

Table 3-13
Vapor-Liquid Two-Phase Downflow

Pipe Internal Diameter: inch	2.067	4.026	6.065
Liquid Flow Rate: lb/h	6930	6930	6930
Liquid Density: lb/ft^3	61.80	61.80	61.80
Vapor Flow Rate: lb/h	1444	1444	1444
Vapor Density: lb/ft^3	0.135	0.135	0.135
Pipe Area: ft^2	0.023	0.088	0.201
Liquid Velocity: ft/s.	1.337	0.352	0.155
Vapor Velocity: ft/s.	127.504	33.609	14.810
Froude Number for Liquid Phase	0.5682	0.1073	0.0385
Froude Number for Vapor Phase	2.5332	0.4784	0.1718
	Flow is pulse and this may result in pipe vibration.	Line is self-venting. Therefore no vibration problems are expected.	Line is self-venting. Therefore no vibration problems are expected.

Table 3-14
Input Data and Computer Output for Vapor-Liquid Two-Phase Vertical Downflow

```
DATA36.DAT
---------------------
2.067   6930.0  61.8
1444.0  0.135


              VAPOR-LIQUID TWO-PHASE VERTICAL DOWNFLOW
*******************************************************************************
         PIPE INTERNAL DIAMETER, inch:                                 2.067
         LIQUID FLOWRATE, lb/h.:                                       6930.
         LIQUID DENSITY, lb/ft^3:                                     61.800
         VAPOR FLOWRATE, lb/h.:                                        1444.
         VAPOR DENSITY, lb/ft^3:                                        .135
         PIPE AREA, ft^2:                                               .023
         LIQUID VELOCITY, ft/s:                                        1.337
         VAPOR VELOCITY, ft/s:                                       127.504
         FROUDE NUMBER FOR LIQUID PHASE:                               .5682
         FROUDE NUMBER FOR VAPOR PHASE:                               2.5332
         FLOW IS PULSE AND THIS MAY RESULT IN PIPE VIBRATION
------------------------------------------------------------------------------
```

Solution

The computer program PROG37 evaluates the pressure drop of any given condensate header. The program also determines whether the velocity of the flashed condensate mixture would cause deterioration in the header line. Table 3-15 illustrates the results for the 4-, 6-, and 8-inch headers. Table 3-16 shows a typical input data and computer output for the 4-inch (Schedule 40) pipe. The computed results show that the 4-inch pipe gives the velocity of the flashed condensate mixture to be 7055 ft/min. This indicates a possible deterioration in the pipe. For the 6- and 8-inch pipes, the velocities are 3109 ft/min, and 1795 ft/min respectively, indicating that the condensate pipe lines will not deteriorate.

Problem 3-8

Calculate the pressure drop in a 60 ft length of 1 1/2 inch (Schedule 40, ID = 1.610 inch), pipe packed with catalyst pellets 1/4 inch in diameter when 104.4 lb/h of gas is passing through the bed. The temperature is constant along the length of pipe at 260°C. The void fraction is 45% and the properties of the gas are similar to those of air at this temperature. The entering pressure is 10 atm [29].

Solution

The computer program PROG38 calculates the pressure drop in a 1.610-inch I.D. packed bed for varying length of catalyst pellets. For air at 260°C and 10 atm, the physical properties are:

Table 3-15
Line Sizes for Flashing Steam Condensate

Pipe Internal Diameter: inch.	4.026	6.065	7.981
Total flow of mixture in condensate heater: lb/h.	10000	10000	10000
Steam condensate pressure before flashing: psia.	114.7	114.7	114.7
Flashed condensate header pressure: psia.	14.7	14.7	14.7
Weight fraction of condensate flashed to vapor.	0.135	0.135	0.135
Flashed Steam flowrate: lb/h.	1346	1346	1346
Flashed condensate liquid flowrate: lb/h.	8654	8654	8654
Temperature of Flashed condensate: °F	212.36	212.36	212.36
Flashed Steam Density: lb/ft^3	0.036	0.036	0.036
Flashed condensate liquid density: lb/ft^3	59.780	59.780	59.780
Density of mixture: lb/ft^3	0.267	0.267	0.267
Friction Factor:	0.0163	0.0149	0.0141
Pressure drop of flashed condensate mixture: psi/100 ft.	1.937	0.228	0.055
Velocity of flashed condensate mixture: ft/min.	7055	3109	1795
	Velocity is greater than 5000 ft/min. Deterioration of the line is possible	Velocity is less than 5000 ft/min. The condensate header line will not deteriorate	Velocity is less than 5000 ft/min. The condensate header will not deteriorate

Table 3-16
Input Data and Computer Output for Flashing Steam Condensate

```
DATA37.DAT
------------------
4.026   10000.0
114.7   14.7


              LINE SIZING FOR FLASHING STEAM CONDENSATE
*****************************************************************************
         PIPE INTERNAL DIAMETER, inch:                            4.026
         TOTAL FLOW OF MIXTURE IN CONDENSATE HEADER, lb/h:       10000.
         STEAM CONDENSATE PRESSURE BEFORE FLASHING, psia:       114.700
         FLASHED CONDENSATE HEADER PRESSURE, psia:               14.700
         WEIGHT FRACTION OF CONDENSATE FLASHED TO VAPOR:           .135
         FLASHED STEAM FLOWRATE, lb/h.:                           1346.
         FLASHED CONDENSATE LIQUID FLOWRATE, lb/h.:               8654.
         TEMPERATURE OF FLASHED CONDENSATE, oF:                 212.360
         FLASHED STEAM DENSITY, lb/ft^3:                           .036
         FLASHED CONDENSATE LIQUID DENSITY, lb/ft^3:             59.780
         DENSITY OF MIXTURE, lb/ft^3:                              .267
         FRICTION FACTOR:                                         .0163
         PRESSURE DROP OF FLASHED, psi:
         CONDENSATE MIXTURE, psi/100ft:                           1.937
         VELOCITY OF FLASHED CONDENSATE MIXTURE, ft/min.:           7055.
         FLASHED CONDENSATE MIXTURE VELOCITY IS GREATER THAN 5000 ft./min.
         DETERIORATION OF THE LINE IS POSSIBLE
-----------------------------------------------------------------------------
```

Table 3-17
Pressure Drop in a 1 1/2 Packed Bed

Particle length inch	Reynolds number, N_{Re}	Friction factor f_p	Pressure drop ΔP, lb/in^2
0.250	4170	1.7860	68.603
0.300	4415	1.7840	64.720
0.350	4609	1.7825	61.951
0.400	4765	1.7815	59.877
0.450	4895	1.7806	58.266

Table 3-18
Input Data and Computer Output for for Pressure Drop in a Packed Bed

```
DATA38.DAT
----------------------
0.134    60.0     104.4
0.25     0.25     0.45
0.413    0.0278
```

```
                       PRESSURE DROP IN A PACKED BED
*******************************************************************************
         PACKED BED DIAMETER, ft.:                                 .134
         LENGTH OF PACKED BED, ft.:                              60.000
         FLUID FLOWRATE THROUGH PACKED BED, lb/h.:                 104.4
         PARTICLE DIAMETER, inch.:                                 .250
         PARTICLE LENGTH, inch.:                                   .250
         FRACTIONAL VOIDS IN PACKED BED:                           .450
         DENSITY OF FLUID, lb/ft^3:                               .4130
         FLUID VISCOSITY, cP:                                     .0278
         CROSS-SECTIONAL AREA OF BED, ft^2:                       .0141
         SUPERFICIAL MASS VELOCITY, lb/h.ft^2:                   7402.9
         AREA OF PARTICLES, ft^2:                                 .2045E-02
         VOLUME OF PARTICLES, ft^3:                               .7102E-05
         THE PACKED BED SURFACE AREA, ft^2/ft^3 BED:            158.400
         EFFECTIVE PARTICLE DIAMETER, ft.:                        .0208
         FLUID REYNOLDS NUMBER:                                    4170.
         FRICTION FACTOR FOR INTERMEDIATE FLOW:                  1.7860
         TOTAL PRESSURE DROP IN PACKED BED, lb/in^2:             68.603
-------------------------------------------------------------------------------
```

density $\rho = 0.413\ lb_m/ft^3$
viscosity $\mu = 0.0278$ cP

Table 3-17 gives the Reynolds number, friction factor, and pressure drop of catalyst pellets of 0.25 inch and at different particle length. Table 3-18 shows a typical input data and computer output with PL = 0.25 inch. The simulation exercise gives a pressure drop of 68.603 lb/in^2. The results show that the pressure drop in a packed bed depends on size and shape of the particles.

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```
      SUBROUTINE PROG31

C     **********************************************************************
C     *  THIS PROGRAM CALCULATES PRESSURE DROP IN A PIPE INCLUDING        *
C     *  PIPE FITTINGS SUCH AS VALVES AND ELBOWS. THE PROGRAM USES THE    *
C     *  CHEN'S METHOD TO DETERMINE THE FRICTION FACTOR FC. THE DARCY     *
C     *  FRICTION FACTOR IS 4 x Chen'S FRICTION FACTOR (F = 4FC).  THE    *
C     *  PROGRAM INCORPORATES THE TWO K-METHOD TO DETERMINE THE NUMBER OF *
C     *  VELOCITY HEADS AND THUS CALCULATES THE EQUIVALENT PIPE LENGTH    *
C     *  DUE TO PIPE FITTINGS.  FROM THE TOTAL LENGTH OF THE PIPE, THE    *
C     *  OVERALL  PRESSURE DROP OF THE PIPE IS CALCULATED.                *
C                                                                        *
C     **********************************************************************

C     **********************************************************************
C     *  AREA   =  PIPE INTERNAL CROSS-SECTIONAL AREA, ft^2.              *
C     *  ID     =  PIPE INTERNAL DIAMETER, ft.                            *
C     *  ED     =  PIPE EXPANSION DIAMETER, ft.                           *
C     *  CD     =  PIPE CONTRACTING DIAMETER, ft.                         *
C     *  F      =  DARCY FRICTION FACTOR                                  *
C     *  L      =  TOTAL FITTING EQUIVALENT LENGTH PLUS STRAIGHT          *
C     *            PIPE LENGTH,ft.                                        *
C     *  LEQ    =  FITTINGS EQUIVALENT LENGTH, ft.                        *
C     *  LST    =  STRAIGHT PIPE LENGTH, ft.                              *
C     *  NF     =  NUMBER OF FITTINGS OF A GIVEN TYPE                     *
C     *  RE     =  REYNOLDS NUMBER                                        *
C     *  P      =  P1 OR P2 (DEPENDING ON INPUT)                          *
C     *  P1     =  PIPE INLET PRESSURE, psia.                             *
C     *  P2     =  PIPE OUTLET PRESSURE, psia.                            *
C     *  DELP   =  PRESSURE DROP psi/100 ft.                              *
C     *  RHO    =  FLUID DENSITY, lb/ft^3.                                *
C     *  Q      =  FLUID FLOW RATE, gal/min.                              *
C     *  W      =  GAS FLOWRATE, lb/h.                                    *
C     *  G      =  ACCELERATION DUE TO GRAVITY, 32.174 ft/sec^2           *
C     *  PR     =  ABSOLUTE ROUGHNESS OF PIPE WALL, 0.00015ft.            *
C     *  V      =  FLUID VELOCITY, ft/sec.                                *
C     *  VIS    =  VISCOSITY OF GAS, cP.                                  *
C     *  EE     =  RELATING TO ENTRANCE AND EXIT LOSSES                   *
C     *  ETV    =  RELATING TO ELBOW, TEES AND VALVES                     *
C     *  FIT    =  PIPE FITTINGS.                                         *
C     **********************************************************************

C     **********************************************************************
C     *         FITTING TYPE       FITTING NO.       K1          KL        *
C     *                                                                    *
C     *  180o ELBOWS (long radius)       1         1000.0      0.30        *
C     *  90o ELBOWS (long radius)        2          800.0      0.20        *
C     *  45o ELBOWS (long radius)        3          500.0      0.15        *
C     *      GATE VALVE                  4          300.0      0.10        *
C     *      BALL VALVE                  5          500.0      0.15        *
C     *      PLUG VALVE                  6         1000.0      0.25        *
C     *      GLOBE VALVE                 7         1500.0      4.00        *
C     *      DIAPHRAM, DAM TYPE VALVE    8         1000.0      2.00        *
C     *      BUTTERFLY VALVE             9          800.0      0.25        *
C     *     SWING CHECK VALVE           10         1500.0      1.50        *
C     *     RUN THRU TEE (flanged/welded)11         150.0      0.05        *
C     *     RUN THRU TEE (stub in type                                     *
C     *     branch                      12          100.0      0.00        *
C     *     PIPE ENTRANCE               13          160.0      0.50        *
```

```
C     *     PIPE EXIT                            14              0.0        1.00       *
C     *********************************************************************************

        CHARACTER*30 INFILE, OUTFIL

        CHARACTER CHOICE
        DIMENSION CHOFIT (14, 4)

        LOGICAL FITT

        COMMON /FILES/ INFILE, OUTFIL
        COMMON/DSCR1/ PID, RLST, Q, W, DEN, VIS, Z, PR1
        COMMON/DSCR2/ V, LEQ, LST, L, DELTAH, DELP, DELPT
        COMMON/DATA1/ PR, D, RE
        COMMON/DATA2/ ICOUNT
        COMMON/DATA3/ CHOFIT
        COMMON/DATA4/ CD, ED, OD, CHOICE
        COMMON/DATA5/ F, K, KOT
        COMMON/DATA6/ THETA1, THETA2, PI

        REAL L, LEQ, RLST, K, OD, KOT, KTOTAL

C       CALCULATE PIPE CROSS-SECTIONAL AREA, ft^2


        KTOTAL = 0.0
        LEQ = 0.0
        PR = 0.00015
        G = 32.2
        PI = 3.1415927
        D = PID/12
        AREA = (PI*(D**2))/4.0

C       CHECK WHETHER THE PIPE ROUGHNESS IS FOR CARBON STEEL
C       (i.e. PR = 0.00015ft).

        IF ( PR .NE. PR1) THEN
        PR = PR1
        ENDIF

C       CHECK WHETHER FLUID FLOW RATE IS IN VOLUMETRIC OR MASS RATE.


        IF ( Q .GT. 0.0) THEN
            GO TO 11
        ELSEIF (W .GT. 0.0) THEN
            GO TO 12
        ENDIF

C       CALCULATE REYNOLDS NUMBER BASED ON VOLUMETRIC RATE

 11     RE = (50.6*DEN*Q)/(PID*VIS)

C       CALCULATE FLUID VELOCITY ft/sec.

        V = (0.408*Q)/PID**2

C       CALCULATE THE FLUID MASS FLOW RATE, lb/hr

        W = (V*(PID**2)*DEN)/.0509
```

```
        GO TO 21

C       CALCULATE REYNOLDS NUMBER BASED ON MASS FLOW RATE, lb/hr.


 12     RE = (6.31*W)/(PID*VIS)


C       CALCULATE FLUID VELOCITY, ft/sec.

        V = (0.0509*W)/(DEN*(PID**2))

C       CALCULATE THE FLUID VOLUMETRIC FLOW RATE, gal/min.


        Q = W/(8.02*DEN)

C       CALCULATE THE DARCY FRICTION FACTOR

 21     IF (RE .GT. 2000.0) THEN

        GO TO 31
        ELSE

        F1 = 64.0/RE
        F = F1
        ENDIF
        GO TO 32

C       CALCULATE THE FRICTION FACTOR USING THE CHEN'S EQUATION

 31     A1 = ((PR/D)/3.7+(6.7/RE)**0.9)
        B1 = -4.0*ALOG10((PR/(3.7*D))-(5.02/RE)*ALOG10(A1))

C       CALCULATE THE DARCY FRICTION FACTOR. F

        F = 4.0/B1**2


C       CHECK WHETHER THERE ARE FITTINGS
C       IF FIT IS TRUE THEN CALL THE PROGRAM SFIT

 32     FITT = .TRUE.
            IF (FITT) THEN

C       THEN CALL FITTINGS

        CALL SFIT(K)
        GO TO 33
        ELSE
        K = 0.0
        GO TO 34
        ENDIF
        FITT = .FALSE.


C       CALCULATE THE TOTAL EQUIVALENT LENGTH , ft.
```

```
 33      LEQ = LEQ + (K*D)/F

C        CALCULATE THE TOTAL VELOCITY HEAD

         KTOTAL = KTOTAL + K + (F*RLST/D)

C        CALCULATE TOTAL FITTING EQUIVALENT LENGTH PLUS
C        STRAIGHT PIPE LENGTH, ft


 34      L = RLST + LEQ


         IF ( RE .LT. 2000.0) THEN
         GO TO 35
         ELSE
         ENDIF



C        CALCULATE THE FLUID PRESSURE DROP PER 100 ft. OF PIPE BASED ON THE
C        MASS FLOW RATE, lb/hr.

         IF (Q .GT. 0.0) THEN
         GO TO 44
         ELSE
         DELP = (0.000336*F*(W**2))/((PID**5)*DEN)
         ENDIF

C        CALCULATE THE OVERALL PRESSURE DROP OF THE PIPE

         DELPT = (DELP*L)/100.0 + ((Z*DEN)/144.0)
         GO TO 55

C        CALCULATE THE FLUID PRESSURE DROP PER 100ft OF PIPE BASED ON THE
C        VOLUMETRIC RATE. gal/min.


 44      DELP = (0.0216*F*DEN*(Q**2))/(PID**5)

C        CALCULATE THE OVERALL PRESSURE DROP OF THE PIPE

         DELPT = (DELP*L)/100.0 + ((Z*DEN)/144.0)

         GO TO 55

C        CALCULATE THE PRESSURE DROP FOR LAMINAR FLOW

 35      IF (Q .GT. 0.0) THEN
                 DELP = (0.0273*VIS*Q)/(PID**4)

C                CALCULATE THE OVERALL PRESSURE DROP psi.

                 DELPT = (DELP*L)/100.0 + ((Z*DEN)/144.0)

C        CALCULATE THE TOTAL HEAD LOSS, ft.

                 DELTAH = (0.0393*VIS*L*Q)/(PID**4*DEN) + Z
```

```
        GO TO 66

C       CALCULATE THE PRESSURE DROP BASED ON THE MASS FLOW RATE.
C       THE PRESSURE DROP IN psi. PER 100ft OF PIPE

        ELSEIF (W .GT. 0.0) THEN

        DELP = (0.0034*VIS*W)/((PID**4)*DEN)

C       CALCULATE THE OVERALL PRESSURE DROP IN psi.

        DELPT = (DELP*L)/100.0 + ((Z*DEN)/144.0)


C       CALCULATE THE TOTAL HEAD LOSS, ft.

        DELTAH = (0.0049*VIS*L*W)/((PID**4)*(DEN**2)) + Z

        ENDIF

        GO TO 66

C       CALCULATE THE TOTAL HEAD LOSS ft.

 55     DELTAH = (0.000483*F*L*(W**2))/((PID**5)*(DEN**2)) + Z

 66     RETURN
        END

C       ****************************************************************
C       * THIS PROGRAM USES THE TWO-K METHOD TO CALCULATE THE TOTAL    *
C       * THE VELOCITY HEAD FOR THE FITTINGS:                          *
C       *                                                              *
C       * CONSTANTS FOR THE TWO-K METHOD                               *
C       ****************************************************************

         SUBROUTINE SFIT (KALL)
         CHARACTER CHOICE

         DIMENSION CHOFIT (14, 4)
         COMMON/DATA1/ PR, D, RE
         COMMON/DATA3/ CHOFIT
         COMMON/DATA4/ CD, ED, OD, CHOICE
         COMMON/DATA5/ F, K, KOT
         COMMON/DATA6/ THETA1, THETA2, PI

         COMMON/DSCR1/ PID, RLST, Q, W, DEN, VIS, Z, PR1

         REAL KALL, KSUM, KLSUM, KEE1, KEE2, KEET, KTOTAL
         REAL  KEX, KCT, KOD, KOT, OD, K


         CHOFIT (6, 3) = CHOFIT (1, 3)
         CHOFIT (8, 3) = CHOFIT (1, 3)
         CHOFIT (9, 3) = CHOFIT (2, 3)
         CHOFIT (5, 3) = CHOFIT (3, 3)
         CHOFIT (10, 3) = CHOFIT (7, 3)
         CHOFIT (5, 4) = CHOFIT (3, 4)
         CHOFIT (9, 4) = CHOFIT (6, 4)
```

```
          KSUM = 0.0
          KLSUM = 0.0
          KEE1 = 0.0
          KEE2 = 0.0
          KTOTAL = 0.0
          KEX = 0.0
          KCT = 0.0
          KOD = 0.0


           DO 10 I = 1, 12

          KSUM = KSUM + CHOFIT (I, 2)*CHOFIT (I, 3)
          KLSUM = KLSUM + CHOFIT (I, 2)*CHOFIT (I, 4)

 10      CONTINUE

          KTOTAL = KTOTAL + (KSUM/RE+(KLSUM*(1.0+(1.0/PID))))
          KEE1=KEE1+(CHOFIT(13,2)*CHOFIT(13,3)+CHOFIT(14,2)*CHOFIT(14,3))
          KEE2=KEE2+(CHOFIT(13,2)*CHOFIT(13,4)+CHOFIT(14,2)*CHOFIT(14,4))
          KEET = (KEE1/RE + KEE2)
          KALL = KTOTAL + KEET


C         CALCULATE THE K VALUES OF THE SUDDEN CHANGES
C         IN PIPE ENLARGEMENT/REDUCTION WITH TAPERED ANGLES OR
C         WITHOUT TAPERED ANGLES.

          IF ( CHOICE .EQ. 'Y' .OR. CHOICE .EQ. 'y') THEN
          GO TO 20
          ELSEIF (CHOICE .EQ. 'N' .OR. CHOICE .EQ. 'n') THEN
          GO TO 75
          ENDIF

 20      IF ( ED .EQ. 0.0) THEN
                 BETA1 = 0.0
          GO TO 30
          ELSE
          BETA1 = PID/ED
          ENDIF

                 IF (THETA1 .EQ. 0.0) THEN
                  GO TO 11
                 ELSEIF (THETA1 .LE. 45.0) THEN
                 CAL1 = 2.6*SIN((THETA1*PI)/(180.0*2.0))
                  GO TO 22
                 ELSEIF (THETA1 .GT. 45.0) THEN
                 ENDIF

 11              IF (RE .LE. 4000.0) THEN
                         BETA1 = 2.0*(1.0 - (BETA1)**4)
                         GO TO 30
                 ELSEIF (RE .GT. 4000.0) THEN
                         BETA1 = (1.0 + 0.8*F)*(1.0 - (BETA1**2))**2
                         GO TO 30
                 ENDIF

 22              IF (RE .LE. 4000.0) THEN
                         BETA1 = CAL1*2.0*(1.0 - (BETA1)**4)
```

```
               GO TO 30
               ELSEIF (RE .GT. 4000.0) THEN
                       BETA1 = CAL1*(1.0+0.8*F)*(1.0-(BETA1**2))**2
               ENDIF

30     KEX = KEX + BETA1

               IF (CD .EQ. 0.0) THEN
               BETA2 = 0.0
               GO TO 40
               ELSE
               BETA2 = PID/CD
               ENDIF

               IF (THETA2 .EQ. 0.0) THEN
                       GO TO 35
               ELSEIF (THETA2 .LT. 45.0) THEN
                       CAL2 = 1.6*SIN((THETA2*PI)/(180.0*2.0))

                       GO TO 45
               ELSEIF (THETA2 .GT. 45.0 .OR. THETA2 .LT. 180.0) THEN
               CAL3 = SIN((THETA2*PI)/(180.0*2.0))

                       CAL3 = SQRT(CAL3)
                       GO TO 55
                       ENDIF

35             IF (RE .LE. 2500.0) THEN
               BETA2 = (1.2 + 160.0/RE)*((BETA2**4) - 1.0)
                       GO TO 40
               ELSEIF (RE .GT. 2500.0) THEN
               BETA2 = (0.6+0.48*F)*(BETA2**2)*((BETA2**2)-1.0)
                       GO TO 40
               ENDIF

45             IF (RE .LE. 2500.0) THEN
                       BETA2 = CAL2*(1.2+160.0/RE)*((BETA2**4)-1.0)
               GO TO 40
               ELSEIF (RE .GT. 2500.0) THEN
               BETA2 = CAL2*(0.6+0.48*F)*(BETA2**2)*((BETA2**2)-1.0)
               GO TO 40
               ENDIF

55             IF (RE .LE. 2500.0) THEN
               BETA2 = CAL3*(1.2+160.0/RE)*((BETA2**4)-1.0)
               GO TO 40
               ELSEIF (RE .GT. 2500.0) THEN
               BETA2 = CAL3*(0.6+0.48*F)*(BETA2**2)*((BETA2**2)-1.0)
               ENDIF
40             KCT = KCT + BETA2

               IF (OD .EQ. 0.0) THEN
               BETA3 = 0.0
               GO TO 41
               ELSE
               BETA3 = OD/PID
               ENDIF

               IF (RE .LE. 2500.0) THEN
               VAL1 = (2.72+((BETA3**2)*(120.0/RE-1.0)))
```

```
              BETA3 = VAL1*(1.0-(BETA3**2))*((1.0/(BETA3**4))-1.0)

                      GO TO 42
              ELSEIF (RE .GT. 2500.0) THEN
              VAL2 = (2.72-((BETA3**2)*(4000.0/RE)))
              BETA3 = VAL2*(1.0-(BETA3**2))*((1.0/(BETA3**4))-1.0)

              ENDIF

 42           KOD = KOD + BETA3

 41           KALL = KALL + KEX + KCT + KOD + KOT

 75      RETURN
         END

C        ****************************************************************
C        *     CONSTANTS FOR THE TWO-K METHOD                            *
C        ****************************************************************

         BLOCK DATA
         DIMENSION CHOFIT (14, 4)
         COMMON/DATA3/ CHOFIT
         DATA CHOFIT(1,3)/1000.0/,CHOFIT(2,3)/800.0/,CHOFIT(3,3)/500.0/
         DATA CHOFIT(4,3)/300.0/,CHOFIT(7,3)/1500.0/,CHOFIT(11,3)/150.0/
         DATA CHOFIT(12,3)/100.0/,CHOFIT(13,3)/160.0/,CHOFIT(14,3)/0.0/
         DATA CHOFIT(1,4)/0.30/,CHOFIT(2,4)/0.20/,CHOFIT(3,4)/0.15/
         DATA CHOFIT(4,4)/0.10/,CHOFIT(6,4)/0.25/,CHOFIT(7,4)/4.0/
         DATA CHOFIT(8,4)/2.0/,CHOFIT(10,4)/1.50/,CHOFIT(11,4)/0.05/
         DATA CHOFIT(12,4)/0.0/,CHOFIT(13,4)/0.50/,CHOFIT(14,4)/1.0/
         END
```

```
        PROGRAM PROG32

C       **********************************************************************
C       *  THIS PROGRAM CALCULATES THE PRESSURE DROP IN A PIPE INCLUDING     *
C       *  PIPE FITTINGS SUCH AS VALVES AND ELBOWS. THE PROGRAM USES THE     *
C       *  CHEN'S METHOD TO DETERMINE THE FRICTION FACTOR - f.  THE DARCY    *
C       *  FRICTION FACTOR IS 4FC (i.e. 4 X CHEN'S FRICTION FACTOR).         *
C       *  THE PROGRAM USES THE VELOCITY HEAD DUE TO PIPE FITTINGS+VALVES    *
C       *  TO CALCULATE THE EQUIVALENT PIPE LENGTH.  THE TOTAL LENGTH OF     *
C       *  PIPE IS THE SUMMATION OF THE EQUIVALENT LENGTH AND THE STRAIGHT   *
C       *  PIPE LENGTH. FROM THE TOTAL LENGTH OF THE PIPE, THE OVERALL       *
C       *  PRESSURE DROP OF THE PIPE IS CALCULATED.                          *
C       **********************************************************************
C
C       **********************************************************************
C       *                           NOMENCLATURE                             *
C       *                           --------------                           *
C       *                                                                    *
C       *  AREA =  PIPE INTERNAL CROSS-SECTIONAL AREA, ft^2.                 *
C       *  PID  =  PIPE INTERNAL DIAMETER, inch.                             *
C       *  ED   =  PIPE EXPANSION DIAMETER, ft.                              *
C       *  CD   =  PIPE CONTRACTING DIAMETER, ft.                            *
C       *  F    =  DARCY FRICTION FACTOR                                     *
C       *  L    =  TOTAL FITTING EQUIVALENT LENGTH PLUS                      *
C       *          STRAIGHT PIPE LENGTH, ft.                                 *
C       *  LEQ  =  FITTINGS EQUIVALENT LENGTH, ft.                           *
C       *  LST  =  STRAIGHT PIPE LENGTH, ft.                                 *
C       *  NF   =  NUMBER OF FITTINGS OF A GIVEN TYPE                        *
C       *  RE   =  REYNOLDS NUMBER                                           *
C       *  P    =  P1 OR P2 (DEPENDING ON INPUT).                            *
C       *  P1   =  PIPE INLET PRESSURE, psia.                                *
C       *  P2   =  PIPE OUTLET PRESSURE, psia.                               *
C       *  DELP =  PRESSURE DROP psi/100 ft.                                 *
C       *  RHO  =  FLUID DENSITY, lb/ft^3.                                   *
C       *  Q    =  FLUID VOLUMETRIC FLOW RATE, gal/min.                      *
C       *  W    =  FLUID MASS FLOWRATE, lb/h.                                *
C       *  G    =  ACCELERATION DUE TO GRAVITY, 32.174 ft/sec^2.             *
C       *  PR   =  ABSOLUTE ROUGHNESS OF PIPE WALL, 0.00015ft.               *
C       *  V    =  FLUID VELOCITY, ft/sec.                                   *
C       *  VIS  =  VISCOSITY OF FLUID, cP.                                   *
C       **********************************************************************

        REAL RL, RLEQ, RLST, RK, KTOTAL

        COMMON/DATA1/ PID, RLST, Q, W, DEN, VIS, Z, PR1
        COMMON/DATA2/ V, RLEQ, KTOTAL, RK, RL, DELTAH, DELP, DELPT
        COMMON/DATA3/ G, PR, D, AREA, RE, FF

C       OPEN THE DATA FILE

        OPEN (UNIT = 3, FILE = 'DATA32.DAT', STATUS = 'OLD', ERR = 18)

C       OPEN FILE FOR PRINTING THE RESULTS.

        OPEN (UNIT = 1, FILE = 'PRN')


        WRITE (1, 50)
 50     FORMAT (///,\)
```

```
        WRITE (1, 100)
 100    FORMAT (5X, 'PRESSURE DROP CALCULATION OF AN INCOMPRESSIBLE',\)

        WRITE (1, 110)
 110    FORMAT (' FLUID IN A PIPE LINE',/1H , 78(1H*))


C       READ IN THE DATA IN THE DATA FILE.


C       READ THE PIPE INTERNAL DIAMERTER, inch: PID
C       READ THE ACTUAL LENGTH OF PIPE, ft.: RLST
C       READ THE FLUID FLOW RATE ( IF VOLUMETRIC FLOWRATE, gal/min.: Q IS GIVEN
C       THEN THE MASS FLOW RATE, lb/hr.: W = 0.0, ALTERNATIVELY, IF THE
C       MASS FLOW RATE, lb/hr.: W IS GIVEN, THEN THE VOLUMETRIC RATE, gal/min.
C       Q = 0.0.
C       READ THE FLUID DENSITY, lb/ft^3.: DEN
C       READ THE FLUID VISCOSITY, cP: VIS
C       READ THE PIPE ELEVATION, ft.: Z (OTHERWISE Z = 0.0)
C       READ THE VELOCITY HEAD DUE TO PIPE FITTINGS, :RK
C       READ THE PIPE ROUGHNESS, ft. PR1 (0.00015)

        READ (3, *, ERR=19) PID, RLST, Q, W

        READ (3, *, ERR=19) DEN, VIS, Z, RK

        READ (3, *, ERR=19) PR1

        GO TO 5

 18     WRITE (*, 120)
 120    FORMAT (5X, 'DATA FILE DOES NOT EXIST')

        GO TO 999

 19     WRITE (*, 130)
 130    FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

C
C       CALCULATE PIPE CROSS-SECTIONAL AREA, ft^2


 5       PI = 3.1415927
         G = 32.2
         D = PID/12
         AREA = (PI*(D**2))/4.0

C        CHECK WHETHER THE PIPE ROUGHNESS IS FOR CARBON STEEL
C        (i.e. PR=0.00015ft).

         IF ( PR .NE. PR1) THEN
         PR = PR1
         ENDIF

C        CHECK WHETHER FLUID FLOW RATE IS IN VOLUMETRIC OR MASS RATE.
```

```
      IF ( Q .GT. 0.0) THEN
      CALL VRATE
      CALL VMOUT
      ELSE
      CALL MRATE
      CALL VMOUT

      ENDIF


      CLOSE (UNIT = 3, STATUS = 'KEEP')
      CLOSE (UNIT = 1)

 999  STOP
      END
C    ******************************************************************
C    THIS PROGRAM CALCULATES THE PRESSURE DROP OF INCOMPRESSIBLE FLUIDS.
C    FOR A GIVEN VOLUMETRIC RATE.
C    ******************************************************************


     SUBROUTINE VRATE

     REAL RL, RLEQ, RLST, RK, KTOTAL

     COMMON/DATA1/ PID, RLST, Q, W, DEN, VIS, Z, PR1
     COMMON/DATA2/ V, RLEQ, KTOTAL, RK, RL, DELTAH, DELP, DELPT
     COMMON/DATA3/ G, PR, D, AREA, RE, FF

     RLEQ = 0.0
     KTOTAL = 0.0


C    CALCULATE THE REYNOLDS NUMBER

     RE = (50.6*DEN*Q)/(PID*VIS)


C    CALCULATE THE FLUID VELOCITY, ft/sec.

     V = (0.408*Q)/PID**2


C    CALCULATE THE FLUID MASS RATE, lb/hr.

     W = (V*PID**2*DEN)/0.0509


C    DETERMINE WHETHER FLUID FLOW IS LAMINAR OR TURBULENT.

     IF (RE .GT. 2000.0) THEN

C    IF FLUID FLOW IS TURBULENT, CALCULATE THE FRICTION FACTOR
C    USING CHEN'S EQUATION.

     CALL CHEN
     ELSE

C    FLUID FLOW IS LAMINAR, CALCULATE THE FRICTION FACTOR.
```

```
      FF = 64.0/RE
      ENDIF

C     CALCULATE THE TOTAL EQUIVALENT LENGTH, ft.

      CALL TLENGTH

C     CALCULATE THE FLUID PRESSURE DROP PER 100ft. OF PIPE, psi/100ft.
C     CHECK WHETHER FLUID FLOW IS LAMINAR OR TURBULENT.

      IF (RE .LT. 2000.0) THEN

      DELP = (0.0273*VIS*Q)/(PID**4)

C     CALCULATE THE OVERALL PRESSURE DROP, psi.

      DELPT = (DELP*RL)/100.0+((Z*DEN)/144.0)

C     CALCULATE THE TOTAL HEAD LOSS, ft.

      DELTAH = (0.0393*VIS*RL*Q)/((PID**4)*DEN) + Z
      ELSE

C     IF FLUID FLOW IS TURBULENT
C     CALCULATE THE PRESSURE DROP PER 100ft. OF PIPE, psi/100ft.

      DELP = (0.0216*FF*DEN*(Q**2))/(PID**5)

C     CALCULATE THE OVERALL PRESSURE DROP, psi.

      DELPT = (DELP*RL)/100.0 + ((Z*DEN)/144.0)

C     CALCULATE THE OVERALL HEAD LOSS, ft.

      DELTAH = (0.0311*FF*RL*(Q**2))/(PID**5) + Z
      ENDIF
      RETURN
      END


C     **************************************************************
C     THIS PROGRAM CALCULATES THE PRESSURE DROP OF INCOMPRESSIBLE
C     FLUIDS FOR A GIVEN MASS RATE.
C     ***************************************************************

      SUBROUTINE MRATE
      REAL RL, RLEQ, RLST, RK, KTOTAL

      COMMON/DATA1/ PID, RLST, Q, W, DEN, VIS, Z, PR1
      COMMON/DATA2/ V, RLEQ, KTOTAL, RK, RL, DELTAH, DELP, DELPT
      COMMON/DATA3/ G, PR, D, AREA, RE, FF

      RLEQ = 0.0
      KTOTAL = 0.0


C     CALCULATE THE REYNOLDS NUMBER

      RE = (6.31*W)/(PID*VIS)
```

```
C         CALCULATE THE FLUID VELOCITY, ft/sec.

          V = (0.0509*W)/(DEN*PID**2)


C         CALCULATE THE FLUID VOLUMETRIC FLOWRATE, gal/min.

          Q = W/(8.02*DEN)

C         DETERMINE WHETHER FLUID FLOW IS LAMINAR OR TURBULENT.

          IF (RE .GT. 2000.0) THEN

C         IF FLUID FLOW IS TURBULENT, CALCULATE THE FRICTION FACTOR,
C         USING CHEN'S EQUATION.

          CALL CHEN
          ELSE

C         IF FLUID FLOW IS LAMINAR, CALCULATE THE FRICTION FACTOR.

          FF = 64.0/RE
          ENDIF

C         CALCULATE THE TOTAL EQUIVALENT LENGTH, ft.

          CALL TLENGTH

C         CALCULATE THE FLUID PRESSURE DROP PER 100ft. OF PIPE, psi/100ft.

          IF (RE .LT. 2000.0) THEN

C         CALCULATE THE PRESSURE DROP FOR LAMINAR FLOW, psi/100ft.

          DELP = (0.0034*VIS*W)/((PID**4)*DEN)

C         CALCULATE THE OVERALL PRESSURE DROP FOR LAMINAR FLOW, psi.

          DELPT = (DELP*RL)/100.0 + ((Z*DEN)/144.0)

C         CALCULATE THE HEAD LOSS FOR LAMINAR FLOW.

          DELTAH = (0.0049*VIS*RL*W)/((PID**4)*(DEN**2)) + Z
          ELSE

C         CALCULATE THE PRESSURE DROP FOR TURBULENT FLOW psi/100ft.

          DELP = (0.000336*FF*(W**2))/((PID**5)*DEN)

C         CALCULATE THE OVERALL PRESSURE DROP, psi.

          DELPT = ((DELP*RL)/100.0) + ((Z*DEN)/144.0)

C         CALCULATE THE TOTAL HEAD LOSS, ft.

          DELTAH =  (0.000483*FF*RL*(W**2))/((PID**5)*(DEN**2)) + Z
          ENDIF

          RETURN
```

```
      END

C     ***************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF PRESSURE DROP OF
C     INCOMPRESSIBLE FLOW USING EITHER VOLUMETRIC FLOW RATE OR
C     MASS FLOW RATE.
C     ***************************************************************

      SUBROUTINE VMOUT

      REAL RL, RLEQ, RLST, RK, KTOTAL

      COMMON/DATA1/ PID, RLST, Q, W, DEN, VIS, Z, PR1
      COMMON/DATA2/ V, RLEQ, KTOTAL, RK, RL, DELTAH, DELP, DELPT
      COMMON/DATA3/ G, PR, D, AREA, RE, FF

      WRITE (1,140) PID, W, Q, VIS
 140  FORMAT(5X,'PIPE INTERNAL DIAMETER, inch:', T60, F8.3,/,
     *       5X,'MASS FLOW RATE, lb/h.:',T60, F10.2,/,
     *       5X,'VOLUMETRIC FLOW RATE, gal/min.:',T60,F10.2,/,
     *       5X,'FLUID VISCOSITY, cP:',T60,F8.4)

      WRITE (1, 150) DEN, V, RK, RLEQ
 150  FORMAT(5X,'FLUID DENSITY, lb/ft^3:', T60, F8.3,/,
     *       5X,'FLUID VELOCITY, ft/sec.:',T60, F8.3,/,
     *       5X,'VELOCITY HEAD LOSS DUE TO FITTINGS:',T60, F8.3,/,
     *       5X,'EQUIVALENT LENGTH OF PIPE, ft.:',T60, F8.3)

      WRITE (1, 160) RLST, RL, RE, PR
 160  FORMAT(5X,'ACTUAL LENGTH OF PIPE, ft.:',T60, F8.3,/,
     *       5X,'TOTAL LENGTH OF PIPE, ft.:', T60, F8.3,/,
     *       5X,'REYNOLDS NUMBER:', T60, F10.0,/,
     *       5X,'PIPE ROUGHNESS, ft.:', T60, F8.6)

      WRITE (1, 170) FF, DELTAH, DELP, DELPT
 170  FORMAT(5X,'DARCY FRICTION FACTOR:', T60, F8.4,/,
     *       5X,'EXCESS HEAD LOSS, ft.:', T60, F8.3,/,
     *       5X,'PIPE PRESSURE DROP /100ft., psi/100ft:', T60, F8.4,/,
     *       5X,'OVERALL PRESSURE DROP OF PIPE, psi:', T60, F8.4)

      WRITE (1, 180)
 180  FORMAT (78(1H-))

C     FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)


      RETURN
      END

C     ******************************************************************
C     THIS PROGRAM CALCULATES THE FRICTION FACTOR USING CHEN'S EQUATION
C
C     ******************************************************************

      SUBROUTINE CHEN

      COMMON/DATA3/ G, PR, D, AREA, RE, FF
```

```
      A1 = ((PR/D)/3.7+(6.7/RE)**0.9)
      B1 = -4.0*ALOG10((PR/(3.7*D))-(5.02/RE)*ALOG10(A1))
      FF = 4.0/B1**2
      RETURN
      END

C     ****************************************************************
C     THIS PROGRAM CALCULATES THE TOTAL LENGTH OF PIPE INCLUDING
C     THE EQUIVALENT LENGTH.
C     ****************************************************************

      SUBROUTINE TLENGTH
      REAL RL, RLEQ, RLST, RK, KTOTAL

      COMMON/DATA1/ PID, RLST, Q, W, DEN, VIS, Z, PR1
      COMMON/DATA2/ V, RLEQ, KTOTAL, RK, RL, DELTAH, DELP, DELPT
      COMMON/DATA3/ G, PR, D, AREA, RE, FF

      RLEQ = 0.0
      KTOTAL = 0.0

C     CALCULATE THE TOTAL EQUIVALENT LENGTH, ft.

      RLEQ = RLEQ+(RK*D)/FF

C     CALCULATE THE TOTAL FITTING EQUIVALENT LENGTH PLUS STRAIGHT PIPE
C     LENGTH, ft.


      RL = RLST + RLEQ

C     CALCULATE THE VELOCITY HEAD, KTOTAL

      KTOTAL = KTOTAL + RK + (FF*RLST/D)

      RETURN
      END
```

```
      PROGRAM PROG33


C     ******************************************************************
C     * THIS PROGRAM CALCULATES THE MAXIMUM FLUID RATE OF A            *
C     * COMPRESSIBLE FLUID FOR A GIVEN PIPE SIZE, PRESSURE DROP AND    *
C     * FLUID FLOW CHARACTERISTICS.                                    *
C     ******************************************************************

C     ******************************************************************
C     *                       NOMENCLATURE                             *
C     *                       ------------                             *
C     *                                                                *
C     *   A      =   PIPE CROSS-SECTIONAL AREA, ft^2.                  *
C     *   d      =   PIPE INTERNAL DIAMETER, inch.                     *
C     *   D      =   PIPE INTERNAL DIAMETER, ft.                       *
C     *   PFF    =   PIPE FRICTION FACTOR                              *
C     *   g      =   ACCELERATION DUE TO GRAVITY, 32.2 ft/sec^2.       *
C     *   g      =   CONVERSION FACTOR (32.174 (lbm/lbf)(ft/s^2)       *
C     *    C                                                           *
C     *   KF      =  RESISTANCE COEFFICIENT DUE TO PIPE FITTINGS+VALVES *
C     *   KP      =  RESISTANCE COEFFICIENT DUE TO PIPE FRICTION       *
C     *   KTOTAL =   TOTAL RESISTANCE COEFFICIENT                      *
C     *   LST     =  LENGTH OF STRAIGHT PIPE, ft.                      *
C     *   MW      =  MOLECULAR WEIGHT OF FLUID (lb/lb mol.)            *
C     *   P1      =  INLET FLUID PRESSURE, psia.                       *
C     *   P2      =  OUTLET FLUID PRESSURE, psia.                      *
C     *   DELP    =  PRESSURE DROP (PRESSURE DIFFERENCE BETWEEN TWO    *
C     *              POINTS), psi.                                     *
C     *   R       =  MOLAR GAS CONSTANT (10.73 psia.ft^3/R.lb mole)    *
C     *           =  1544 lbf.ft/oR. lb mole.                          *
C     *   SG      =  MOLECULAR WEIGHT OF GAS/MOLECULAR WEIGHT OF AIR   *
C     *   T       =  FLUID TEMPERATURE: oF.                            *
C     *   VG      =  FLUID VELOCITY, ft/sec.                           *
C     *   VS      =  FLUID SONIC VELOCITY, ft/sec.                     *
C     *   RHO     =  FLUID DENSITY, lb/ft^3.                           *
C     *   VIS     =  FLUID VISCOSITY, cP.                              *
C     *   Z       =  FLUID COMPRESSIBILITY FACTOR (Z=1).               *
C     ******************************************************************


      CHARACTER*10 REGIME(3), REG(3)

      COMMON/DATA1/ D, RE
      COMMON/DATA2/ RHO, DELP
      COMMON/DATA3/ VG, VS, MACH, MACR, PC
      COMMON/DATA4/ KP, KTOTAL
      COMMON/DATA5/ REG, REGIME, IR

      REAL ID, LST, KF, KP, MW, MACH, MACR, KTOTAL

C     FLOW PATTERNS OF COMPRESSIBLE FLUID FLOW IN A PIPE (Subsonic, Sonic
C     Supersonic).

      DATA REG/ 'SUBSONIC ', 'SONIC     ', 'SUPERSONIC'/
```

```
C     OPEN THE DATA FILE.

      OPEN (UNIT = 3, FILE = 'DATA33.DAT', STATUS = 'OLD', ERR = 18)

C     OPEN FILE FOR PRINTING THE RESULTS.

      OPEN (UNIT = 1, FILE = 'PRN')


      WRITE (1, 100)
 100  FORMAT (///,10X,'COMPRESSIBLE FLUID FLOW CALCULATIONS IN A',\)

      WRITE (1, 110)
 110  FORMAT (' PIPE LINE',/78(1H*))

C     READ IN THE DATA

C     READ THE INTERNAL PIPE DIAMETER, inch.: ID
C     READ THE STRAIGHT LENGTH OF PIPE, ft.: LST
C     READ THE PIPE FRICTION FACTOR: PFF
C     READ THE RESISTANCE COEFFICIENT DUE TO PIPE FITTINGS + VALVES: KF
C     READ THE FLUID COMPRESSIBILITY FACTOR: (Z=1.0)
C     READ THE FLUID TEMPERATURE, oF: T
C     READ THE FLUID MOLECULAR WEIGHT: MW
C     READ THE FLUID INLET PRESSURE, psia: P1
C     READ THE FLUID OUTLET PRESSURE, psia: P2
C     READ THE RATIO OF SPECIFIC HEAT CAPACITIES, Cp/Cv: RATIOK
C     READ THE FLUID VISCOSITY, cP: VIS.



      READ (3, *, ERR=19) ID, LST, PFF
      READ (3, *, ERR=19) KF, Z, T, MW
      READ (3, *, ERR=19) P1, P2, RATIOK, VIS

      GO TO 20

 18   WRITE (*, 120)
 120  FORMAT (5X, 'DATA FILE DOES NOT EXIST')
      GO TO 999

 19   WRITE (*, 130)
 130  FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
      GO TO 999

C     THIS CALLS FOR THE MAXIMUM FLUID FLOWRATE CALCULATION

 20   CALL CALC1 (ID, LST, PFF, KF, Z, T, MW, P1, P2, RATIOK, VIS, G)

C     THIS CALLS FOR THE RESULTS TO BE PRINTED.

      CALL OUT1 (ID, LST, PFF, KF, Z, T, MW, G, P1, P2, RATIOK, VIS)

      CLOSE (3, STATUS = 'KEEP')
      CLOSE (1)

 999  STOP
      END
```

```
C       *****************************************************************
C       THIS PROGRAM CALCULATES THE MAXIMUM COMPRESSIBLE FLUID RATE FOR
C       A GIVEN PRESSURE LOSS AND FLUID SYSTEM CHARACTERISTICS.
C
C       *****************************************************************

        SUBROUTINE CALC1 (ID, LST, PFF, KF, Z, T, MW, P1, P2, RATIOK,
     *                    VIS, G)

        CHARACTER*10, REGIME(3), REG(3)

        COMMON/DATA1/ D, RE
        COMMON/DATA2/ RHO, DELP
        COMMON/DATA3/ VG, VS, MACH, MACR, PC
        COMMON/DATA4/ KP, KTOTAL
        COMMON/DATA5/ REG, REGIME, IR

        REAL ID, LST, KF, KP, KTOTAL, MW, MACH, MACR

        T = T + 460.0
        PI = 3.1415927

C       CALCULATE THE PIPE AREA, ft^2.

        D = ID/12.0
        AREA = (PI*D*D)/4.0

C       CALCULATE THE INLET FLUID DENSITY, lb/ft^3.

        RHO = (P1*MW)/(10.72*T*Z)

C       CALCULATE THE PRESSURE DIFFERENCE, psi.

        DELP = P1 - P2

C       CALCULATE THE RESISTANCE COEFFICIENT, KP DUE TO PIPE FRICTION.

        KP = (PFF*LST)/D

C       CALCULATE THE TOTAL RESISTANCE COEFFICIENT.
        KTOTAL = KF + KP

C       CALCULATE THE MAXIMUM FLUID RATE FOR THE INLET AND OUTLET
C       PRESSURES, psia.

        C1 = 1335.6*(ID**2)
        C2 = SQRT(RHO/(KTOTAL+(2.0*ALOG(P1/P2))))*SQRT((P1**2-P2**2)/P1)
        G = C1*C2

C       CALCULATE THE FLUID'S REYNOLDS NUMBER AT THE MAXIMUM FLOW

        RE = (6.31*G)/(D*VIS)

C       CALCULATE THE FLUID VELOCITY, ft/sec.

        VG = (0.0509*G)/(RHO*ID**2)

C       CALCULATE THE SONIC VELOCITY, ft/sec.

        VS = 223.0*SQRT((RATIOK*T)/MW)
```

```
C       CALCULATE THE INLET MACH NUMBER

        MACH = VG/VS

C       CALCULATE THE EXIT MACH NUMBER FOR ISOTHERMAL FLOW
C       i.e. THE MACH NUMBER AT CRITICAL CONDITION.

        MACR = 1.0/SQRT(RATIOK)

C       CHECK WHETHER FLUID FLOW IS SUBSONIC, SONIC OR SUPERSONIC

        IF (MACH .LT. MACR) THEN
                IR = 1
                REGIME(IR) = REG(IR)
        GO TO 10
                  ELSEIF (MACH .EQ. MACR) THEN
                  IR = 2
                  REGIME(IR) = REG(2)
                  GO TO 10
                      ELSEIF (MACH .GT. MACR) THEN
                      IR = 3
                      REGIME(IR) = REG(3)
        ENDIF

C       CALCULATE THE CRITICAL PRESSURE AT SONIC CONDITION
C       USING CROCKER'S EQUATION, psia.

 10     SG = MW/29.0
        R = 1544.0/(29.0*SG)
        PC = (G/(11400.0*ID**2))*SQRT((R*T)/(RATIOK*(RATIOK+1.0)))

        T = T - 460.0

        RETURN
        END


C       ***************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF THE MAXIMUM COMPRESSIBLE
C       FLUID FLOW ONTO A PRINTER.
C       ***************************************************************

        SUBROUTINE OUT1 (ID,  LST,  PFF,  KF,  Z,  T,  MW, G, P1, P2,
     *                  RATIOK, VIS)

        CHARACTER*10, REGIME(3), REG(3)
C
        COMMON/DATA1/ D, RE
        COMMON/DATA2/ RHO, DELP
        COMMON/DATA3/ VG, VS, MACH, MACR, PC
        COMMON/DATA4/ KP, KTOTAL
        COMMON/DATA5/ REG, REGIME, IR

        REAL ID, LST, KF, KP, KTOTAL, MW,  MACH, MACR

        WRITE (1, 140) ID, LST, G, RHO, PFF, Z, T, MW, RATIOK, VIS
 140    FORMAT (5X,'PIPE INTERNAL DIAMETER, inch:', T60, F8.3,/,
     1          5X,'STRAIGHT LENGTH OF PIPE, ft.:', T60, F8.3,/,
     2          5X,'MAXIMUM FLUID FLOWRATE, lb/h.:', T60, F10.2,/,
```

```
     3          5X,'FLUID DENSITY, lb/ft^3:', T60, F8.3,/,
     4          5X,'PIPE FRICTION FACTOR:', T60, F8.4,/,
     5          5X,'FLUID COMPRESSIBILITY FACTOR:', T60, F8.4,/,
     6          5X,'FLUID TEMPERATURE, oF:', T60, F8.3,/,
     7          5X,'FLUID MOLECULAR WEIGHT, Mw:', T60, F8.3,/,
     8          5X,'RATIO OF SPECIFIC HEAT CAPACITIES, Cp/Cv:',T60,
     9          F8.3,/,
     *          5X,'FLUID VISCOSITY, cP:', T60, F8.4)

        WRITE (1, 150) KP, KF, KTOTAL
 150    FORMAT (5X, 'RESISTANCE COEFF. DUE TO FRICTIONAL LOSS:',T60,
     1          F8.3,/,5X,'RESISTANCE COEFF. DUE TO FITTINGS + VALVES:',
     2          T60, F8.3,/,5X,'TOTAL RESISTANCE COEFFICIENT:',T60,F8.3)

        WRITE (1,160) P1, P2, DELP
 160    FORMAT (5X,'INLET FLUID PRESSURE, psia:', T60, F9.3,/,
     1          5X,'OUTLET FLUID PRESSURE, psia:', T60, F9.3,/,
     2          5X,'PRESSURE DROP, psi:', T60, F9.3)

        WRITE (1, 170) VG, VS, MACH, MACR
 170    FORMAT (5X,'FLUID VELOCITY, ft/sec.:', T60, F9.3,/,
     1          5X,'FLUID SONIC VELOCITY, ft/sec.:', T60, F9.3,/,
     2          5X,'MACH MUMBER AT INLET:', T60, F8.4,/,
     3          5X,'MACH NUMBER AT CRITICAL CONDITION:', T60, F8.4)

        WRITE (1, 180) RE, PC
 180    FORMAT (5X,'REYNOLDS NUMBER:', T60, F10.0/,
     1          5X,'CRITICAL PRESSURE, psia:', T60, F9.3)

        WRITE (1, 190) REGIME(IR)
 190    FORMAT (5X,'FLUID FLOW IS:', T60, A10)

        WRITE (1, 200)
 200    FORMAT (78(1H-))

C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
        PROGRAM PROG34


C       *********************************************************************
C       * THIS PROGRAM CALCULATES THE PRESSURE DROP OF A                    *
C       * COMPRESSIBLE FLUID FOR A GIVEN FLUID FLOW RATE, PIPE SIZE         *
C       * AND FLUID FLOW CHARACTERISTICS.                                   *
C       *                                                                   *
C       *********************************************************************

C       *********************************************************************
C       *                           NOMENCLATURE                            *
C       *                           ------------                            *
C       *                                                                   *
C       *   A       =  PIPE CROSS-SECTIONAL AREA, ft^2.                     *
C       *   d       =  PIPE INTERNAL DIAMETER, inch.                        *
C       *   D       =  PIPE INTERNAL DIAMETER, ft.                          *
C       *   FD      =  DARCY FRICTION FACTOR                                *
C       *   g       =  ACCELERATION DUE TO GRAVITY, 32.2 ft/sec^2.          *
C       *   g       =  CONVERSION FACTOR (32.174 (lbm/lbf)(ft/s^2)          *
C       *    C                                                              *
C       *   KF      =  RESISTANCE COEFFICIENT DUE TO PIPE FITTINGS+VALVES   *
C       *   KP      =  RESISTANCE COEFFICIENT DUE TO PIPE FRICTION          *
C       *   KTOTAL  =  TOTAL RESISTANCE COEFFICIENT                         *
C       *   LST     =  LENGTH OF STRAIGHT PIPE, ft.                         *
C       *   MW      =  MOLECULAR WEIGHT OF FLUID (lb/lb mol.)               *
C       *   P1      =  INLET FLUID PRESSURE, psia.                          *
C       *   P2      =  OUTLET FLUID PRESSURE, psia.                         *
C       *   DELP    =  PRESSURE DROP (PRESSURE DIFFERENCE BETWEEN TWO       *
C       *              POINTS), psi.                                        *
C       *   PR      =  PIPE ROUGHNESS (i.e. PR=0.00015ft.)                  *
C       *   R       =  MOLAR GAS CONSTANT (10.73 psia.ft^3/R.lb mole)       *
C       *           =  1544 lbf.ft/oR. lb mole                              *
C       *   SG      =  MOLECULAR WEIGHT OF GAS/MOLECULAR WEIGHT OF AIR      *
C       *   T       =  FLUID TEMPERATURE: DEG.F                             *
C       *   VG      =  FLUID VELOCITY, ft/sec.                              *
C       *   VS      =  FLUID SONIC VELOCITY, ft/sec.                        *
C       *   RHO     =  FLUID DENSITY, lb/ft^3.                              *
C       *   VIS     =  FLUID VISCOSITY, cP                                  *
C       *   Z       =  FLUID COMPRESSIBILITY FACTOR (Z=1)                   *
C       *********************************************************************


        CHARACTER*10 REGIME(3), REG(3)

        COMMON/DATA1/ D, RE, FD
        COMMON/DATA2/ RHO, DELP
        COMMON/DATA3/ VG, VS, MACH, MACR, PC
        COMMON/DATA4/ KF, KP, KTOTAL
        COMMON/DATA5/ REG, REGIME, IR

        REAL ID, LST, KF, KP, MW, MACH, MACR, KTOTAL

C       FLOW PATTERNS IN COMPRESSIBLE FLOW IN A PIPE (Subsonic, Sonic
C       Supersonic).


        DATA REG/'SUBSONIC  ', 'SONIC     ', 'SUPERSONIC'/
```

```
C       OPEN THE DATA FILE.

        OPEN (UNIT = 3, FILE = 'DATA34.DAT', STATUS = 'OLD', ERR = 18)

C       OPEN FILE FOR PRINTING THE RESULTS.

        OPEN (UNIT = 1, FILE = 'PRN')


        WRITE (1, 100)
 100    FORMAT (///,10X,'COMPRESSIBLE FLUID FLOW CALCULATIONS IN A',\)
        WRITE (1, 110)
 110    FORMAT (' PIPE LINE',/78(1H*))

C       READ IN THE DATA

C       READ THE PIPE INSIDE DIAMETER, inch: ID
C       READ THE STRAIGHT LENGTH OF PIPE, ft: LST
C       READ THE FLUID FLOW RATE, lb/hr.: W
C       READ THE RESISTANCE COEFF. DUE TO PIPE FITTINGS (e.g. BENDS,
C       VALVES, ENTRANCE AND EXIT LOSSES): KF
C       READ THE FLUID VISCOSITY, cP: VIS
C       READ THE FLUID COMPRESSIBILITY FACTOR: Z
C       READ THE FLUID TEMPERATURE, oF: T
C       READ THE FLUID MOLECULAR WEIGHT: MW
C       READ THE PIPE ROUGHNESS, ft: PR1
C       READ THE RATIO OF SPECIFIC HEAT CAPACITIES, Cp/Cv: RATIOK
C       READ THE FLUID INLET PRESSURE, psia: P1

        READ (3, *, ERR=19) ID, LST, W, KF
        READ (3, *, ERR=19) VIS, Z, T, MW
        READ (3, *, ERR=19) PR1, RATIOK, P1

        GO TO 20

 18     WRITE (*, 120)
 120    FORMAT (5X, 'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 130)
 130    FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999


C       THIS CALLS FOR THE PRESSURE DROP CALCULATION

 20     CALL CALC2 (ID, LST, W, VIS, Z, T, MW, PR1, RATIOK, P1, P2)

C       THIS CALLS FOR THE RESULTS TO BE PRINTED.

        CALL OUT2 (ID, LST, W, Z, T, MW, RATIOK, VIS, PR1, P1, P2)

        CLOSE (3, STATUS = 'KEEP')
        CLOSE (1)

 999    STOP
        END

C
```

```
C     *******************************************************************
C     THIS PROGRAM CALCULATES THE PRESSURE DROP OF A COMPRESSIBLE FLUID
C     FOR A GIVEN FLOW RATE AND FLUID SYSTEM CHARACTERISTICS.
C     *******************************************************************

      SUBROUTINE CALC2 (ID, LST, W, VIS, Z, T, MW, PR1, RATIOK,
     *                  P1, P2)

      CHARACTER*10, REGIME(3), REG(3)

      COMMON/DATA1/ D, RE, FD
      COMMON/DATA2/ RHO, DELP
      COMMON/DATA3/ VG, VS, MACH, MACR, PC
      COMMON/DATA4/ KF, KP, KTOTAL
      COMMON/DATA5/ REG, REGIME, IR

      REAL ID, LST, KF, KP, KTOTAL, MW, MACH, MACR

      PR = 0.00015
      T = T + 460.0
      PI = 3.1415927

C     CALCULATE THE PIPE AREA, ft^2.

      D = ID/12.0
      AREA = (PI*D*D)/4.0

C     CALCULATE THE INLET FLUID DENSITY, lb/ft^3.

      RHO = (P1*MW)/(10.72*T*Z)


C     CHECK WHETHER THE PIPE ROUGHNESS IS FOR CARBON STEEL
C     i.e. PR = 0.00015ft

      IF (PR .NE. PR1) THEN
      PR = PR1
      ENDIF

C     CALCULATE THE FLUID'S REYNOLDS NUMBER

      RE = (6.31*W)/(ID*VIS)
      IF (RE .GT. 2000.0) THEN
      A1 = ((PR/D)/3.7+(6.7/RE)**0.9)
      B1 = -4.0*ALOG10((PR/(3.7*D))-(5.02/RE)*ALOG10(A1))
      FD = 4.0/B1**2
      ELSE
      FD = 64.0/RE
      ENDIF

C     CALCULATE THE RESISTANCE COEFFICIENT DUE TO PIPE FRICTION

      KP = (FD*LST)/D

C     CALCULATE THE TOTAL RESISTANCE COEFFICIENT
C     (i.e. FRICTIONAL LOSS + PIPE FLTTINGS)

      KTOTAL = KP + KF

C     CALCULATE THE OUTLET PRESSURE OF THE FLUID, psia.
```

```
C
        C1 = 1335.6*(ID**2)
        C2 = (W**2*P1*KTOTAL)/(C1**2*RHO)
        P2 = SQRT(P1**2-C2)

C       CALCULATE THE PRESSURE DROP, psi.

        DELP = P1 - P2

C       CALCULATE THE FLUID VELOCITY, ft/sec.
C
        VG = (0.0509*W)/(RHO*ID**2)
C
C       CALCULATE THE SONIC VELOCITY, ft/sec.

        VS = 223.0*SQRT((RATIOK*T)/MW)

C       CALCULATE THE INLET MACH NUMBER

        MACH = VG/VS

C       CALCULATE THE EXIT MACH NUMBER FOR ISOTHERMAL FLOW
C       i.e. THE MACH NUMBER AT CRITICAL (CHOKING) CONDITION.

        MACR = 1.0/SQRT(RATIOK)

C       CHECK WHETHER FLUID FLOW IS SUBSONIC, SONIC OR SUPERSONIC

        IF (MACH .LT. MACR) THEN
                IR = 1
                REGIME(IR)=REG(IR)
        GO TO 10
                    ELSEIF (MACH .EQ. MACR) THEN
                    IR = 2
                    REGIME(IR)=REG(2)
                    GO TO 10
                        ELSEIF (MACH .GT. MACR) THEN
                        IR = 3
                        REGIME(IR)=REG(3)
        ENDIF


C       CALCULATE THE CRITICAL PRESSURE AT SONIC CONDITION
C       USING CROCKER'S EQUATION, psia.

 10     SG = MW/29.0
        R = 1544.0/(29.0*SG)
        PC = (W/(11400.0*ID**2))*SQRT((R*T)/(RATIOK*(RATIOK+1.0)))

        T = T - 460.0

        RETURN
        END

C       ***************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF THE MAXIMUM COMPRESSIBLE
C       FLUID FLOW ONTO A PRINTER.
C       ***************************************************************

        SUBROUTINE OUT2 (ID, LST, W, Z, T, MW, RATIOK, VIS, PR1, P1, P2)
```

```
        CHARACTER*10, REGIME(3), REG(3)

        COMMON/DATA1/ D, RE, FD
        COMMON/DATA2/ RHO, DELP
        COMMON/DATA3/ VG, VS, MACH, MACR, PC
        COMMON/DATA4/ KF, KP, KTOTAL
        COMMON/DATA5/ REG, REGIME, IR

        REAL ID, LST, MW, KF, KP, KTOTAL, MACH, MACR

        WRITE (1, 140) ID, LST, W, RHO, VIS, PR1, Z, T, MW, RATIOK
 140    FORMAT (5X,'PIPE INTERNAL DIAMETER, inch:', T60, F8.3,/,
     1          5X,'STRAIGHT LENGTH OF PIPE, ft.:', T60, F8.3,/,
     2          5X,'FLUID FLOWRATE, lb/h.:', T60, F10.2,/,
     3          5X,'FLUID DENSITY, lb/ft^3:', T60, F8.3,/,
     4          5X,'FLUID VISCOSITY, cP:', T60, F8.4,/,
     5          5X,'PIPE ROUGHNESS, ft.:', T60, F8.3,/,
     6          5X'FLUID COMPRESSIBILITY FACTOR:', T60, F8.4,/,
     7          5X,'FLUID TEMPERATURE, oF:', T60, F8.3,/,
     8          5X,'FLUID MOLECULAR WEIGHT, Mw:', T60, F8.3,/,
     9          5X,'RATIO OF SPECIFIC HEAT CAPACITIES, Cp/Cv:',T60,F8.3)


        WRITE (1, 150) KP, KF, KTOTAL
 150    FORMAT (5X,'RESISTANCE COEFF. DUE TO FRICTIONAL LOSS:',T60,
     1       F8.3,/,5X,'RESISTANCE COEFF. DUE TO FITTINGS + VALVES:',
     2       T60, F8.3,/,5X,'TOTAL RESISTANCE COEFFICIENT:', T60, F8.3)

        WRITE (1, 160) P1, P2, DELP
 160    FORMAT (5X,'INLET FLUID PRESSURE, psia:', T60, F9.3,/,
     1         5X,'OUTLET FLUID PRESSURE, psia:', T60, F9.3,/,
     2         5X,'PRESSURE DROP, psi:', T60, F9.3)

        WRITE (1, 170) VG, VS, MACH, MACR
 170    FORMAT (5X,'FLUID VELOCITY, ft/sec.:', T60, F9.3,/,
     1         5X,'FLUID SONIC VELOCITY, ft/sec.:', T60, F9.3,/,
     2         5X,'MACH MUMBER AT INLET:', T60, F8.4,/,
     3         5X,'MACH NUMBER AT CRITICAL CONDITION:', T60, F8.4)

        WRITE (1, 180) FD, RE
 180    FORMAT (5X,'DARCY FRICTION FACTOR:',T60, F8.4,/,
     *          5X,'REYNOLDS NUMBER:', T60, F10.0)


        WRITE (1, 190) PC, VIS
 190    FORMAT (5X,'CRITICAL PRESSURE, psia:', T60, F9.3,/,
     1         5X,'FLUID VISCOSITY, cP:', T60, F8.4)

        WRITE (1, 200) REGIME(IR)
 200    FORMAT (5X, 'FLUID FLOW IS:', T60, A10)

        WRITE (1, 210)
 210    FORMAT (78(1H-))

C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
      PROGRAM PROG35


C     ***********************************************************************
C     *THIS PROGRAM USES THE GENERAL METHOD OF LOCKHART AND MARTINELLI      *
C     *COUPLED WITH OVID BAKER'S TWO-PHASE FLOW CORRELATIONS TO DETERMINE  *
C     *THE TWO-PHASE PRESSURE DROP IN PROCESS PIPE LINES.  THE PROGRAM     *
C     *ASSUMES THAT THE TWO-PHASE FLOW IS ISOTHERMAL AND TURBULENT IN BOTH *
C     *LIQUID AND VAPOR PHASES, AND THAT THE PRESSURE LOSS IS NOT MORE     *
C     *THAN 10 PER CENT OF THE ABSOLUTE UPSTREAM PRESSURE.                 *
C     *THE PROGRAM USES THE EXPLICIT EQUATIONS FOR FRICTION FACTOR         *
C     *DEVELOPED BY CHEN.  IN ADDITION, THE PROGRAM DETERMINES WHETHER     *
C     *EROSION AND CORROSION IN THE PIPE MAY OCCUR.                        *
C     ***********************************************************************

C     ***********************************************************************
C     *                           NOMENCLATURE                              *
C     *                           ------------                              *
C     *                                                                     *
C     * RE     =  REYNOLDS NUMBER                                           *
C     * Wx     =  LIQUID OR GAS FLOW, lb/h.                                 *
C     * ID     =  PIPE INSIDE DIAMETER, inch.                               *
C     * VIS    =  VISCOSITY OF LIQUID OR GAS, cP.                           *
C     * FF     =  FRICTION FACTOR                                           *
C     * DELTP  =  PRESSURE DROP OF LIQUID OR GAS IF FLOWING IN THE PIPE     *
C     *           ALONE, psi/100 ft.                                        *
C     * DEN    =  DENSITY OF LIQUID OR GAS, lb/ft^3.                        *
C     * PR     =  PIPE ROUGHNESS, ft.                                       *
C     * VEL    =  VELOCITY OF FLUID IN PIPE, ft/s.                          *
C     * DENG   =  GAS DENSITY, lb/ft^3.                                     *
C     * DENL   =  LIQUID DENSITY, lb/ft^3.                                  *
C     * WG     =  GAS FLOW, lb/h.                                           *
C     * WL     =  LIQUID FLOW, lb/h.                                        *
C     * A      =  CROSS-SECTIONAL AREA OF PIPE, ft^2.                       *
C     * VISL   =  VISCOSITY OF LIQUID, cP.                                  *
C     * VISG   =  VISCOSITY OF VAPOUR, cP.                                  *
C     * ST     =  SURFACE TENSION OF LIQUID, dyne/cm.                       *
C     * A0-A3  =  CONSTANTS FOR TWO-PHASE MODULUS EQUATION                  *
C     * Hx     =  HUNTINGTON CORRELATION                                    *
C     * FH     =  HUNTINGTON FRICTION FACTOR                                *
C     * XD     =  DAVIS TWO-PHASE CORRELATION=X IN DISPERSED FLOW EQUATION  *
C     * P      =  PARACHOR FOR HYDROCARBON                                  *
C     * MW     =  MOLECULAR WEIGHT OF HYDROCARBON                           *
C     * BX     =  BAKER'S PARAMETER IN THE LIQUID-PHASE                     *
C     * BY     =  BAKER'S PARAMETER IN THE VAPOR-PHASE                      *
C     * PR     =  ABSOLUTE ROUGHNESS OF PIPE WALL, ft.                      *
C     * K      =  VELOCITY HEAD TO DUE PIPE FITTINGS.                       *
C     * YG     =  TWOPHASE FLOW MODULUS.                                    *
C     ***********************************************************************

      CHARACTER*10 REGIME(7),REG(7)

      COMMON/OVID1/ WL, VISL, DENL, ST
      COMMON/OVID2/ WG, VISG, DENG
      COMMON/OVID3/ ID, D, PR
      COMMON/OVID4/ DPST
      COMMON/OVID5/ DPW
      COMMON/OVID6/ DPP
      COMMON/OVID7/ DPSL
```

```
      COMMON/OVID8/ DPB
      COMMON/OVID9/ DPAN
      COMMON/OVID10/ DPD
      COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
      COMMON/OVID12/ X, VEL
      COMMON/OVID13/ BX, BY
      COMMON/OVID14/ REL, LFF, REGG, GFF
      COMMON/OVID15/ REG
      COMMON/OVID16/ LEQ, LST, L
      COMMON AREA
      REAL ID, L, LEQ, LFF, LST, K


C     THE FLOW REGIMES FOR TWO-PHASE FLOWS ARE:
C     Stratified, Wave, Plug, Slug, Bubble, Annular, Dispersed

      DATA REG /'STRATIFIED', 'WAVE      ', 'PLUG      ', 'SLUG      ',
     * 'BUBBLE    ', 'ANNULAR   ', 'DISPERSED '/


C     *****************************************************************


C     OPEN THE DATA FILE.

      OPEN (UNIT = 3, FILE = 'DATA35.DAT', STATUS = 'OLD', ERR = 18)

C     OPEN FILE FOR PRINTING THE RESULTS.

      OPEN (UNIT = 1, FILE = 'PRN')


      WRITE (1, 100)
 100  FORMAT (///,10X,'TWO-PHASE PRESSURE LOSS CALCULATION IN A',\)
      WRITE (1, 110)
 110  FORMAT (' PIPE LINE', /78(1H*))


C     READ IN THE DATA IN DATAFILE

C     READ THE PIPE INSIDE DIAMETER, inch: ID
C     READ THE STRAIGHT LENGTH OF PIPE, ft.: LST
C     READ THE LIQUID FLOW RATE, lb/hr.: WL
C     READ THE LIQUID VISCOSITY, cP: VISL
C     READ THE LIQUID DENSITY, lb/ft^3.: DENL
C     READ THE LIQUID SURFACE TENSION, dyne/cm.: ST
C     READ THE GAS FLOW RATE, lb/hr.: WG.
C     READ THE GAS VISCOSITY, cP: VISG.
C     READ THE GAS DENSITY, lb/ft^3.:
C     READ THE PIPE ROUGHNESS, ft.: PR1
C     READ THE VELOCITY HEAD DUE TO PIPE FITTINGS (e.g. bends, valves
C     otherwise give the default value of zero): K


      READ (3, *, ERR=19) ID, LST, WL, VISL
      READ (3, *, ERR=19) DENL, ST, WG, VISG
      READ (3, *, ERR=19) DENG, PR1, K

      GO TO 20
```

```
 18       WRITE (*, 120)
 120      FORMAT (5X, 'DATA FILE DOES NOT EXIST')
          GO TO 1000

 19       WRITE (*, 130)
 130      FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
          GO TO 1000

 20       LEQ = 0.0
          FACTOR = 0.0
          PR = 0.00015
          PI = 3.1415927


C         CALCULATE THE PIPE AREA, ft^2.

          D = ID/12.0
          AREA = (PI*D*D)/4.0

C         CHECK WHETHER THE PIPE ROUGHNESS IS CARBON STEEL (i.e. PR=0.00015 ft)

          IF (PR .NE. PR1) THEN
          PR = PR1
          ENDIF


C         DETERMINE THE FLOW REGIME FROM THE BAKER MAP

          CALL BAKER

C         CALCULATE THE EQUIVALENT LENGTH OF PIPE DUE TO FITTINGS, ft.

          LEQ = (K*D)/LFF

C         CALCULATE THE TOTAL LENGTH OF PIPE, ft.

          L = LST + LEQ

C         *****************************************************************
C         *   CONSIDER WHETHER PIPE EROSION/CORROSION MAY OCCUR           *
C         *****************************************************************

C         CALCULATE THE SUPERFICIAL LIQUID AND GAS VELOCITIES, ft/sec.

          UL = WL/(DENL*AREA*3600.0)
          UG = WG/(DENG*AREA*3600.0)

C         CALCULATE VELOCITY OF THE MIXTURE

          UM = UL + UG

C         CALCULATE DENSITY OF THE MIXTURE

          DENM = (WL + WG)/((WL/DENL) +(WG/DENG))

C         CALCULATE THE INDEX FOR EROSION

          FACTOR = FACTOR + DENM*(UM**2)
C
```

```
      C1 = 17578.98/(BX**0.6548)

      IF (BY .GT. C1) THEN
              GO TO 30
      ELSE

      C2 = 5866.07/(BX**0.1901)

      ENDIF
      IF (BY .GT. C2) THEN
            GO TO 35
      ENDIF

C     ****************************************************************
C     USING THE REGIME FOR STRATIFIED FLOW, DETERMINE THE TWO-PHASE
C     MODULUS

      CALL STRAT (YG, REGIME, IR)

            GO TO 999

C     USING THE REGIME FOR WAVE FLOW, DETERMINE THE TWO-PHASE MODULUS

   35 CALL WAVE (YG, REGIME, IR)

      GO TO 999

   30 C5 = 2126105.0/(BX**1.0173)

      IF (BY .GT. C5) THEN
            GO TO 40
      ELSE

      C6 = 2491.41/(BX**0.2189)

      ENDIF
      IF (BY .GT. C6) THEN
            GO TO 41
      ENDIF

C     USING THE REGIME FOR PLUG FLOW, DETERMINE THE TWO-PHASE FLOW
C     MODULUS.

      CALL PLUG (YG, REGIME, IR)
            GO TO 999

   41 C4 = 10.7448-(1.6265*ALOG(BX))+(0.2839*(ALOG(BX))**2)
      C4 = EXP(C4)
      IF (BY .GT. C4) THEN
      GO TO 45
      ELSE
      ENDIF

C     USING THE REGIME FOR SLUG FLOW, DETERMINE THE TWO-PHASE FLOW
C     MODULUS.

      CALL SLUG (YG, REGIME, IR)
              GO TO 999

   40 IF (BX .GT. 150.0) THEN
```

```
      GO TO 50
      ELSE
            GO TO 45
      ENDIF

C     USING THE REGIME FOR BUBBLE FLOW, DETERMINE THE TWO-PHASE FLOW
C     MODULUS.

   50 CALL BUBBLE (YG, REGIME, IR)
      GO TO 999

   45 C3 = 11.3976-(0.6084*ALOG(BX))+(0.0779*(ALOG(BX))**2)
      C3 = EXP(C3)

      IF (BY .GT. C3) THEN
            GO TO 55
      ELSE
      ENDIF

C     USING THE REGIME FOR ANNULUS FLOW, DETERMINE THE TWO-PHASE FLOW
C     MODULUS.

      CALL ANNUL (YG, REGIME, IR)
            GO TO 999


C     USING THE REGIME FOR DISPERSED FLOW, DETERMINE THE TWO-PHASE FLOW
C     MODULUS.

   55 CALL DISPER (YG, REGIME, IR)

  999 CALL OUTPUT (WL, REL, LFF, DELTPL, WG, REGG, GFF, DELTPG, BX,
     *             BY, YG, FACTOR, IR, REGIME, DELTP, DELTPT)

      CLOSE (3, STATUS = 'KEEP')
      CLOSE (1)

 1000 STOP
      END

C     ******************************************************************
C     THIS PROGRAM USES THE SEMI-EMPIRICAL METHOD OF LOCKHART-
C     MARTINELLI FOR CALCULATING THE PRESSURE DROP OF EITHER THE LIQUID
C     OR THE GAS PHASE FLOW IN A PIPELINE
C     ******************************************************************

      SUBROUTINE BAKER

      COMMON/OVID1/ WL, VISL, DENL, ST
      COMMON/OVID2/ WG, VISG, DENG
      COMMON/OVID3/ ID, D, PR
      COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
      COMMON/OVID12/ X, VEL
      COMMON/OVID13/ BX, BY
      COMMON/OVID14/ REL, LFF, REGG, GFF
      COMMON/OVID16/ LEQ, LST, L
      COMMON AREA

      REAL ID, L, LEQ, LST, LFF
```

```
C       CALCULATE THE LIQUID REYNOLDS NUMBER THROUGH PIPE AND THE
C       FRICTION FACTOR OF THE PIPE.

        REL = (6.31*WL)/(ID*VISL)

        IF (REL .LE. 2100.0) THEN
              GO TO 20
        ELSE
        A1 = ((PR/D)/3.7+(6.7/REL)**0.9)
        B1 = -4.0*ALOG10((PR/(3.7*D))-(5.02/REL)*ALOG10(A1))
        LFF = 4.0/B1**2
        ENDIF

        GO TO 30

   20   LFF = 64.0/REL

C       CALCULATE LIQUID PRESSURE DROP OF THE PIPE

   30   DELTPL = (0.000366*LFF*(WL**2))/((ID**5)*DENL)

C       *******************************************************************
C       CALCULATE THE GAS REYNOLDS NUMBER THROUGH PIPE AND THE FRICTION
C       FACTOR OF THE PIPE.
C       *******************************************************************

        REGG = (6.31*WG)/(ID*VISG)

        IF ( REGG .LE. 2100.0) THEN
              GO TO 50
        ELSE
        A2 = ((PR/D)/3.7+(6.7/REGG)**0.9)
        B2 = -4.0*ALOG10((PR/(3.7*D))-(5.02/REGG)*ALOG10(A1))
        GFF = 4.0/B2**2
        ENDIF
        GO TO 60

   50   GFF = 64.0/REGG

C       CALCULATE THE GAS PRESSURE DROP OF THE PIPE

   60   DELTPG = (0.000366*GFF*(WG**2))/((ID**5)*DENG)

C       *******************************************************************
C       LOCKHART-MARTINELLI TWO-PHASE FLOW MODULUS
C       *******************************************************************

        X = SQRT(DELTPL/DELTPG)

C       CALCULATE THE VELOCITY OF THE TWO-PHASE MIXTURE IN THE PIPE

        VEL = (0.0509/(ID**2))*((WG/DENG)+(WL/DENL))

C       *******************************************************************
C       CALCULATE BAKER'S PARAMETERS, BX AND BY
C       *******************************************************************

        VAL3 = SQRT(DENL*DENG)/(DENL**(2./3.))
        VAL4 = (VISL**(1./3.))/ST
        BX = 531.0*(WL/WG)*VAL3*VAL4
```

```
        BY = 2.16*(WG/AREA)/SQRT(DENL*DENG)

        RETURN
        END

C       ******************************************************************
C       THIS PROGRAM CALCULATES THE TWO PHASE FLOW MODULUS AND PRESSURE
C       DROPS FOR STRATIFIED FLOW REGIME
C       ******************************************************************

        SUBROUTINE STRAT (YGST, REGIME, IR)

        CHARACTER*10 REGIME(7),REG(7)
        COMMON/OVID1/ WL, VISL, DENL, ST
        COMMON/OVID4/ DPST
        COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
        COMMON/OVID12/ X, VEL
        COMMON/OVID15/ REG
        COMMON/OVID16/ LEQ, LST, L
        COMMON AREA

        REAL LEQ, LST, L

        IR = 1
        VAL5 = 15400.0*X
        VAL6 = (WL/AREA)**0.8
        YGST = (VAL5/VAL6)**2
        DPST = DELTPG*YGST
        DELTP = DPST
        DELTPT = DELTP*L/100.0
        REGIME(IR) = REG(1)

        RETURN
        END

C       *****************************************************************
C       THIS PROGRAM CALCULATES THE TWO PHASE FLOW MODULUS AND PRESSURE
C       DROPS FOR WAVE FLOW REGIME.
C       *****************************************************************

        SUBROUTINE WAVE (YGW, REGIME, IR)

        CHARACTER*10 REGIME(7),REG(7)
        COMMON/OVID1/ WL, VISL, DENL, ST
        COMMON/OVID2/ WG, VISG, DENG
        COMMON/OVID3/ ID, D, PR
        COMMON/OVID5/ DPW
        COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
        COMMON/OVID15/ REG
        COMMON/OVID16/ LEQ, LST, L
        COMMON AREA,FH

        REAL ID, LEQ, LST, L

        IR = 2
        HX = (WL/WG)*(VISL/VISG)
        VAL7 = (0.2111*ALOG(HX))-3.993
        FH = EXP(VAL7)
        DPW = (0.000366*FH*(WG**2))/((ID**5)*DENG)
        YGW = 0.0
```

```
      DELTP = DPW
      DELTPT = DELTP*L/100.0
      REGIME(IR) = REG(2)

      RETURN
      END

C     ******************************************************************
C     THIS PROGRAM CALCULATES THE TWO PHASE FLOW MODULUS AND PRESSURE
C     DROPS FOR PLUG FLOW REGIME.
C     ******************************************************************

      SUBROUTINE PLUG (YGP, REGIME, IR)
      CHARACTER*10 REGIME(7),REG(7)

      COMMON/OVID1/ WL, VISL, DENL, ST
      COMMON/OVID6/ DPP
      COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
      COMMON/OVID12/ X, VEL
      COMMON/OVID15/ REG
      COMMON/OVID16/ LEQ, LST, L
      COMMON AREA

      REAL LEQ, LST, L

      IR = 3
      VAL8 = 27.315*(X)**0.855
      VAL9 = (WL/AREA)**0.17
      YGP = (VAL8/VAL9)**2
      DPP = DELTPG*YGP
      DELTP = DPP
      DELTPT = DELTP*L/100.0
      REGIME(IR) = REG(3)

      RETURN
      END

C     ******************************************************************
C     THIS PROGRAM CALCULATES THE TWO PHASE FLOW MODULUS AND PRESSURE
C     DROPS FOR SLUG FLOW REGIME.
C     ******************************************************************

      SUBROUTINE SLUG (YGSL, REGIME, IR)

      CHARACTER*10 REGIME(7),REG(7)
      COMMON/OVID1/ WL, VISL, DENL, ST
      COMMON/OVID7/ DPSL
      COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
      COMMON/OVID12/ X, VEL
      COMMON/OVID15/ REG
      COMMON/OVID16/ LEQ, LST, L
      COMMON AREA

      REAL LEQ, LST, L

      IR = 4
      VAL10 = 1190.0*(X)**0.815
      VAL11 = (WL/AREA)**0.5
      YGSL = (VAL10/VAL11)**2
      DPSL = DELTPG*YGSL
```

```
        DELTP = DPSL
        DELTPT = DELTP*L/100.0
        REGIME(IR) = REG(4)

        RETURN
        END

C       *****************************************************************
C       THIS PROGRAM CALCULATES THE TWO PHASE FLOW MODULUS AND PRESSURE
C       DROPS FOR BUBBLE FLOW REGIME.
C       *****************************************************************

        SUBROUTINE BUBBLE (YGB, REGIME, IR)
        CHARACTER*10 REGIME(7),REG(7)
        COMMON/OVID1/ WL, VISL, DENL, ST
        COMMON/OVID8/ DPB
        COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
        COMMON/OVID12/ X, VEL
        COMMON/OVID15/ REG
        COMMON/OVID16/ LEQ, LST, L
        COMMON AREA

        REAL LEQ, LST, L

        IR = 5
        VAL12 = 14.2*(X**0.75)
        VAL13 = (WL/AREA)**0.1
        YGB = (VAL12/VAL13)**2
        DPB = DELTPG*YGB
        DELTP = DPB
        DELTPT = DELTP*L/100.0
        REGIME(IR) = REG(5)

        RETURN
        END

C       ******************************************************************
C       THIS PROGRAM CALCULATES THE TWO PHASE FLOW MODULUS AND PRESSURE
C       DROPS FOR ANNULAR FLOW REGIME.
C       *****************************************************************

        SUBROUTINE ANNUL (YGAN, REGIME, IR)

        CHARACTER*10 REGIME(7),REG(7)
        COMMON/OVID3/ ID, D, PR
        COMMON/OVID9/ DPAN
        COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
        COMMON/OVID12/ X, VEL
        COMMON/OVID15/ REG
        COMMON/OVID16/ LEQ, LST, L

        REAL ID, LEQ, LST, L

        IR = 6
        IF (ID .GT. 12.0) THEN
              GO TO 5
        ELSE
         C1 = 4.8-0.3125*ID
                 C2 = 0.343-0.021*ID
```

```
        ENDIF
        GO TO 15

    5   D = 10.0
        C1 = 4.8-0.3125*D
        C2 = 0.343-0.021*D

   15   VAL14 = C1*(X**C2)
        YGAN = VAL14**2
        DPAN = DELTPG*YGAN
        DELTP = DPAN
        DELTPT = DELTP*L/100.0
        REGIME(IR) = REG(6)

        RETURN
        END


C       ******************************************************************
C       THIS PROGRAM CALCULATES THE TWO PHASE FLOW MODULUS AND PRESSURE
C       DROPS FOR DISPERSED FLOW REGIME.
C       ******************************************************************

        SUBROUTINE DISPER (YGD, REGIME, IR)

        CHARACTER*10 REGIME(7),REG(7)
        COMMON/OVID10/ DPD
        COMMON/OVID11/ DELTPL, DELTPG, DELTP, DELTPT
        COMMON/OVID12/ X, VEL
        COMMON/OVID15/ REG
        COMMON/OVID16/ LEQ, LST, L

        REAL LEQ, LST, L

        IR = 7
        A0 = 1.4659
        A1 = 0.4914
        A2 = 0.0489
        A3 = -0.0003487
        VAL15 = A0+A1*ALOG(X)+A2*(ALOG(X))**2+A3*(ALOG(X))**3
        YGD = (EXP(VAL15))**2
        DPD = DELTPG*YGD
        DELTP = DPD
        DELTPT = DELTP*L/100.0
        REGIME(IR) = REG(7)

        RETURN
        END

C       ******************************************************************
C       *  THIS PROGRAM PRINTS THE RESULTS OF THE TWO-PHASE FLOW         *
C       ******************************************************************

        SUBROUTINE OUTPUT (WL, REL, LFF, DELTPL, WG, REGG, GFF, DELTPG,
     1  BX, BY, YG, FACTOR, IR, REGIME, DELTP, DELTPT)

        CHARACTER*10 REGIME(7), REG(7)
        COMMON/OVID3/ ID, D, PR
        COMMON/OVID12/ X, VEL
        COMMON/OVID15/ REG
```

```
      COMMON/OVID16/ LEQ, LST, L
      COMMON FH

      REAL ID, LEQ, LST, L, LFF

      WRITE (1, 140) ID, LEQ, LST, L
140   FORMAT (5X,'PIPE INTERNAL DIAMETER, inch:', T60, F9.3,/,
     1        5X,'EQUIVALENT LENGTH OF PIPE, ft.:', T60, F9.3,/,
     2        5X,'ACTUAL LENGTH OF PIPE, ft.:', T60, F9.3,/,
     3        5X,'TOTAL LENGTH OF PIPE, ft.:', T60, F9.3)

      WRITE (1, 150) WL, REL, LFF, DELTPL
150   FORMAT (5X,'LIQUID FLOWRATE, lb/hr.:', T60, F12.3,/,
     1        5X,'LIQUID REYNOLDS NUMBER:', T60, F12.0,/,
     2        5X,'LIQUID FRICTION FACTOR:', T60, F8.4,/,
     3        5X,'PRESSURE DROP OF LIQUID,  psi/100ft.:', T60,F8.4)

      WRITE (1, 160) WG, REGG, GFF, DELTPG
160   FORMAT (5X,'GAS FLOW RATE, lb/hr.:', T60, F12.3,/,
     1         5X,'GAS REYNOLDS NUMBER:', T60, F12.0,/,
     2         5X,'GAS FRICTION FACTOR:', T60, F8.4,/,
     3         5X,'PRESSURE DROP OF GAS, psi/100ft.:', T60, F8.4)

      WRITE (1, 170) REGIME(IR)
170   FORMAT (5X,'FLOW REGIME IS:',T60, A)

      WRITE (1, 180) X
180   FORMAT (5X,'LOCKHART-MARTINELLI TWO PHASE FLOW MODULUS:',
     *       T60,F8.4)

      WRITE (1, 190) VEL, BX, BY
190   FORMAT (5X,'VELOCITY OF FLUID IN PIPE, ft./sec.:', T60, F8.3,/,
     1         5X,'BAKER PARAMETER IN THE LIQUID PHASE:', T60, F12.3,/,
     2         5X,'BAKER PARAMETER IN THE GAS PHASE:', T60, F12.3)

      IF (YG .EQ. 0.0) THEN

      WRITE (1, 200) FH
200   FORMAT (5X,'HUNTINGTON FRICTION FACTOR:', T60, F8.4)

      ELSE

      WRITE (1, 210) YG
210   FORMAT (5X,'TWO-PHASE FLOW MODULUS:', T60, F8.4)
      ENDIF

      WRITE (1, 220) DELTP, DELTPT
220   FORMAT (5X,'PRESSURE DROP OF TWO-PHASE MIXTURE, psi/100ft:',
     1     T60, F8.4,/,
     2     5X,'OVERALL PRESSURE DROP OF THE TWO-PHASE MIXTURE, psi:',
     3       T60, F8.4)


      IF (FACTOR .GT. 10000.0) THEN

      WRITE (1, 230) FACTOR
230   FORMAT (5X,'INDEX', 1X, F10.0, '  IS GREATER THAN 10000',\)

      WRITE (1, 240)
240   FORMAT ('  PIPE EROSION IS POSSIBLE')
```

```
      ELSE

      WRITE (1, 250) FACTOR
 250  FORMAT (5X,'INDEX',1X, F10.0, '  IS LESS THAN 10000'\)

      WRITE (1, 260)
 260  FORMAT ('  PIPE EROSION IS UNLIKELY')
      ENDIF

      WRITE (1, 270)
 270  FORMAT (78(1H-))

C     FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)

      RETURN
      END
```

```
        PROGRAM PROG36


C       ****************************************************************
C       THIS PROGRAM WILL CALCULATE THE FROUDE NUMBERS OF VAPOR-LIQUID
C       TWO-PHASE VERTICAL PIPE.  IT FURTHER PRINTS OUT A MESSAGE IF
C       THE PIPE IS SELF-VENTING, IF PULSATION FLOW OCCURS, OR IF NO
C       PRESSURE GRADIENT IS NEEDED.
C       ****************************************************************
C
C       AREA    =   INSIDE CROSS-SECTIONAL AREA OF PIPE, ft^2.
C       D       =   INSIDE DIAMETER OF PIPE, inch.
C       FRNL    =   FROUDE NUMBER FOR LIQUID PHASE
C       FRNG    =   FROUDE NUMBER FOR GAS PHASE
C       G       =   GRAVITATIONAL CONSTANT (32.2 ft/s^2)
C       DENL    =   LIQUID DENSITY, lb/ft^3
C       VL      =   LIQUID VELOCITY, ft/s.
C       VG      =   VAPOR VELOCITY,  ft/s.
C       WL      =   LIQUID FLOWRATE, lb/h.
C       WG      =   VAPOR FLOWRATE, lb/h.
C       ****************************************************************

C       OPEN FILES TO READ THE DATA AND TO PRINT THE RESULTS

        PARAMETER (G = 32.2, PI = 3.1415927)


C       OPEN THE DATA FILE.

        OPEN (UNIT = 3, FILE = 'DATA36.DAT', STATUS = 'OLD', ERR = 18)

C       OPEN FILE FOR PRINTING THE RESULTS.

        OPEN (UNIT = 1, FILE = 'PRN')

        WRITE (1, 100)
 100    FORMAT (///,15X, 'VAPOR-LIQUID TWO-PHASE VERTICAL DOWNFLOW',/1H ,
     *         78(1H*))


C       READ THE INPUT DATA

C       READ THE PIPE INSIDE DIAMETER, inch: D
C       READ THE LIQUID FLOW RATE, lb/hr.: WL
C       READ THE LIQUID DENSITY, lb/ft^3: DENL
C       READ THE GAS FLOW RATE, lb/hr.: WG.
C       READ THE GAS DENSITY, lb/ft^3.: DENG.


        READ (3, *, ERR=19) D, WL, DENL
        READ (3, *, ERR=19) WG, DENG
        GO TO 10

 18     WRITE (*, 110)
 110    FORMAT (5X, 'DATA FILE DOES NOT EXIST')

        GO TO 999
```

```
  19    WRITE (*, 120)
  120   FORMAT (5X,'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

 10     D1 = D/12.
        AREA = (PI*D1**2)/4.0

        WRITE (1, 130) D
 130    FORMAT (10X, 'PIPE INTERNAL DIAMETER, inch:', T65, F8.3)


        WRITE (1, 140) WL, DENL
 140    FORMAT (10X, 'LIQUID FLOWRATE, lb/h.:', T65, F8.0, /, 10X,
     *          'LIQUID DENSITY, lb/ft^3:', T65, F8.3)

        WRITE (1, 150) WG, DENG
 150    FORMAT (10X, 'VAPOR FLOWRATE, lb/h.:', T65, F8.0, /, 10X,
     *          'VAPOR DENSITY, lb/ft^3:', T65, F8.3)

        WRITE (1, 160) AREA
 160    FORMAT (10X, 'PIPE AREA, ft^2:', T65, F8.3)

C       CALCULATE LIQUID AND VAPOR VELOCITIES

        VL = WL/(3600.0*DENL*AREA)
        VG = WG/(3600.0*DENG*AREA)

        WRITE (1, 170) VL, VG
 170    FORMAT (10X, 'LIQUID VELOCITY, ft/s:', T65, F8.3, /, 10X,
     *          'VAPOR VELOCITY, ft/s:', T65, F8.3)

C       CALCULATE THE LIQUID PHASE AND THE VAPOR PHASE FROUDE NUMBERS

        FRNL = (VL/((G*D1)**0.5))*(DENL/(DENL-DENG))**0.5
        FRNG = (VG/((G*D1)**0.5))*(DENG/(DENL-DENG))**0.5


        WRITE (1, 180) FRNL, FRNG
 180    FORMAT (10X, 'FROUDE NUMBER FOR LIQUID PHASE:', T65, F8.4, /,
     *      10X, 'FROUDE NUMBER FOR VAPOR PHASE:', T65, F8.4)

C       TEST FOR SELF-VENTING, PULSE FLOW OR NO PRESSURE GRADIENT.

        IF ( FRNL .LT. 0.31) THEN

        WRITE (1, 190)
 190    FORMAT (10X, 'LINE IS SELF-VENTING THEREFORE NO VIBRATION',\)

        WRITE (1, 200)
 200    FORMAT (' PROBLEMS ARE EXPECTED')
        ELSEIF ( FRNL .GE. 0.31 .AND. FRNL .LT. 1.0) THEN

        WRITE (1, 210)
 210    FORMAT (10X, 'FLOW IS PULSE AND THIS MAY RESULT IN PIPE'\,)

        WRITE (1, 220)
 220    FORMAT (' VIBRATION')
        ELSEIF ( FRNL .GT. 1.0) THEN

        WRITE (1, 230)
```

```
 230     FORMAT (10X, 'NO PRESSURE GRADIENT')
         ENDIF

         WRITE (1, 240)
 240     FORMAT (78(1H-))

C        FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

         WRITE (1, *) CHAR(12)


         CLOSE (3, STATUS = 'KEEP')
         CLOSE (1)

 999     STOP
         END
```

```
        PROGRAM PROG37


C       *******************************************************************
C       THIS PROGRAM CALCULATES LINE SIZES FOR FLASHING STEAM CONDENSATE.
C       THE PROGRAM WILL COMPUTE THE FOLLOWING:
C
C       1.  CALCULATES THE AMOUNT OF CONDENSATE FLASHED FOR ANY GIVEN
C           CONDENSATE HEADER PRESSURE FROM 15 TO 140 psia. AND INITIAL
C           STEAM PRESSURES MAY VARY BETWEEN 40 AND 165 psia.
C       2.  THE RETURN CONDENSATE HEADER TEMPERATURE.
C       3.  THE PRESSURE DROP (psi/100ft.) OF THE STEAM CONDENSATE
C           MIXTURE IN THE RETURN HEADER.
C       4.  THE VELOCITY OF THE STEAM CONDENSATE MIXTURE AND
C       5.  INDICATES A WARNING MESSAGE IF VELOCITY IS EQUAL TO OR
C           GREATER THAN 5000 ft/min.
C       ******************************************************************

C                           NOMENCLATURE.
C                           --------------

C       D       =       PIPE INTERNAL DIAMETER, inch.
C       DELTP   =       PRESSURE DROP OF FLASHED CONDENSATE MIXTURE,
C                       psi/100ft.
C       DENG    =       FLASHED STEAM DENSITY, lb/ft^3.
C       DENL    =       FLASHED CONDENSATE LIQUID DENSITY, lb/ft^3.
C       DENMIX  =       DENSITY OF MIXTURE (FLASHED CONDENSATE/STEAM)
C                       lb/ft^3.
C       FF      =       FRICTION FACTOR.
C       PC      =       STEAM CONDENSATE PRESSURE BEFORE FLASHING,  psia.
C       PH      =       FLASHED CONDENSATE HEADER PRESSURE, psia.
C       TFL     =       TEMPERATURE OF FLASHED CONDENSATE, oF.
C       VEL     =       VELOCITY OF FLASHED CONDENSATE MIXTURE, ft/min.
C       W       =       TOTAL FLOW OF MIXTURE IN CONDENSATE HEADER, lb/h.
C       WFRFL   =       WEIGHT FRACTION OF CONDENSATE FLASHED TO VAPOR.
C       WG      =       FLASHED STEAM FLOWRATE, lb/h.
C       WL      =       FLASHED CONDENSATE LIQUID FLOWRATE, lb/h.
C       ****************************************************************

C       OPEN FILES TO READ THE DATA AND TO PRINT THE RESULTS

        OPEN ( UNIT = 3, FILE = 'DATA37.DAT', STATUS = 'OLD', ERR = 18)

        OPEN (UNIT = 1, FILE = 'PRN')

        WRITE (1, 100)
 100    FORMAT (///, 15X, 'LINE SIZING FOR FLASHING STEAM CONDENSATE',/,
     *          78(1H*))


C       READ THE INPUT DATA

C       READ THE PIPE INTERNAL DIAMETER, inch: D
C       READ THE FLUID FLOW RATE, lb/hr.: W
C       READ THE CONDENSATE STEAM PRESSURE BEFORE FLASHING, psia.: PC
C       READ THE FLASHED CONDENSATE HEADER PRESSURE, psia.: PH
```

```
       READ (3, *, ERR=19) D, W
       READ (3, *, ERR=19) PC, PH

       GO TO 10

 18    WRITE (*, 110)
 110   FORMAT (10X, 'DATA FILE DOES NOT EXIST')

       GO TO 999

 19    WRITE (*, 120)
 120   FORMAT (10X, 'ERROR MESSAGE IN THE DATA VALUE')
       GO TO 999

 10    X = 6.122 - (16.919/ALOG(PH))
       A = 0.00671*(ALOG(PH))**2.27
       B = EXP(X)*(10**(-4)) + 0.0088


C      CALCULATE WEIGHT FRACTION OF CONDENSATE FLASHED TO VAPOR.

       WFRFL = B*(ALOG(PC))**2 - A

C      CALCULATE FLASHED STEAM FLOWRATE AND FLASHED STEAM
C      CONDENSATE LIQUID FLOWRATE, lb/h.

       WG = WFRFL*W

       WL = W - WG

       WRITE (1, 130) D, W
 130   FORMAT (10X, 'PIPE INTERNAL DIAMETER, inch:', T65, F8.3, /,
     * 10X,'TOTAL FLOW OF MIXTURE IN CONDENSATE HEADER, lb/h:',
     * T65, F8.0)

       WRITE (1, 140) PC, PH
 140   FORMAT (10X,'STEAM CONDENSATE PRESSURE BEFORE FLASHING, psia:',
     * T65, F8.3, /, 10X,'FLASHED CONDENSATE HEADER PRESSURE, psia:',
     * T65, F8.3)

       WRITE (1, 150) WFRFL
 150   FORMAT (10X,'WEIGHT FRACTION OF CONDENSATE FLASHED TO VAPOR:',
     * T65, F8.3)

       WRITE (1, 160) WG, WL
 160   FORMAT (10X, 'FLASHED STEAM FLOWRATE, lb/h.:', T65, F8.0,/,
     * 10X,'FLASHED CONDENSATE LIQUID FLOWRATE, lb/h.:', T65, F8.0)


C      CALCULATE THE TEMPERATURE OF FLASHED CONDENSATE.

       TFL = 115.68*(PH)**0.226

C      CALCULATE THE FLASHED STEAM DENSITY, FLASHED CONDENSATE LIQUID
C      DENSITY AND DENSITY OF MIXTURE (FLASHED CONDENSATE/STEAM) lb/ft^3


       DENG = 0.0029*(PH)**0.938
       DENL = 60.827-(0.078*PH)+(0.00048*(PH)**2)-(0.0000013*(PH)**3)
       DENMIX = W/(WG/DENG + WL/DENL)
```

```
C     FOR TURBULENT FLOW, CALCULATE THE FRICTION FACTOR.

      FF = 0.25/(-ALOG10(0.000486/D))**2
      DELTP = (0.000336*FF*W**2)/(DENMIX*D**5)

C     CALCULATE THE VELOCITY OF FLASHED CONDENSATE MIXTURE, ft/min.

      VEL = (3.054/D**2)*(WG/DENG + WL/DENL)

      WRITE (1, 170) TFL, DENG
 170  FORMAT (10X, 'TEMPERATURE OF FLASHED CONDENSATE, oF:', T65,
     * F8.3, /, 10X, 'FLASHED STEAM DENSITY, lb/ft^3:', T65, F8.3)


      WRITE (1, 180) DENL, DENMIX
 180  FORMAT (10X, 'FLASHED CONDENSATE LIQUID DENSITY, lb/ft^3:',
     * T65, F8.3, /, 10X, 'DENSITY OF MIXTURE, lb/ft^3:', T65, F8.3)

      WRITE (1, 190) FF, DELTP, VEL
 190  FORMAT (10X, 'FRICTION FACTOR:', T65, F8.4, /, 10X,
     * 'PRESSURE DROP OF FLASHED, psi:',/,10X,
     * 'CONDENSATE MIXTURE, psi/100ft:', T65,
     * F8.3,/,10X, 'VELOCITY OF FLASHED CONDENSATE MIXTURE, ft/min.:',
     * T65, F10.0)


C     DETERMINE WHETHER PROCESS LINE MAY DETERIORATE i.e. WHETHER
C     VELOCITY IS EQUAL OR GREATER THAN 5000 ft./min.



      IF ( VEL .GE. 5000.0) THEN

      WRITE (1, 200)
 200  FORMAT (10X, 'FLASHED CONDENSATE MIXTURE VELOCITY IS GREATER',\)

      WRITE (1, 210)
 210  FORMAT (' THAN 5000 ft./min.')

      WRITE (1, 220)
 220  FORMAT (10X, 'DETERIORATION OF THE LINE IS POSSIBLE')

      ELSE

      WRITE (1, 230)
 230  FORMAT (10X, 'FLASHED CONDENSATE MIXTURE IS LESS THAN',\)

      WRITE (1, 240)
 240  FORMAT (' 5000 ft/min.')

      WRITE (1, 250)
 250  FORMAT (10X,'THE CONDENSATE HEADER LINE WILL NOT DETERIORATE')
      ENDIF

      WRITE (1, 260)
 260  FORMAT (78(1H-))

C     FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)


      CLOSE (3, STATUS = 'KEEP')
      CLOSE (1)

 999  STOP
      END
```

```
      PROGRAM PROG38


C      THIS PROGRAM CALCULATES THE TOTAL PRESSURE DROP IN A PACKED BED
C      WHEN LIQUID OR VAPOR STREAMS ARE PASSED THROUGH IT.  THE
C      PROGRAM ALSO CALCULATES THE FLUID REYNOLDS NUMBER AND THE
C      FRICTION FACTOR.
C      ***************************************************************

C                            NOMENCLATURE
C                          ------------------
C
C      A       =   CROSS-SECTIONAL AREA OF BED, ft^2.
C      AP      =   AREA OF PARTICLES, ft^2.
C      BD      =   PACKED BED DIAMTER, ft.
C      BL      =   PACKED BED LENGTH, ft.
C      DEN     =   DENSITY OF FLUID AT FLOWING CONDITIONS, lb/ft^3.
C      DELPT   =   TOTAL PRESSURE DROP IN PACKED BED, lb/in^2.
C      FV      =   FRACTION VOIDS IN PACKED BED.
C      FP      =   FRICTION FACTOR.
C      G       =   SUPERFICIAL MASS VELOCITY    lb/h.ft^2.
C      GC      =   GRAVITATIONAL CONSTANT = 4.17 x 10^8 (lbm/lbf)(ft/h^2)
C      MW      =   MOLECULAR WEIGHT OF FLUID.
C      P       =   FLUID PRESSURE, psia.
C      PD      =   PARTICLE DIAMETER, inch.
C      PL      =   PARTICLE LENGTH, inch.
C      RE      =   REYNOLDS NUMBER
C      S       =   PACKED BED SURFACE AREA,  (ft^2/ft^3 BED).
C      T       =   FLUID TEMPERATURE, oR.
C      VIS     =   FLUID VISCOSITY, cP.
C      W       =   FLUID FLOWRATE, lb/h.
C      Z       =   COMPRESSIBILITY FACTOR ( Z=1.0)
C      *************************************************************


      PARAMETER ( PI = 3.1415927, GC = 4.17*10**8)

C      OPEN FILES TO READ THE DATA AND TO PRINT THE RESULTS.

      OPEN (UNIT = 3, FILE ='DATA38.DAT', STATUS = 'OLD', ERR = 18)
      OPEN (UNIT = 1, FILE = 'PRN')


      WRITE (1, 100)
 100  FORMAT (///, 25X,'PRESSURE DROP IN A PACKED BED',/1H ,
     *        78(1H*))


C      READ THE DATA VALUES.

C      READ THE PACKED BED DIAMERTER, ft.: BD
C      READ THE PACKED BED LENGTH, ft.: BL
C      READ THE FLUID FLOW RATE, lb/hr.: W
C      READ THE PARTICLE DIAMETER, inch: PD
C      READ THE PARTICLE LENGTH, inch: PL
C      READ THE FRACTION OF VOIDS IN PACKED BED, inch: FV
C      READ THE DENSITY OF FLUID AT FLOWING CONDITION, lb/ft^3.: DEN
```

```
C       READ THE FLUID VISCOSITY, cP: VIS

        READ (3, *, ERR=19) BD, BL, W
        READ (3, *, ERR=19) PD, PL, FV
        READ (3, *, ERR=19) DEN, VIS

        GO TO 10

 18     WRITE (*, 110)
 110    FORMAT (10X, 'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 120)
 120    FORMAT (10X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999


 10     WRITE (1, 130) BD, BL, W
 130    FORMAT (10X, 'PACKED BED DIAMETER, ft.:', T60, F8.3, /, 10X,
     *          'LENGTH OF PACKED BED, ft.:', T60, F8.3, /, 10X,
     *          'FLUID FLOWRATE THROUGH PACKED BED, lb/h.:', T60, F10.1)

        WRITE (1, 140) PD, PL, FV
 140    FORMAT (10X, 'PARTICLE DIAMETER, inch.:' T60, F8.3, /, 10X,
     *          'PARTICLE LENGTH, inch.:', T60, F8.3, /, 10X,
     *          'FRACTIONAL VOIDS IN PACKED BED:', T60, F8.3)

        WRITE (1, 150) DEN, VIS
 150    FORMAT (10X, 'DENSITY OF FLUID, lb/ft^3:', T60, F8.4, /, 10X,
     *          'FLUID VISCOSITY, cP:', T60, F8.4)


C       CALCULATE THE CROSS-SECTIONAL AREA OF BED, ft^2.

        A = (PI*BD**2)/4.0

C       CALCULATE THE SUPERFICIAL MASS VELOCITY, W/A

        G = W/A

C       CALCULATE THE AREA OF PARTICLES AND THE VOLUME OF PARTICLES.

        AP = (1.0/144.0)*((PI*PD**2)/2.0 + (PI*PD*PL))
        VP = (1.0/1728.0)*(((PD**2)*PI*PL)/4.0)


C       CALCULATE THE PACKED BED SURFACE AREA, ft^2/ft^3. BED.

        S = AP*(1 - FV)/VP

C       CALCULATE THE EFFECTIVE PARTICLE DIAMETER, ft.

        DP = 6.0*(1-FV)/S

C       CALCULATE THE FLUID REYNOLDS NUMBER, RE

        RE = (G*DP)/(2.419*VIS*(1.0 - FV))
```

```
       WRITE (1, 160) A, G
 160   FORMAT (10X, 'CROSS-SECTIONAL AREA OF BED, ft^2:', T60, F8.4,
     *        /, 10X, 'SUPERFICIAL MASS VELOCITY, lb/h.ft^2:', T60,
     *        F8.1)

       WRITE (1, 170) AP, VP
 170   FORMAT (10X, 'AREA OF PARTICLES, ft^2:', T60, E12.4, /, 10X,
     *        'VOLUME OF PARTICLES, ft^3:', T60, E12.4)

       WRITE (1, 180) S, DP
 180   FORMAT (10X, 'THE PACKED BED SURFACE AREA, ft^2/ft^3 BED:',
     * T60, F8.3, /, 10X,'EFFECTIVE PARTICLE DIAMETER, ft.:',T60, F8.4)

       WRITE (1, 190) RE
 190   FORMAT (10X, 'FLUID REYNOLDS NUMBER:', T60, F10.0)


C      DETERMINE THE FRICTION FACTOR FOR LAMINAR, INTERMEDIATE OR
C      TURBULENT FLOW.

       IF (RE .LT. 1.0) THEN

       FP = 150.0/RE

       WRITE (1, 200) FP
 200   FORMAT (10X, 'FRICTION FACTOR FOR LAMINAR FLOW:', T60, F8.4)
       ELSEIF (RE .GT. 1.0 .AND. RE .LT. 10**4) THEN

       FP = 150.0/RE+1.75

       WRITE (1, 210) FP
 210   FORMAT (10X,'FRICTION FACTOR FOR INTERMEDIATE FLOW:', T60,
     *        F8.4)

       ELSEIF (RE .GT. 10**4) THEN
       FP = 1.75

       WRITE (1, 220)
 220   FORMAT (10X,'FRICTION FACTOR FOR TURBULENT FLOW:', T60, F8.2)

       ENDIF


C      CALCULATE THE TOTAL PRESSURE DROP IN PACKED BED, DELTP.


       VAL1 = (BL*(1-FV)*G**2)/(144.0*(FV**3)*DP*GC*DEN)
       VAL2 = ((150.0*2.419*VIS*(1.0-FV)/(DP*G))+1.75)
       DELTP = VAL1 * VAL2

       WRITE (1, 230) DELTP
 230   FORMAT (10X, 'TOTAL PRESSURE DROP IN PACKED BED, lb/in^2:',
     * T60, F8.3)

       WRITE (1, 240)
 240   FORMAT (78(1H-))

C      FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

       WRITE (1, *) CHAR(12)

       CLOSE (3, STATUS = 'KEEP')
       CLOSE (1)

 999   STOP
       END
```

CHAPTER 4

Equipment Sizing

INTRODUCTION

The process engineer is often required to design separators or knockout drums for removing liquids from process gas streams. This chapter reviews the design of horizontal and vertical separators and the sizing of partly filled horizontal and cylindrical vessels. The chapter concludes by reviewing the sizing of a cyclone and a solid-desiccant gas dryer.

Vessels used for processing in the chemical process industries (CPI) are principally of two kinds: those that are without internals and those with internals. Empty separators are drums that provide intermediate storage or surge of a process stream for a limited or extended period. Alternatively, they provide phase separation by settling.

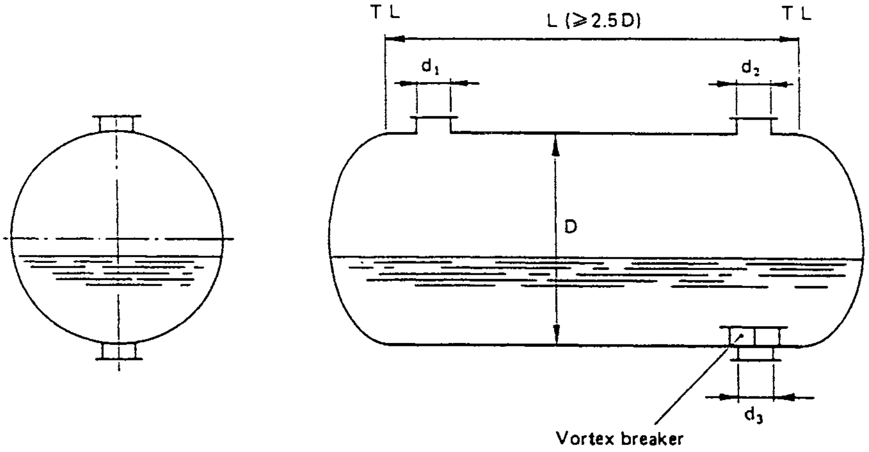
The second category comprises equipment such as reactors, mixers, distillation columns, and heat exchangers. In some cases, it is important to separate liquid and gas flowing simultaneously through a pipe. This is because the conditions of the flowing mixture and the efficiency of separation may vary widely. Therefore, a separator for such duty must be adequate. In addition, there are constraints due to space or weight that often affect the choice of separators, the need to handle solids or effect a three-phase separation, and the requirements for liquid hold-up. In practice, most separation problems are solved by the following types of separating equipment.

Knockout or Surge Drums (Figures 4-1 and 4-2). A knockout drum is suitable for a bulk separation of gas and liquid, particularly when the liquid volume fraction is high with stratified or plug flow in the pipe. Also, it is useful when vessel internals are required to be kept to a minimum, e.g., in relief systems or in fouling service. It is unsuitable if a mist is being separated or if high separating efficiency is required.

Cyclones (Figure 4-3). These are robust and not susceptible to fouling or wax. Multicyclones are compact and are reasonably efficient for foam, but not for slugs. The efficiency of a cyclone decreases with increasing diameter, and cyclones are not applicable above 5 ft. diameter. They possess a good efficiency for smaller flow rates. However, cyclones are expensive to operate, especially under vacuum conditions, because they have a higher pressure drop than either a knockout drum or a demister separator.

Demister Separators. A demister separator is fitted either with a vane demister package or with a wire mesh demister mat. The latter type is much preferred, although it is unsuitable for fouling service. The wire mesh demister is a widely applied type of separator, and is adequate for all gas-liquid flow regimes over a wide range of gas flow rates.

A knockout drum or demister separator may be either a vertical or a horizontal vessel. A vertical vessel is generally preferred because its efficiency does not vary with the liquid level. Alternatively, a horizontal



Note: TL = Tangent line

Figure 4-1. Horizontal knock-out drum.

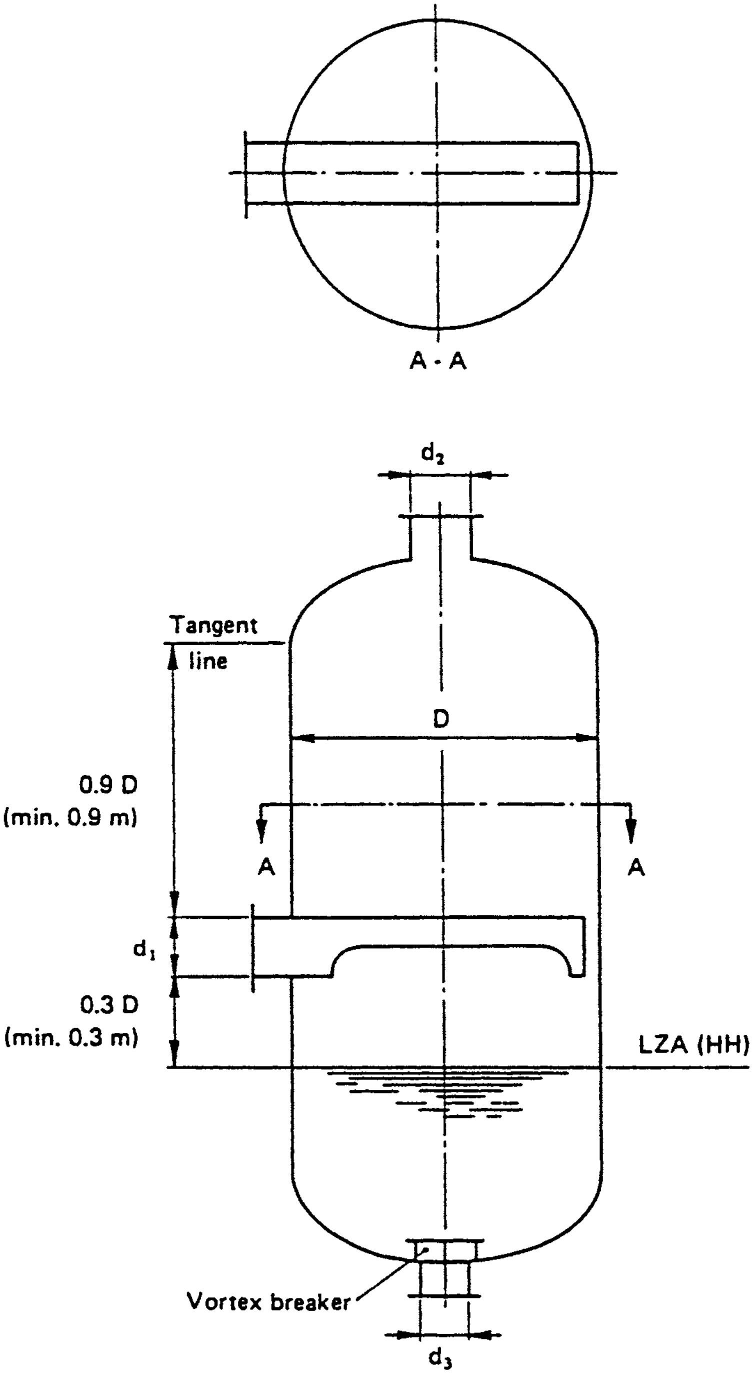


Figure 4-2. Vertical knock-out drum.

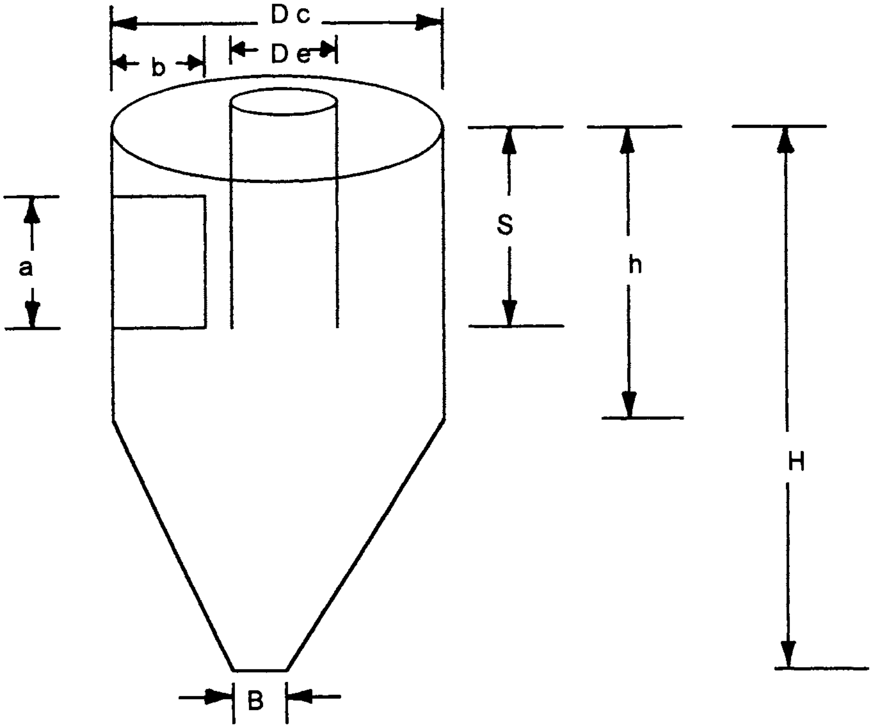


Figure 4-3. A cyclone: design configurations.

vessel is chosen when it offers a clear size advantage, if the headroom is restricted or if a three-phase separation is required. Knockout drums and cyclones are recommended for waxy and coking feeds. Demister mats are not suitable because of the danger of plugging. Vane demister packages are used as alternatives, but provision should be made for cleaning.

SIZING OF VERTICAL AND HORIZONTAL SEPARATORS

Vertical Separators

Vertical liquid-vapor separators are used to disengage a liquid from a vapor when the volume of liquid is small compared with that of vapor volume. The maximum allowable vapor velocity in a vertical separator that reduces the liquid carryover is dependent on the following:

- liquid and vapor densities.
- a constant K based on surface tension, droplet size, and physical characteristics of the system.

The proportionality constant, K, is 0.35 for oil and gas systems with at least 10-inch disengaging height between the mist eliminator bottom and gas liquid interface. For vertical vessels, K can vary between 0.1 and 0.35, if mist eliminators (demisters) are used to enhance disentrainment. The value of K also depends on the operating pressure of the vessel. At pressures above 30 psig, the K value decreases with pressure with an approximate value of 0.30 at 250 psig and 0.275 at 800 psig. Watkins [1] has developed a correlation between the separation factor and K. Figure 4-4 illustrates Watkin's vapor velocity factor chart, based on five percent of the liquid being entrained with the vapor.

Blackwell [2] has developed a polynomial equation using Watkin's data to calculate the K value for a range of separation factors between 0.006 and 5.0. Watkins proposed a method for sizing reflux drums based upon several factors, as illustrated in Tables 4-1 and 4-2. Table 4-1 gives the recommended design surge times. Table 4-2 gives the multiplying factors for various operator efficiencies. The operating factor is based upon the external unit and its operation, its instrumentation and response to control, the efficiency of labor, and chronic mechanic problems, and the possibility of short or long term interruptions [1].

The multiplying factors F_1 and F_2 represent the instrument and the labor factors.

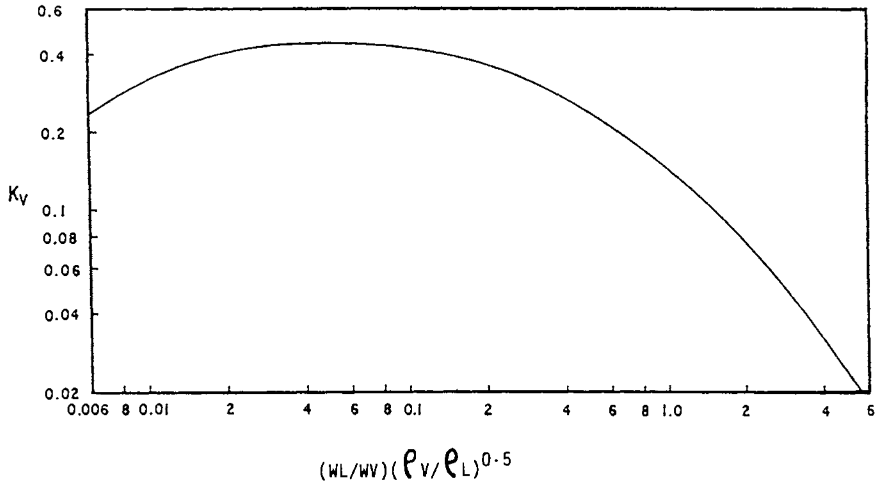


Figure 4-4. Design vapor velocity factor for vertical vapor-liquid separators at 85% of flooding.

Table 4-1
Design Criteria for Reflux Distillate Accumulators

			Minutes		
	Instrument Factor F_1		Labor Factor F_2		
Operation	w/Alarm	w/o Alarm	Good	Fair	Poor
FRC	$\frac{1}{2}$	1	1	1.5	2
LRC	1	$1\frac{1}{2}$	1	1.5	2
TRC	$1\frac{1}{2}$	2	1	1.5	2

Table 4-2
Operation Factors for External Units

Operating Characteristics	Factor F_3
Under good control	2
Under fair control	3
Under poor control	4
Feed to or from storage	1.25
	Factor F_4
Board mounted level recorder	1.0
Level indicator on board	1.5
Gauge glass at equipment only	2.0

A multiplying factor, F_3, is applied to the net overhead product going downstream. F_4 depends on the kind and location of level indicators.

It is recommended that 36 inches plus one-half the feed nozzle, OD, (48 inches minimum) be left above the feed nozzle for vapor. Below the feed nozzle, allowance of 12 inches plus one-half the feed nozzle, OD, is required for clearance between the maximum liquid level and the feed nozzle (minimum of 18 inches). At some value between L/D ratios of 3 and 5, a minimum vessel weight will occur resulting in minimum costs for the separator. Figure 4-5 shows the dimensions of a vertical separator.

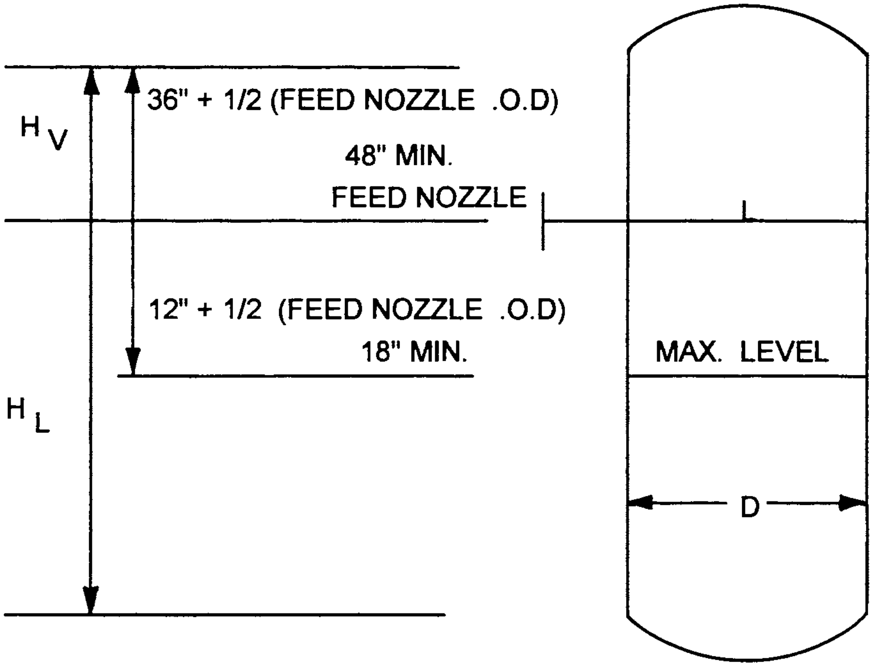


Figure 4-5. Dimension of a vertical separator.

Calculation Method for a Vertical Drum

The following steps are used to size a vertical drum.

Step 1. Calculate the vapor-liquid separation factor.

$$\text{S. Fac} = \frac{\text{WL}}{\text{WV}}\left(\frac{\rho_V}{\rho_L}\right)^{0.5} \tag{4-1}$$

Step 2. From Blackwell's correlation, determine the design vapor velocity factor, K_v, and the maximum design vapor velocity.

$$X = \ln(\text{S. Fac}) \tag{4-2}$$

$$K_v = \exp(B + DX + EX^2 + FX^3 + GX^4) \tag{4-3}$$

where B = –1.877478
D = –0.814580
E = –0.187074
F = –0.014523
G = –0.001015

$$V_{max} = K_v \left(\frac{\rho_L - \rho_V}{\rho_V} \right)^{0.5} \quad (4\text{-}4)$$

Step 3. Calculate the minimum vessel cross-sectional area.

$$Q_v = \frac{WW}{3600.\rho_V}, \quad ft^3/s \quad (4\text{-}5)$$

$$A_v = \frac{Q_v}{V_{max}}, \quad ft^2 \quad (4\text{-}6)$$

Step 4. Set a vessel diameter based on 6-inch increments and calculate cross-sectional area.

$$D_{min} = \left(\frac{4.A_v}{\pi} \right)^{0.5}, \quad ft \quad (4\text{-}7)$$

$D = D_{min}$ to next largest 6 inch

$$Area = \frac{\pi.D^2_{min}}{4} \quad (4\text{-}8)$$

Step 5. Estimate the vapor-liquid inlet nozzle based on the following velocity criteria.

$$(U_{max})_{nozzle} = \frac{100}{\rho^{0.5}_{mix}} \quad ft/s \quad (4\text{-}9)$$

$$(U_{min})_{nozzle} = \frac{60}{\rho^{0.5}_{mix}} \quad ft/s \quad (4\text{-}10)$$

where

$$\rho_{mix} = \left(\frac{WL + WV}{\frac{WL}{\rho_L} + \frac{WV}{\rho_V}} \right) \frac{lb_m}{ft^3} \quad (4\text{-}11)$$

Step 6. From Figure 4-5, make a preliminary vessel sizing for the height above the center line of a feed nozzle to top seam. Use 36 inches + 1/2 feed nozzle, OD, or 48 inches minimum. Use 12 inches + 1/2 feed nozzle, OD, or 18 inch minimum to determine the distance below the center line of the feed nozzle to the maximum liquid level.

Step 7. From Table 4-1 or 4-2, select the appropriate full surge volume in seconds. Calculate the required vessel volume.

$$Q_L = \frac{WL}{3600.\rho_L} \quad ft^3/s \tag{4-12}$$

$$\begin{aligned} V &= (Q_L)(\text{design time to fill}), \quad ft^3 \\ &= (60.0)(Q_L)(T), \quad ft^3 \end{aligned} \tag{4-13}$$

The liquid height is:

$$H_L = V.\left(\frac{4}{\pi.D^2}\right), \quad ft \tag{4-14}$$

Step 8. Check geometry. $(H_L + H_V)/D$ must be between 3 and 5. For small volumes of liquid, it may be necessary to provide more liquid surge than is necessary to satisfy the $L/D > 3$. If the required liquid surge volume is greater than that obtained in a vessel having $L/D < 5$, a horizontal drum must be provided.

Calculation Method for a Horizontal Drum

Horizontal vessels are used for substantial vapor-liquid separation where the liquid holdup space must be large. Maximum vapor velocity and minimum vapor space are determined as in the vertical drum, except that K_H for horizontal separators is generally set at $1.25K_v$. The following steps are carried out in sizing horizontal separators.

Step 1. Calculate the vapor-liquid separation factor by Equation 4-1, and K_v by Equations 4-2 and 4-3.

Step 2. For horizontal vessels

$$K_H = 1.25K_v \tag{4-15}$$

Step 3. Calculate the maximum design vapor velocity.

$$(U_v)_{max} = K_H\left(\frac{\rho_L - \rho_V}{\rho_V}\right)^{0.5} \quad \text{ft/s} \tag{4-16}$$

Step 4. Calculate the required vapor flow area.

$$(A_v)_{min} = \frac{Q_v}{(U_v)_{max}} \quad \text{ft}^2 \tag{4-17}$$

Step 5. Select appropriate design surge time from Table 4-1 or Table 4-2, and calculate full liquid volume by Equations 4-12 and 4-13.

The remainder of the sizing procedure is carried out by trial and error as follows:

Step 6. When the vessel is full, the separator vapor area can be assumed to occupy only 15 to 25 percent of the total cross-sectional area. Here, a value of 20 percent is used and the total cross-sectional area is expressed as:

$$(A_{total})_{min} = \frac{(A_v)_{min}}{0.2} \tag{4-18}$$

$$D_{min} = \left(\frac{4.(A_{total})_{min}}{\pi}\right)^{0.5} \tag{4-19}$$

Step 7. Assume the length-to-diameter ratio of 3 (i.e, L/D = 3). Calculate the vessel length.

$$L = (3)(D_{min}) \tag{4-20}$$

Step 8. Because the vapor area is assumed to occupy 20 percent of the total cross-sectional area, the liquid area will occupy 80 percent of the total cross-sectional area.

$$A_L = (0.8)(A_{total})_{min}, \quad \text{ft}^2 \tag{4-21}$$

Step 9. Calculate the vessel volume.

$$V_{VES} = (A_{total})_{min}(L), \quad \text{ft}^3 \tag{4-22}$$

Step 10. Calculate liquid surge time.

$$T = \frac{(60.0)(A_L)(L)(\rho_L)}{WL} \text{ min.} \tag{4-23}$$

Liquid Holdup and Vapor Space Disengagement

The dimensions of both vertical and horizontal separators are based on rules designed to provide adequate liquid holdup and vapor disengaging space. For instance, the desired vapor space in a vertical separator is at least $1\frac{1}{2}$ times the diameter, with 6 inches as the minimum above the top of the inlet nozzle. In addition, a 6-inch minimum is required between the maximum liquid level and the bottom of the inlet nozzle. For a horizontal separator, the minimum vapor space is equal to 20 percent of the diameter or 12 inches.

Wire Mesh Pad

Pads of fine wire mesh induce coalescence of impinging droplets into larger ones, which then separate freely from the gas phase. No standard equations have been developed for the pressure drop across wire mesh because there are no standardized mesh pads. However, as a rule of thumb, the pressure drop of a wire mesh is $\Delta P = 1.0$ in H_2O. Every manufacturer makes a standard high efficiency, very-high efficiency, or high-throughput mesh under various trade names, each for a specific requirement.

Standards for Horizontal Separators

The following specifications are generally standard in the design of horizontal separators [3]:

1. The maximum liquid level shall provide a minimum vapor space height of 15 inches, but should not be below the center line of the separator.
2. The volume of dished heads is not considered in vessel sizing calculations.
3. The inlet and outlet nozzles shall be located as closely as practical to the vessel tangent lines. Liquid outlets shall have anti-vortex baffles.

Piping Requirements

Pipes that are connected to and from the process vessels must not interfere with the good working of the vessels. Therefore, the following guidelines should be observed:

- There should be no valves, pipe expansions or contractions within 10-pipe diameters of the inlet nozzle.

- There should be no bends within 10-pipe diameters of the inlet nozzle except:

  for knockout drums and demisters, a bend in the feed pipe is permitted if this is in a vertical plane through the axis of the feed nozzle.

  for cyclones, a bend in the feed pipe is allowed if this is in a horizontal plane and the curvature is in the same direction as the cyclone vortex.
- A pipe reducer may be used in the vapor line leading from the separator, but it should be no nearer to the top of the vessel than twice the outlet pipe diameter.
- A gate or ball type valve that is fully opened in normal operation should be used, where a valve in the feed line near the separator cannot be avoided.
- High pressure drops that cause flashing and atomization should be avoided in the feed pipe.
- If a pressure reducing valve in the feed pipe cannot be avoided, it should be located as far upstream of the vessel as practicable.

Nomenclature

A = cross-sectional area of vertical separator, ft^2
A_L = cross-sectional area of horizontal vessel occupied by liquid phase, ft^2
A_T = total cross-sectional area of horizontal vessel, ft^2
A_v = minimum cross-sectional area of vertical separator, ft^2
D = vessel diameter, ft
H_L = liquid height, ft
H_v = vapor height, ft
K = proportionality constant
K_H = vapor velocity factor for horizontal separator
K_v = vapor velocity factor for vertical separator
L = horizontal vessel level, ft
S.Fac = separation factor
Q_L = liquid volumetric flow, ft^3/s
Q_v = vapor volumetric flow, ft^3/s
T = liquid surge time, min.
V_{max} = maximum vapor velocity, ft/s
V_{VES} = horizontal vessel volume, ft^3
WL = liquid flow rate, lb/h
WV = vapor flow rate, lb/h

$X = \ln(S.Fac)$
ρ_L = liquid density, lb/ft^3
ρ_v = vapor density, lb/ft^3

SIZING OF PARTLY FILLED VESSELS AND TANKS

Cylindrical vessels and horizontal tanks are used for the storage of fluids in the chemical process industries. Various level instruments are employed to determine the liquid level in process vessels. The exact liquid volume can be obtained either by calibration of the vessels or by tedious calculations. Partial volumes for horizontal, cylinders with flat, dished, elliptical, and hemispherical ends, and for vertical cylinders are employed for storing process fluids.

Kowal [4] presented charts that allow designers to determine the volume of vessels for different dimensions. In addition, parameters for tray designs and tray layout in distillation columns, such as chord length and circle area, are computed in this chapter.

The Equations

Calculate the area of the segment of a circle from Figure 4-6:

$$\text{Cos}(\alpha) = \frac{R - H}{R} \tag{4-24}$$

$$\alpha = \text{Cos}^{-1}\left(\frac{R - H}{R}\right) \tag{4-25}$$

Area of the triangle:

$$\text{Area of } \Delta = (R - H)(2RH - H^2) \tag{4-26}$$

Therefore, area of the segment of a circle from Figure 4-6 is:

$$A_s = R^2\text{Cos}^{-1}\left(\frac{R - H}{R}\right) - (R - H)(2RH - H^2)^{0.5} \tag{4-27}$$

Figure 4-7 is a nomograph based upon the area of the segment of a circle [5]. The nomograph converts the height (rise) over diameter ratios directly to percent of area. The procedure in using the nomograph is:

1. Start at the left-hand side of the nomograph with the trial diameter.

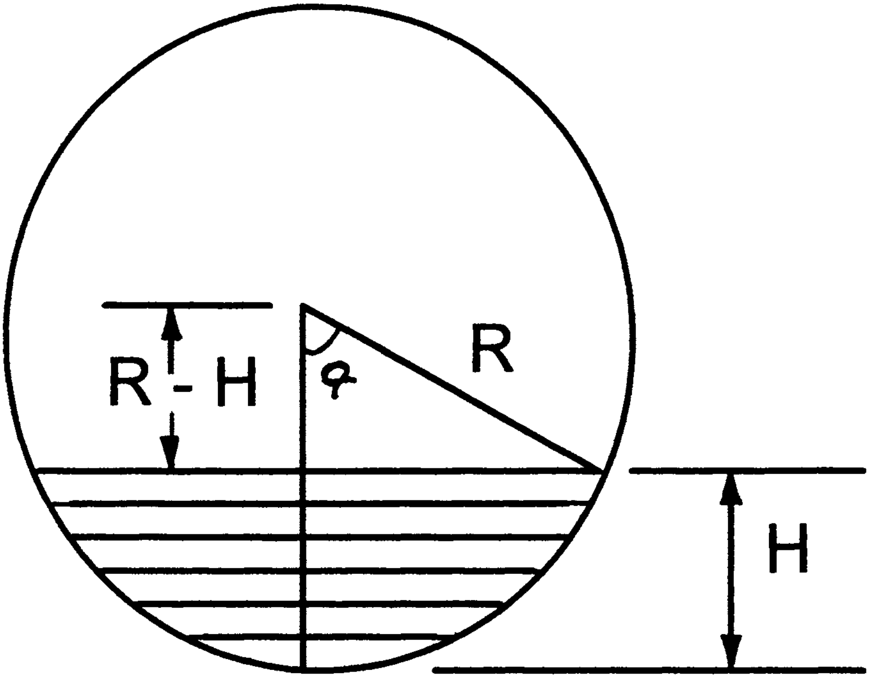


Figure 4-6. Area of the segment.

2. Align the internal diameter with the height of the vapor space and then with the rise of the minimum liquid level. Read the area occupied by these segments.
3. Subtract the sum of these segments from 100%. The difference is the area available for liquid holding time.

Chord length of segmental area, CL:

$$CL = 2(DH - H^2)^{0.5} \tag{4-28}$$

Partial volume of a horizontal cylinder:

$$V_{HC} = A_s . L \tag{4-29}$$

Partial volume of dished heads:

$$V_{DH} = 0.215483H^2(1.5D - H) \tag{4-30}$$

Partial volume of elliptical heads:

$$V_{ELL} = 0.52360H^2(1.5D - H) \tag{4-31}$$

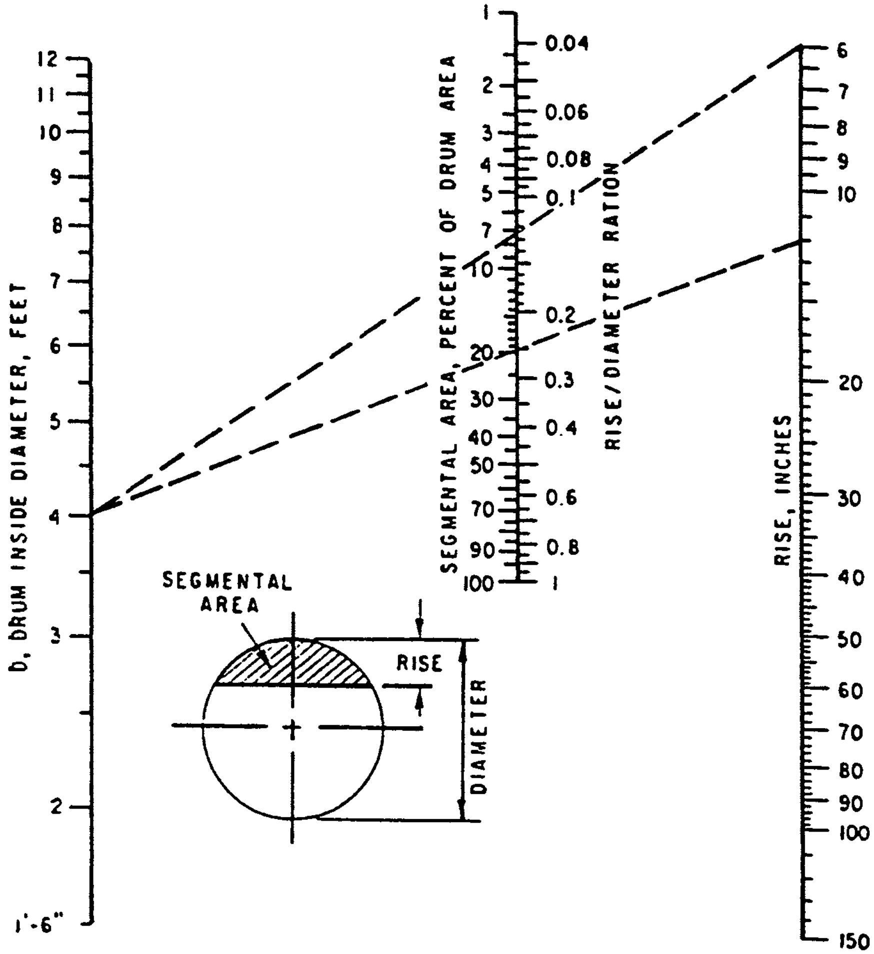


Figure 4-7. Nomograph to find segmental area available for liquid holding time.

Partial volume of hemispherical heads:

$$V_{HS} = 2V_{ELL} \tag{4-32}$$

The total volume V_T:

$$V_T = V_{HC} + V_H \tag{4-33}$$

where V_H = head volume

$$\text{Area} = \frac{\pi . D^2}{4} \tag{4-34}$$

Volume of a vertical tank:

$$V_{VT} = 0.25\pi D^2 H \tag{4-35}$$

Conversions:

$$ft^3 = in^3/1728$$

$$gal = (in^3)(0.004329)$$

$$bbl = (in^3)(0.00010307)$$

Nomenclature

Area = circle area, in^2
A_s = segmental area of a circle, in^2
CL = chord length of segmental area, inch
bbl = volume in barrels
d = vessel tank, or circle diameter, inch
H = chord or liquid height, inch
L = vessel length, inch
R = radius of vessel or tank, inch
V_{DH} = volume of dished head, in^3
V_{ELL} = volume of elliptical heads, in^3
V_H = head volumes, in^3
V_{HC} = volume of horizontal cylinder, in^3
V_{HS} = volume of hemispherical heads, in^3
V_T = total volume of horizontal vessel, in^3
V_{VT} = volume of vertical tank, in^3

PRELIMINARY VESSEL DESIGN

Columns and towers are the most essential aspects of the refinery system in the petrochemical or in the process chemical industries. They are divided into three separate functions: distillation, fractionation, and chemical operations. Stills are cylindrical chambers in which the application of heat to the charge stock changes from a liquid to a vapor. The vapor is then condensed in another vessel. Columns and towers are stills that increase the degree of separation that can be obtained during the distillation of crude oil. Fractionation towers are used for light end products. Generally, towers are large cylindrical vessels that have plates (trays spaced inside the shell) to promote mixing of the downward flow of liquid with the upward flow of the vapors. These vessels require self-supporting, especially when they are exposed to high winds or to seismic risk.

Process conditions in the CPI often change, and a tower that is initially designed for vacuum operation may at a later stage be employed at pressure greater than atmospheric. Therefore, thin-walled vessels are often rated for both pressure and vacuum conditions. If the vessel is thick-walled and designed for high pressure service, no vacuum rating will be required. Tall vessels have one of a number of closures such as hemispherical, ellipsoidal, torispherical, conical, or flat ends.

The ellipsoidal shape is usual for closures of vessels that are six feet in diameter or greater. The hemispherical shape is preferred for vessels of a lesser diameter. The basic relationships for thin cylindrical shells under internal pressure assume that circumferential stress is dependent on the pressure and vessel diameter, but independent of the shell thickness.

That is:

$$f = \frac{P.D}{2t} \tag{4-36}$$

or

$$t = \frac{P.D}{2f} \tag{4-37}$$

Equation 4-36 is for membrane shells with a negligible thickness. As the pressure and the shell thickness increase, the stress distribution across the thickness is non-uniform. Therefore, some correction to the membrane theory is required. The modified code equation as given by the ASME Unfired Pressure Code, Section VIII, Division 1 is:

$$t = \frac{P.R}{S.E - 0.6P} + c \tag{4-38}$$

where c is the corrosion allowance

For a hemispherical head:

$$t_{HH} = \frac{P.R}{2S.E - 0.2P} \tag{4-39}$$

For ellipsoidal dished head:

$$t_{ELL} = \frac{P.D}{2S.E - 0.2P} + c \tag{4-40}$$

For torispherical head:

$$t_{TOR} = \frac{0.885P.R_c}{S.E - 0.1P} + c \tag{4-41}$$

The weight of the vessel shell is:

$$W_{TS} = \frac{1}{12}(OD + t)(\pi)(SL)\left(\frac{t}{12}\right)(\rho_s) \tag{4-42}$$

The head blank diameter is:

$$BD = \frac{\{(OD)(H.Fac) + 2SF\}}{12} \tag{4-43}$$

Weight of head:

$$W_{TH} = 0.25(BD)^2(\pi)\left(\frac{t}{12}\right)(\rho_s)(2) \tag{4-44}$$

The total weight:

$$W_{TOT} = W_{TS} + W_{TH} \tag{4-45}$$

The total weight excludes the nozzles, attachments, and vessel internals. Table 4-3 shows the head blank diameter factor for different types of head.

Nomenclature

BD = head blank diameter, inch
c = corrosion allowance, inch
D = inside diameter of shell or head, inch
E = joint efficiency
H.Fac = head blank diameter factor
OD = outside diameter of head, inch
P = internal design pressure, psig
R = inside radius, inch
R_c = crown radius of torispherical head, inch
S = allowable stress, lb/in^2

Table 4-3
Head Blank Diameter Factor (H.Fac)

Head Type	OD/t	H.Fac
Torispherical	>50	1.09
	30–50	1.11
	20–30	1.15
Ellipsoidal	>20	1.24
	10–20	1.30
Hemispherical	>30	1.60
	18–30	1.65
	10–18	1.70

SF = straight flange length, inch
SL = shell length, ft
t = shell thickness, ft
t_{ELL} = ellipsoidal head thickness, inch
t_{HH} = hemispherical head thickness, inch
t_{TOR} = torispherical head thickness, inch
W_{TH} = weight of head, lb
W_{TS} = weight of vessel shell, lb
W_{TOT} = total weight of vessel, lb
ρ_s = density of vessel material, lb/ft^3

CYCLONE DESIGN

Introduction

Cyclones are widely used for the separation and recovery of industrial dusts from air or process gases. Pollution and emission regulations have compelled designers to study the efficiency of cyclones. Cyclones are the principal type of gas-solids separators using centrifugal force. They are simple to construct, of low cost, and are made from a wide range of materials with an ability to operate at high temperatures and pressures. Cyclones are suitable for separating particles where agglomeration occurs. These types of equipment have been employed in the cement industry, and with coal gases for chemical feedstock, and gases from fluidized-bed combustion, as well as in the processing industry for the recovery of spray-dried products, and recently, in the oil industry for separating gas from liquid.

Cyclone reactors permit study of flow pattern and residence time distribution [6,7]. See for example, the studies by Coker [8,9] of synthetic detergent production with fast reaction. Reactor cyclones are widely used to separate a cracking catalyst from vaporized reaction products.

Reverse flow cyclones, in which the dust-laden gas stream enters the top section of the cylindrical body either tangentially or via an involute entry, are the most common design. The cylindrical body induces a spinning, vortexed flow pattern to the gas-dust mixture. Centrifugal force separates the dust from the gas stream; the dust travels to the walls of the cylinder and down the conical section to the dust outlet. The spinning gas also travels down the wall toward the apex of the cone, then reverses direction in an air-core and leaves the cyclone through the gas outlet tube at the top. This tube consists of a cylindrical sleeve and the vortex finder, whose lower end extends below the level of the feed port. Separation depends on particle settling velocities, which are governed by size, density, and shape.

Stairmand [10], Strauss [11], Koch and Licht [12] have given guidelines for designing cyclones. The effects of feed and cyclone parameters on the efficiency are complex, because many parameters are interdependent. Figure 4-3 shows the design dimensions of a cyclone and Table 4-4 gives the effects on cyclone performance in the important operating and design parameters.

Cyclone Design Procedure

The computation of a cyclone fractional or grade efficiency depends on cyclone parameters and flow characteristics of particle-laden gases. The procedure involves a series of equations containing exponential and logarithmic functions. Koch and Licht [12] described a cyclone using seven geometric ratios in terms of its diameter as:

$$\frac{a}{D_C}, \frac{b}{D_C}, \frac{D_C}{D_C}, \frac{S}{D_C}, \frac{h}{D_C}, \frac{H}{D_C}, \frac{B}{D_C}$$

They further stated that certain constraints are observed in achieving a sound design. These are:

$a < S$ to prevent short circuiting

Table 4-4
Effects of Variables on Cyclone Performance

Variable	Effect
Pressure drop increases	Cut size (diameter of particles of which 50% are collected) decreases, flow rate increases; sharpness increases.
Solids content of feed increases	Cut size increases (large effect above 15–20% v/v).
$(\rho_p - \rho_f)$ increases	Cut size decreases.
Viscosity of liquid phase increases	Little effect below 10 mPas.
Cyclone diameter (D_c) increases	Cut size increases; pressure drop usually decreases.
Cyclone inlet (a) diameter increases	Gravitational force in cyclone decreases; cut size increases; capacity falls; pressure drop decreases.
Overflow diameter increases	Cut size increases; risk of coarse sizes appearing.
Underflow diameter increases	Brings excess fines from liquid phase into underflow.
Cyclone shape becomes longer	Decreases cut size; sharpens separation.

$b < \frac{1}{2}(D_c - D_e)$ to avoid sudden contraction

$S + l \le H$ to keep the vortex inside the cyclone

$S < h$

$h < H$

$\Delta P < 10 \text{ in } H_2O$

$v_i / v_s \le 1.35$ to prevent reentrainment

$v_i / v_s \cong 1.25$ for optimum efficiency

The Equations

Natural length, l: the distance below the gas outlet where the vortex turns.

$$l = 2.3D_e\left(\frac{D_c^2}{ab}\right)^{1/3} \tag{4-46}$$

For l < (H – S), the cyclone volume at the natural length (excluding the core) is V_{nl}:

$$V_{nl} = \frac{\pi D_c^2}{4}(h - S) + \left(\frac{\pi D_c^2}{4}\right)\left(\frac{l + S - h}{3}\right)\left(1 + \frac{d}{D_c} + \frac{d^2}{D_c^2}\right) - \frac{\pi D_e^2 l}{4} \tag{4-47}$$

The diameter of a central core at a point of vortex turns, d:

$$d = D_c - (D_c - B)\left(\frac{S - l - h}{H - h}\right) \tag{4-48}$$

For l > (H – S), the cyclone volume below the exit duct (excluding the core) V_H:

$$V_H = \frac{\pi D_c^2}{4}(h - S) + \left(\frac{\pi D_c^2}{4}\right)\left(\frac{H - h}{3}\right)\left(1 + \frac{B}{D_c} + \frac{B^2}{D_c^2}\right) - \frac{\pi D_e^2}{4}(H - S) \tag{4-49}$$

For a vortex exponent, n:

$$n = 1 - \left\{1 - \frac{(12D_c)^{0.14}}{2.5}\right\}\left\{\frac{T + 460}{530}\right\}^{0.3} \tag{4-50}$$

The cyclone volume constant, K_c, using V_{nl} or V_H:

$$K_c = \frac{(2V_s + V_{nl,H})}{2D_c^3} \tag{4-51}$$

where

$$V_s = \left\{\frac{\pi(S - a/2)(D_c^2 - D_e^2)}{4}\right\} \tag{4-52}$$

The relaxation time (τ_i) for particle species i of diameter d_{pi} is

$$\tau_i = \frac{\rho_p (d_{pi})^2}{18\mu} \tag{4-53}$$

Cyclone configuration factor G: This is specified by the geometric ratios that describe the cyclone's shape. The cyclone configuration factor G is a function only of the configuration and is specified by the seven geometrical ratios that describe its shape. G is expressed as:

$$G = \frac{8K_C}{K_a^2 K_b^2} \tag{4-54}$$

where

$$K_a = \frac{a}{D_c}, \quad K_b = \frac{b}{D_c} \tag{4-55}$$

Substituting the values of K_a, K_b, and K_c in Equation 4-54.

$$G = \left\{2\left[\pi(S - a/2)(D_c^2 - D_e^2)\right] + 4V_{H,nl}\right\}\frac{D_c}{a^2 b^2} \tag{4-56}$$

The fractional or grade efficiency, η_i, can be expressed as:

$$\eta_i = 1 - \exp\left\{-2\left[\frac{G\tau_i Q}{D_c^3}(n+1)\right]^{0.5/(n+1)}\right\} \tag{4-57}$$

Saltation Velocity

Koch and Licht [12] expressed the saltation velocity as:

- The minimum fluid velocity necessary to prevent the settling out of solid particles carried in the stream.
- The necessary velocity that picks up deposited particles and transports them without settling.

Zenz [13] has shown that the velocity given by the latter differs from the former by a factor of 2 to 2.5. Kalen and Zenz [14] have applied the saltation concept to cyclone design by assuming:

- There is no slippage between fluid and particles. The cyclone inlet width is the effective pipe diameter for calculating saltation effects.
- Grain loading (dust concentration) is less than 10 grains/ft^3.
- The diameter effect on the saltation velocity is proportional to the 0.4 power of the inlet width.

The saltation velocity, v_s, is dependent on cyclone dimensions, particle and fluid properties. v_s is expressed as:

$$v_s = 2.055\omega\left\{\frac{b/D_c}{(1 - b/D_c)^{1/3}}\right\}D_c^{0.067}v_i^{2/3} \quad \text{ft/s} \tag{4-58}$$

where

$$\omega = \left\{\frac{4g\mu(\rho_p - \rho_f)}{3\rho_f^2}\right\}^{1/3} \tag{4-59}$$

Inlet velocity, v_i: ft/s

$$v_i = \frac{Q}{(ab)} \tag{4-60}$$

Kalen and Zenz have shown that maximum cyclone collection efficiency occurs at $v_i/v_s = 1.25$, and Zenz has found experimentally that fluid reentrainment occurs at $v_i/v_s = 1.36$.

Pressure Drop (ΔP)

Several attempts have been made to calculate the frictional loss or ΔP of a cyclone, although none has been very satisfactory. These are because assumptions made have not considered entrance compression, wall friction, and exit contraction, all of which have a major effect. Consequently, no general correlation of cyclone ΔP has been adopted. Pressure drop in a cyclone with collection efficiency is important in evaluating its cost. Correlations for the pressure drop have been empirical and are acceptable up to ΔP = 10 in. H_2O. The pressure drop (ΔP) or the frictional loss is expressed in terms of the velocity head based on the cyclone inlet area. The frictional loss through cyclones is from 1 to 20 inlet velocity heads and depends on the geometric ratios. ΔP through a cyclone is given by

$$\Delta P = 0.003\rho_f v_i^2 N_H \tag{4-61}$$

where

$$N_H = K\left(\frac{ab}{D_e^2}\right) \quad (4\text{-}61)$$

K = 16 for no inlet vane

K = 7.5 with a neutral inlet vane

ΔP depends strongly on the inlet velocity and high velocities can cause both reentrainment and high pressure drop. However, entrainmnent can be reduced to a minimum, if the cyclone has a small base angle.

Trouble Shooting Cyclone Maloperations

In general, cyclones are used to separate particles from the gas stream, but recent developments have enabled cyclones to function as reactors. Some cyclone reactors can separate cracking catalyst from vaporized reaction products in the range of 950°F and 1,000°F, or can function as regenerators for flue gases between 1,250°F and 1,500°F. In both cases, the high particle velocities can cause rapid erosion of the cyclone material. This often results in poor performance of the cyclone. Other causes of poor cyclone performance are:

- Hole in cyclone body
- Cyclone volute plugged
- Dipleg unsealed
- Dipleg plugged
- Dipleg failure

Lieberman [15] has reviewed the causes of these maloperations, which often result in loss catalyst and reduced efficiency. A deficient cyclone reactor is identified by bottom sediment and water levels in the slurry oil product. For a regenerator cyclone, problems are visibly identified by the increased opacity of the regenerator flue gas or by reduced rates of spent catalyst withdrawal.

Cyclone Collection Efficiency

Many theories have been proposed to predict the performance of a cyclone, although no fundamental relationship has been accepted. Attempts have been made to predict the critical particle diameter, $(D_p)_{crit}$.

This is the size of the smallest particle that is theoretically separated from the gas stream with 50 percent efficiency. The critical particle diameter is defined by [16]

$$(D_p)_{crit} = \left[\frac{9\mu D_c}{4\pi N_t v_i(\rho - \rho_g)}\right]^{0.5} \tag{4-62}$$

where N_t = effective number of turns made by the gas stream in the cyclone, and is defined by

$$N_t = (v_i)\left[0.1079 - 0.00077v_i + 1.924(10^{-6})v_i^2\right] \tag{4-63}$$

and v_i = is the inlet linear velocity.

Figure 4-8 shows the percentage removal of particles in a cyclone as a function of the ratio of the particle to the critical diameter.

Cyclone Design Factor

Cyclones are designed to meet specified ΔP limitations. The factor that controls the collection efficiency is the cyclone diameter, and a smaller diameter cyclone at a fixed ΔP will have a higher efficiency. Therefore, small diameter cyclones require a multiple of units in parallel for a given capacity. Reducing the gas outlet diameter results in an increased collection efficiency and ΔP. High-efficiency cyclones have cone lengths in the range of 1.6 to 3.0 times the cyclone diameters.

Collection efficiency increases as the gas throughput increases. Kalen and Zenz [14] reported that collection efficiency increases with increasing gas inlet velocity to a minimum tangential velocity. This reaches the point where the dust is re-entrained or not deposited because of saltation. Koch and Licht [12] showed that saltation velocity is consistent with cyclone inlet velocities in the range of 50 to 90ft/sec.

Cyclones offer the least expensive means of dust collection. They give low efficiency for collection of particles smaller than 5μm. A high efficiency of 98 percent can be achieved on dusts with particle sizes of 0.1 to 0.2μm that are highly flocculated.

Cyclone Design Procedure

The following design procedures can be used to size a cyclone with a specified fluid flow rate and physical property data:

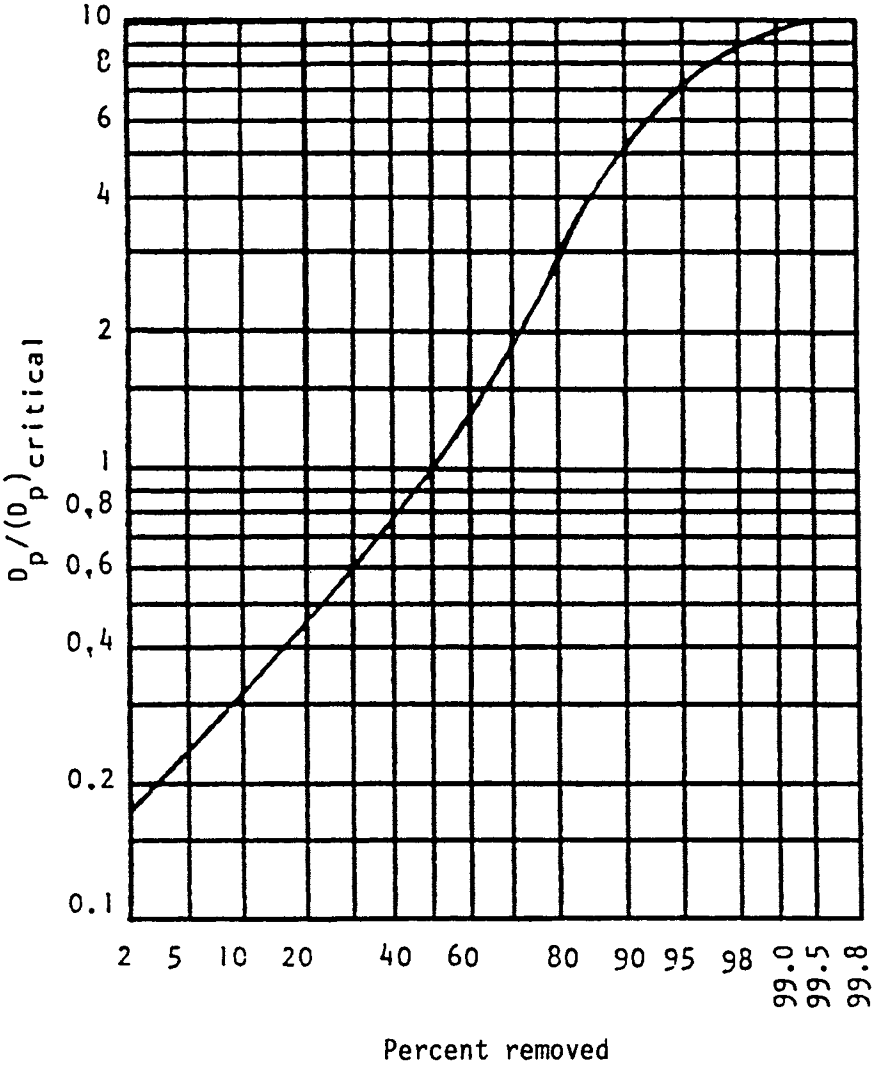


Figure 4-8. Percentage removal of particles as a function of particle diameter relative to the critical diameter.

1. Select either the high-efficiency or high-throughput design depending on the performance required.
2. Obtain an estimate of the particle size distribution of the solids in the stream to be treated.
3. Estimate the number of cyclones needed in parallel.
4. Calculate the cyclone diameter for an inlet velocity of 50 ft/sec.

5. Calculate the scale-up factor for the transposition of grade efficiency and particle size.
6. Calculate the cyclone performance and overall efficiency (recovery of solids). If unsatisfactory, try a smaller diameter.
7. Calculate the cyclone pressure drop and, if required, select a suitable blower.
8. Cost the system and optimize to make the best use of the pressure drop available or, if a blower is required, to give the lowest operating cost.

Nomenclature

a = inlet height, ft
b = inlet width, ft
B = cyclone dust-outlet diameter, ft
d = diameter of central core at a point where vortex turns, ft
d_{pi} = diameter of particle in size range i, ft
D_c = cyclone diameter, ft
D_e = cyclone gas-outlet diameter, ft
g = acceleration due to gravity, 32.2 ft/s^2
G = cyclone configuration factor
h = cylindrical height of cyclone, ft
i = subscript denotes interval in particle size range
$K_a = a/D_c$
$K_b = b/D_c$
K_c = cyclone volume constant
l = natural length (distance below gas outlet where vortex turns), ft
n = vortex exponent
N_H = number of inlet velocity heads
ΔP = pressure drop, in H_2O
Q = total gas flowrate, actual ft^3/s
S = gas outlet length, ft
T = temperature, °F
v_i = inlet velocity, ft/s
v_s = saltation velocity, ft/s
V_H = volume below exit duct (excluding core), ft^3
V_{nl} = volume at natural length (excluding core), ft^3
V_s = annular volume above exit duct to middle of entrance duct, ft^3
η_i = grade efficiency for particle size at midpoint of interval i, %
μ = fluid viscosity, lb$_m$/ft.s
ρ_f = fluid density, lb$_m$/ft^3

ρ_p = particle density, lb_m/ft^3
τ = relaxation time, s
ϖ = Equation 4-59

GAS DRYER (DEHYDRATION) DESIGN

Liquid water and sometimes water vapor are removed from natural gas to prevent corrosion and formation of hydrates in transmission lines and to attain a water dew point requirement of the sales of gas. Many sweetening agents employ an aqueous solution for treating the gas. Therefore dehydrating the natural gas that normally follows the sweetening process involves:

- dehydration by refrigeration
- absorption by liquid desiccants
- adsorption by solid desiccants

Adsorption is a process that involves the transfer of a material from one phase to a surface where it is bound by intermolecular forces. The process involves the transfer from a gas or liquid to a solid surface. It could also involve the transfer from a gas to a liquid surface. The adsorbate is the material being concentrated on the surface and the material that it accumulates is defined as the adsorbent.

The oil and chemical industries use the adsorption process in the cleanup and purification of wastewater streams and for the dehydration of gases. The process is also used in gas purification involving the removal of sulfur dioxide from a stack gas. In addition, adsorption is employed to fractionate fluids that are difficult to separate by other separating methods. The amount of adsorbate that is collected on a unit of surface area is negligible. Therefore, porous desiccants (adsorbent) having a large internal surface area are used for industrial applications.

There are many solid desiccants that can adsorb water from natural gas. The common commercial desiccants are alumina, silica gel, and molecular sieves. The molecular sieves possess the highest water capacity, will give the lowest water dew points, and can be applied to sweeten dry gases and liquids. Figure 4-9 shows how desiccants can be used in dehydrators containing two or more towers. One of the towers operates using steam to adsorb water from the gas, while the other tower is regenerated and cooled. The regenerated gas is heated to a range of 450°F and 600°F, depending on the type of solid desiccant and the nature of service [17].

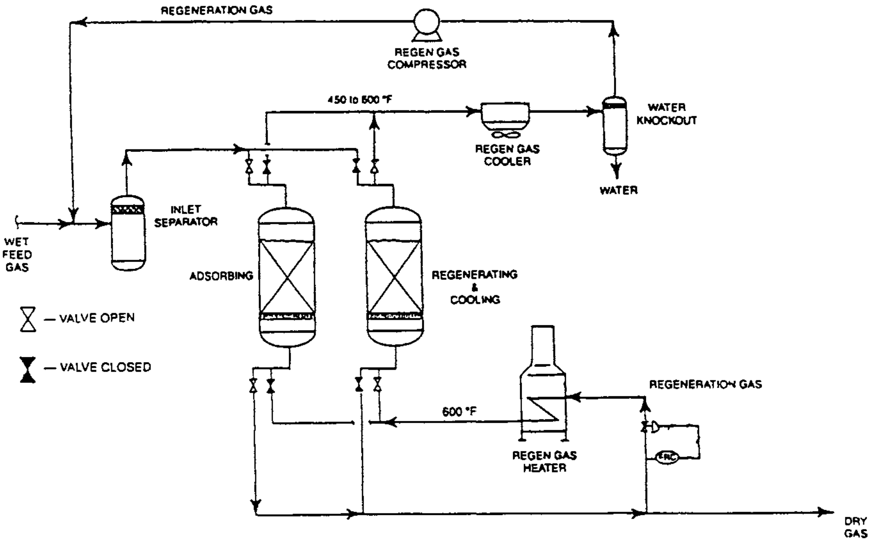


Figure 4-9. Solid desiccant dehydrator twin tower system. Courtesy: Gas Processors Suppliers Association *Engineering Data Book,* Tenth Edition.

The use of solid desiccant is limited to applications such as those with very low water dewpoint requirements, simultaneous control of water and hydrocarbon dewpoints, and in very sour gases. In cryogenic plant, solid-desiccant dehydration is much preferred over methanol injection to prevent hydrate and ice formation.

The basic design procedures for dehydrating saturated natural gas at a specified dew point are:

1. Determine the process conditions and the dryer process flow diagrams.
2. Select a drying cycle and calculate the water load.
3. Select the type of desiccant and compute the capacity and volume required.
4. Size the dryer and check for the pressure drop.
5. Calculate the desiccant reactivation heating and cooling requirements.

Here, design procedures are presented for sizing a solid desiccant dryer in removing moisture from gas streams. The process involves the following calculations.

1. the water pickup
2. desiccant volume

3. desiccant bed
4. gas velocity through the bed
5. vessel weight
6. dryer regeneration requirements

The design is based upon the following assumptions [2]:

1. The temperature difference between the heater outlet temperature and the peak vessel outlet temperature is 50°F.
2. The average bed temperature is based on 75 percent of the bed at heater outlet temperature and 25 percent at the peak vessel outlet temperature Equation 4-73.
3. Specific heats: steel, 0.12 Btu/lb °F, and desiccant 0.25 Btu/lb °F.
4. Heat of water desorption 1400 Btu/lb H_2O adsorbed.
5. Flat heads used on vessel ends; steel density is 480 lb/ft^3.
6. Total vessel weight increased by 10 percent for supports.
7. Heat losses to the dryer during heating period calculated at 5 percent.

The Equations

The equations used for calculating these requirements are:
The total water adsorbed, lb

$$H_2O\ \text{load} = \frac{(\text{Flow})(\text{Cycle})(H_2O\ \text{Cont})}{24}$$

$$= \frac{\left(\dfrac{\text{MMstd ft}^3}{\text{day}}\right)(\text{h})\left(\dfrac{\text{lb}}{\text{MMstd ft}^3}\right)}{(\text{h/day})} \tag{4-64}$$

Desiccant volume

$$V_{DES} = \frac{(H_2O\ \text{load})(100)}{(\text{pickup})(\rho_D)} \tag{4-65}$$

The calculated area based on desiccant volume

$$A_{DES} = \frac{V_{DES}}{L} \tag{4-66}$$

The bed diameter

$$D_{BED} = \left(\frac{4A_{DES}}{\pi}\right)^{0.5} \tag{4-67}$$

actual desiccant bed area

$$A = \frac{\pi D_{BED}^2}{4} \tag{4-68}$$

The actual gas flowrate at flowing conditions, ft^3/min

$$\begin{aligned} Q &= (\text{Flow})\left(\frac{14.7}{P + 14.7}\right)\left(\frac{T}{520}\right)\left(\frac{1}{1440}\right)(Z) \\ &= (\text{Flow})\left(\frac{T}{P + 14.7}\right)(Z)(19.6314) \end{aligned} \tag{4-69}$$

Superficial gas velocity, ft/min

$$V_{GAS} = \frac{Q}{A} \tag{4-70}$$

Superficial gas velocities for adequate contact time should range between 30 and 60ft/min

Dryer shell thickness, inch

$$t = \frac{PR}{SE - 0.6P} \tag{4-71}$$

Vessel weight

$$W_{VES} = 480\pi D\left(\frac{t}{12}\right)(L + h + R)(1.10) \tag{4-72}$$

Add an extra 2 ft (h = 2) of straight side (i.e., for 6 in. of 3/8-in. inert balls above and below the desiccant bed and 1 ft for an inlet-gas distributor).

Temperature of desiccant bed, °F

$$T_{BED} = 0.75(HT) + 0.25(HT - 50) \tag{4-73}$$

Total heat required to regenerate the dryer (ideal), Btu

$$\begin{aligned} H_{TOT} = \{&(W_{VES})(0.12)(T_{BED} - T) + (W_D)(0.25)(T_{BED} - T) \\ &+ (H_2O\ \text{load})(1400)\}(1.05) \end{aligned} \tag{4-74}$$

where

$$W_D = (\rho_D)(V_{DES})$$

loss factor for non-steady state heating, F

$$F = \ln\left(\frac{HT - T}{50}\right) \tag{4-75}$$

Heat added to regeneration gas to regenerate the desiccant bed

$$H_{REG} = H_{TOT} \cdot F \tag{4-76}$$

The total regeneration gas requirement, lb

$$H_{GAS} = \frac{H_{REG}}{H_1 - H_2} \tag{4-77}$$

Standard cubic feet of regeneration gas

$$SCF = \frac{H_{GAS}(380)}{MW} \tag{4-78}$$

Pressure Drop (ΔP)

The pressure drop is estimated from the desiccant manufacturer's data and correlations. In addition, ΔP can be calculated by Wunder's [18] graphical correlation of gas superficial velocity against ΔP in ft water per ft bed. Wunder used a factor of 1.6 for a fouled bed. ΔP through a new desiccant bed is initially low. After a short time in service, ΔP rises because of bed settling and then slowly increases over the active life of the desiccant because of more settling and some attrition. Figure 4-10 shows ΔP for an 8-inch silica gel desiccant. These data are based on air. For other gases, the given values should be multiplied by (MW gas/MW air)$^{0.9}$. The pressure drop for a clean bed is given by:

$$\Delta P = \left(\frac{\text{ft } H_2O}{\text{ft bed}}\right)\left(\frac{0.4335\text{psi}}{\text{ft } H_2O}\right)\left(\frac{\text{MWgas}}{\text{MWair}}\right)^{0.9} \tag{4-79}$$

Fouled bed:

$$\Delta P = \text{clean bed } \Delta P \times 1.6 \tag{4-80}$$

Desiccant attrition due to high gas velocities is controlled by proper bed design. The superficial gas velocity is used to estimate Alcoa's

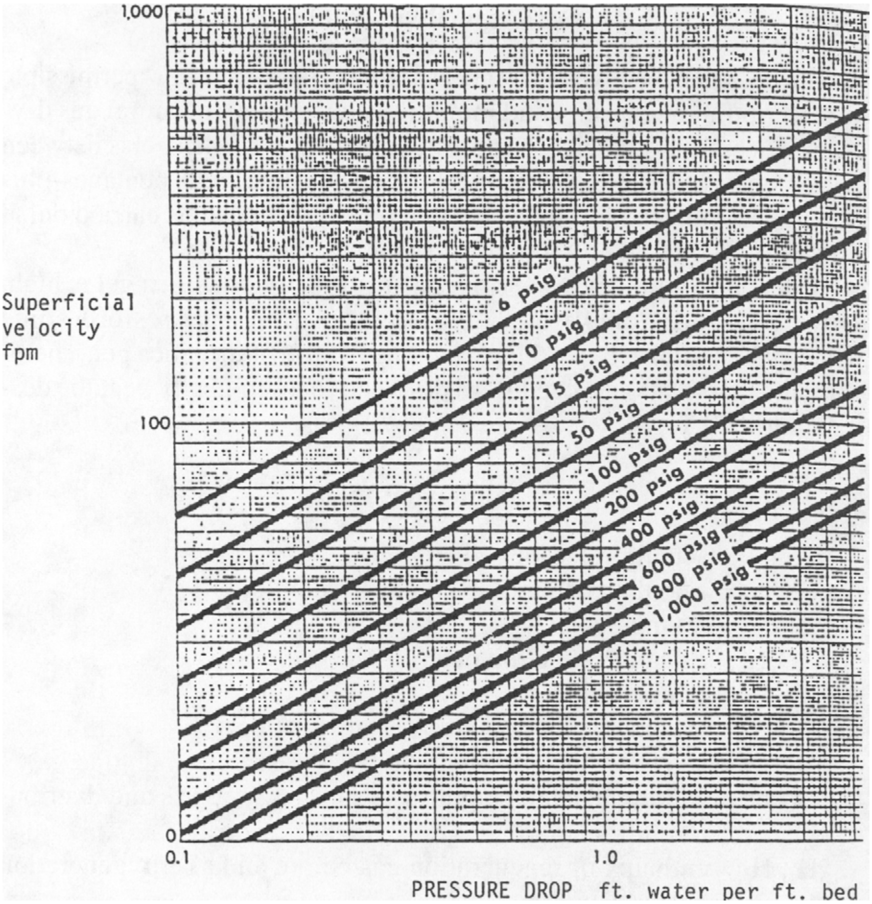


Figure 4-10. Pressure drop for an 8 mesh silica gel desiccant (by permission Oil & Gas Journal).

momemtum downflow velocities [18]. However, desiccant attrition should not be a problem when the momentum number is equal to or less than 30,000. Although, this number is based on granular alumina, it can be used for silica gel, which has crushing characteristics similar to alumina. The momentum is expressed as:

$$\text{Momentum} = (V_{GAS})(MW)\left(\frac{P + 14.7}{14.7}\right) \leq 30,000 \qquad (4\text{-}81)$$

where V_{GAS} = superficial gas velocity, ft/min
MW = molecular weight of gas
P = system pressure in psig

Desiccant Reactivation

The desiccant bed is reactivated at as high a temperature as permissible to start optimum capacity and minimum dew points. In natural gas drying service, the normal reactivation temperature for silica gel is between 350°F and 400°F. Because the feed gas contains high pentanes-plus materials, Wunder [18] suggested that reactivation can be carried out at 450°F to desorb the heavy hydrocarbons.

At a temperature above 450°F, the attrition rate for silica gel is high. However, occasionally at 600°F, reactivation will restore some desiccant's initial activity thus extending the life of the silica gel. Therefore, the reactivation procedure is designed to periodically heat the desiccant to 600°F [18].

Nomenclature

A = actual desiccant bed area, ft^2
A_{DES} = calculated area based on desiccant volume, ft^2
Cycle = drying cycle, h
D_{BED} = calculated bed diameter, ft
E = joint efficiency
F = loss factor for non-steady state heating
Flow = gas flow rate, 10^6 std ft^3/day
h = additional shell height for desiccant supports and distributor, ft
H_1, H_2 = enthalpy of regeneration gas before and after regeneration heater, Btu/lb
H_{GAS} = total regeneration gas requirement, lb
H_{REG} = heat added to regeneration gas to regenerate desiccant bed
H_{TOT} = heat required to regenerate dryer (ideal), Btu
HT = heater temperature, °F
H_2O load = total water adsorbed, lb
H_2O Cont = water content of gas, lb/10^6 std ft^3
L = desiccant bed length, ft
MW = molecular weight of regeneration gas
P = dryer operating pressure, psig
PICKUP = useful design capacity of desiccant, %
Q = actual gas flow rate at flowing conditions, ft^3/min
R = radius of desiccant bed, ft
S = allowable stress, lb/in^2
SCF = standard cubic feet of regeneration gas

t = dryer shell thickness, inch
T = gas flowing temperature, °R
TB = temperature of desiccant bed, °F
V_{DES} = desiccant volume, ft^3
V_{GAS} = superficial gas velocity, ft/min
W_D = desiccant weight, lb
WS = steel weight of shell and heads, lb
W_{VES} = vessel weight, lb
Z = compressibility factor
ρ_D = desiccant density, lb/ft3

PROBLEMS AND SOLUTIONS

Problem 4-1

Size a vertical separator under the following conditions:

WL = 5000 lb/h	WV = 37,000 lb/h
ρ_L = 61.87 lb/ft^3	ρ_V = 0.374 lb/ft^3

The liquid surge time is five minutes.

Size a horizontal separator for the following conditions:

WL = 56,150 lb/h	WV = 40,000 lb/h
ρ_L = 60.0 lb/ft^3	ρ_V = 1.47 lb/ft^3

The liquid surge time is six minutes.

Use L/D = 3.0

Solution

The computer program PROG41 sizes both the vertical and horizontal separators. Table 4-5 shows the input data and computer output for both separators. From the computed output, the diameter of the vertical separator with the given flow data and physical properties is 2.88 ft, the liquid height is 1.03 ft and the vessel volume is 6.74 ft^3. The computer output for the horizontal separator gives its diameter as 4.13 ft, the vessel length is 12.39 ft, and volume is 165.82 ft^3.

Figure 4-7 gives a nomograph of the vapor rise in horizontal vessels. A check of the vapor area with 20 percent of the total cross-sectional

Table 4-5
Input Data and Computer Output for Vertical and Horizontal Separators

```
DATA41.DAT
-------------------
1
5000.0  37000.0
61.87    0.374
5.0
2
56150.0  40000.0
60.0     1.47    6.0
3.0


                        VERTICAL SEPARATOR SIZING
*****************************************************************************
    LIQUID FLOWRATE, lb/hr.:                                         5000.
    VAPOR FLOWRATE, lb/hr.:                                         37000.
    LIQUID DENSITY, lb/ft^3.:                                      61.870
    VAPOR DENSITY, lb/ft^3.:                                         .374
    LIQUID VOLUMETRIC RATE, ft^3/sec.:                             92.1232
    VAPOR VOLUMETRIC RATE, ft^3/sec.:                                .0224
    LIQUID SURGE TIME, min.:                                       5.0
    SEPARATION FACTOR:                                             .0105
    VAPOR VELOCITY FACTOR:                                           .329
    MAXIMUM VAPOR VELOCITY, ft/s.:                                 4.213
    VESSEL DIAMETER, ft:                                           2.882
    MINIMUM VAPOR-LIQUID NOZZLE VELOCITY, ft/s.:                  27.481
    MAXIMUM VAPOR-LIQUID NOZZLE VELOCITY, ft/s.:                 153.539
    REQUIRED VESSEL VOLUME, ft^3:                                  6.735
    LIQUID HEIGHT, ft.:                                            1.032
-----------------------------------------------------------------------------

                        HORIZONTAL SEPARATOR SIZING
*****************************************************************************
    LIQUID FLOWRATE, lb/hr.:                                        56150.
    VAPOR FLOWRATE, lb/hr.:                                         40000.
    LIQUID DENSITY, lb/ft^3.:                                      60.000
    VAPOR DENSITY, lb/ft^3.:                                        1.470
    LIQUID VOLUMETRIC RATE, ft^3/sec.:                              .2600
    VAPOR VOLUMETRIC RATE, ft^3/sec.:                              7.5586
    LIQUID SURGE TIME, min.:                                        6.000
    LENGTH TO DIAMETER RATIO (L/D):                                3.0
    SEPARATION FACTOR:                                              .220
    VAPOR VELOCITY FACTOR:                                          .447
    VAPOR VOLUMETRIC RATE, ft^3/s.:                                7.559
    MAXIMUM VAPOR VELOCITY, ft/s.:                                 2.823
    VESSEL DIAMETER, ft.:                                          4.129
    VESSEL LENGTH, ft.:                                           12.386
    VESSEL VOLUME, ft^3.:                                        165.815
    CALCULATED LIQUID SURGE TIME, min.:                            8.505
-----------------------------------------------------------------------------
```

area and the computed diameter of 4.13 ft shows that the vapor rise is approximately 12 inches.

Problem 4-2

Estimate the liquid volume in a horizontal storage tank that has a diameter of 120 inches, a length of 200 inches, and contains 40 inches of liquid. Calculate the liquid volume for a vertical tank and for tanks with either flat heads, dished heads, elliptical and hemispherical.

Solution

The computer program PROG42 calculates the liquid volume in a horizontal tank and for tanks with flat, dished, elliptical and hemispherical heads. Table 4-6 shows the input data and computer output for a vertical tank and tanks with flat, dished, elliptical and hemispherical heads.

Problem 4-3

Estimate the weight of a pressure vessel with hemispherical heads. The vessel is 2 ft 6 in ID × 10 ft – 0 in T/T and has a design pressure of 1000 psig.

2SF = 4 in	$E_{shell} = 0.85$
c = 0.125 in	$E_{head} = 1.0$
$\rho_s = 489.024$ lb/ft^3	S = 17,500 lb/in^2

Solution

The computer program PROG43 determines the vessel weight of the pressure vessel with hemispherical, elliptical, and torispherical heads. Table 4-7 gives input data and computer output for 2 ft 6 in.-diameter vessel. The output gives the shell and head thicknesses, the weights of the shell and head, and the total weight of the vessel with hemispherical, elliptical and torispherical heads.

Problem 4-4

Determine the efficiency and pressure drop (ΔP) based on cyclone dimensions and the gas flow rate at 516.7 ft^3/s. and a density of 0.075 lb/ft^3 containing particles with density of 62.43 lb/ft^3.

The dimensions and data required are:

Cyclone gas inlet height, ft	4.5
Cyclone gas inlet width, ft	1.896
Cyclone gas outlet length, ft	3.448
Cyclone gas outlet diameter, ft	3.792
Cyclone overall height, ft	26.333
Cyclone cylindrical height, ft	8.552
Cyclone diameter, ft	6.333

(text continued on page 296)

Table 4-6
Input Data and Computer Outputs for Tank Volume with Flat, Dished, Elliptical and Hemispherical Heads, and Vertical Tank Volume

```
DATA42.DAT
----------------
1
120.  40.  200.
2
120.  40.  200.
3
120.  40.  200.
4
120.  40.  200.
5
120.  40.  200.
```

```
                        TANK VOLUME WITH FLAT HEADS
*****************************************************************************
    TANK DIAMETER, in.:                                        120.000
    LIQUID DEPTH, in.:                                          40.000
    TANK LENGTH, in.:                                          200.000
    TANK VOLUME, in.^3:                                         .660017E+06
    TANK VOLUME, ft.^3:                                         .381954E+03
    TANK VOLUME, gal:                                           .285721E+04
    TANK VOLUME, bbl:                                           .680279E+02
-----------------------------------------------------------------------------


                        TANK VOLUME WITH DISHED HEADS
*****************************************************************************
    TANK DIAMETER, in.:                                        120.000
    LIQUID DEPTH, in.:                                          40.000
    TANK LENGTH, in.:                                          200.000
    TANK VOLUME, in^3:                                          .662430E+06
    TANK VOLUME, ft.^3:                                         .383351E+03
    TANK VOLUME, gal:                                           .286766E+04
    TANK VOLUME, bbl:                                           .682767E+02
-----------------------------------------------------------------------------


                        TANK VOLUME WITH ELLIPTICAL HEADS
*****************************************************************************
    TANK DIAMETER, in.:                                        120.000
    LIQUID DEPTH, in.:                                          40.000
    TANK LENGTH, in.:                                          200.000
    TANK VOLUME, in.^3:                                         .894589E+06
    TANK VOLUME, ft.^3:                                         .517702E+03
    TANK VOLUME, gal:                                           .387268E+04
    TANK VOLUME, bbl:                                           .922053E+02
-----------------------------------------------------------------------------


                        TANK VOLUME WITH HEMISPHERICAL HEADS
*****************************************************************************
    TANK DIAMETER, in.:                                        120.000
    LIQUID DEPTH, in.:                                          40.000
    TANK LENGTH, in.:                                          200.000
    TANK VOLUME, in.^3:                                         .112916E+07
    TANK VOLUME, ft.^3:                                         .653450E+03
    TANK VOLUME, gal:                                           .488814E+04
    TANK VOLUME, bbl:                                           .116383E+03
-----------------------------------------------------------------------------


                        VERTICAL TANK VOLUME
*****************************************************************************
    TANK DIAMETER, in.:                                        120.000
    LIQUID DEPTH, in.:                                          40.000
    TANK LENGTH, in.:                                          200.000
```

Table 4-6
(continued)

```
    TANK VOLUME, in.^3:                                               .452389E+06
    TANK VOLUME, ft.^3:                                               .261799E+03
    TANK VOLUME, gal:                                                 .195839E+04
    TANK VOLUME, bbl:                                                 .466278E+02
-------------------------------------------------------------------------------
```

Table 4-7
Input Data and Computer Outputs for Vessel Design with Hemispherical, Ellipsoidal and Torispherical Heads

```
DATA43.DAT
--------------------------
1
30.0  10.0   1000.0
2.0   0.125  489.024
0.85  1.0    17500.
2
30.0  10.0   1000.0
2.0   0.125  489.024
0.85  1.0    17500.0
3
30.0  10.0   1000.0
2.0   0.125  489.024
0.85  1.0    17500.0 2.0
```

```
                        VESSEL DESIGN WITH HEMISPHERICAL HEADS
*******************************************************************************
    INTERNAL DIAMETER, in.:                                      30.000
    SHELL LENGHT, ft.:                                           10.000
    INTERNAL DESIGN PRESSURE, psig:                            1000.000
    STRAIGHT FLANGE LENGTH, in.:                                  2.000
    CORROSION ALLOWANCE, in.:                                      .125
    DENSITY OF VESSEL MATERIAL, lb/ft^3.:                       489.024
    JOINT EFFICIENCY OF SHELL:                                     .850
    JOINT EFFICIENCY OF HEAD:                                     1.000
    ALLOWABLE STRESS, lb/in^2.:                               17500.000
    CALCULATED SHELL THICKNESS, in.:                              1.176
    CALCULATED HEAD THICKNESS, in.:                                .431
    WEIGHT OF VESSEL SHELL, lb:                                     4205.77
    WEIGHT OF VESSEL HEAD, lb:                                       595.80
    TOTAL VESSEL WEIGHT, lb:                                        4801.58
-------------------------------------------------------------------------------


                        VESSEL DESIGN WITH ELLIPSOIDAL HEADS
*******************************************************************************
    INTERNAL DIAMETER, in.:                                      30.000
    SHELL LENGTH, ft.:                                           10.000
    INTERNAL DESIGN PRESSURE, psig.:                           1000.000
    STRAIGHT FLANGE LENGTH, in.:                                  2.000
    CORROSION ALLOWANCE, in.:                                      .125
    DENSITY OF VESSEL MATERIAL, lb/ft^3.:                       489.024
    JOINT EFFICIENCY OF SHELL:                                     .850
    JOINT EFFICIENCY OF HEAD:                                     1.000
    ALLOWABLE STRESS, lb/in^2.:                               17500.000
    CALCULATED SHELL THICKNESS, in.:                              1.176
    CALCULATED HEAD THICKNESS, in.:                                .987
    WEIGHT OF VESSEL SHELL, lb:                                     4205.77
    WEIGHT OF VESSEL HEAD, lb:                                       853.98
    TOTAL VESSEL WEIGHT, lb:                                        5059.75
-------------------------------------------------------------------------------


                        VESSEL DESIGN WITH TORISPHERICAL HEADS
```

(table continued on next page)

Table 4-7
(continued)

```
******************************************************************************
    INTERNAL DIAMETER, in.:                                   30.000
    SHELL LENGTH, ft.:                                        10.000
    INTERNAL DESIGN PRESSURE, psig.:                        1000.000
    STRAIGHT FLANGE LENGTH, in.:                               2.000
    CORROSION ALLOWANCE, in.:                                   .125
    DENSITY OF VESSEL MATERIAL, lb/ft^3.:                    489.024
    JOINT EFFICIENCY OF SHELL:                                  .850
    JOINT EFFICIENCY OF HEAD:                                  1.000
    ALLOWABLE STREES, lb/in.^2:                            17500.000
    CALCULATED SHELL THICKNESS, in.:                           1.176
    CALCULATED HEAD THICKNESS, ft.:                             .227
    WEIGHT OF VESSEL SHELL, lb:                                  4205.77
    WEIGHT OF VESSEL HEAD, lb:                                    155.37
    TOTAL VESSEL WEIGHT, lb:                                     4361.15
------------------------------------------------------------------------------
```

(text continued from page 293)

Cyclone dust-outlet diameter, ft	2.533
Gas rate, ft^3/s	516.7
Gas density, lb/ft^3	0.075
Gas viscosity, lb/ft s	1.28×10^{-5}
Temperature, °F	110
Particle size, ft	3.281×10^{-5}

Solution

The computer program PROG44 calculates the pressure drop and the efficiency of the cyclone using the cyclone geometry, fluid and particle specifications. Table 4-8 gives the input data and computer results with an efficiency of 63.305%, and a pressure drop of 7.834 in H_2O. The calculated ratio of the particle diameter relative to the critical diameter is 0.51. From Figure 4-8, the percentage removal of the particle is 23%.

Problem 4-5

Size a dryer to operate under the following conditions as shown in Table 4-9 using silica gel as the adsorbent.

Solution

The computer program PROG45 calculates the size of the dryer using silica gel, and Table 4-10 illustrates the input data and computer output. The total regeneration flow is 44649.0 lb and the momentum is 30,584. The heat requirement for dryer regeneration is 5.6×10^8 Btu. The calculated superficial gas velocity is 34.95ft/min.

Table 4-8
Input Data and Computer Output for Cyclone Design

```
DATA44.DAT
-----------------------------
26.333  8.552  6.333  2.533
4.5     1.896  3.448  3.792
516.7   62.43  0.075  0.0000128
110.0   0.00003281
```

```
                              CYCLONE DESIGN
*****************************************************************************
    CYCLONE OVERALL HEIGHT, ft:                                 26.333
    CYCLONE CYLINDRICAL HEIGHT, ft.:                             8.552
    CYCLONE DIAMETER, ft.:                                       6.333
    CYCLONE DUST-OUTLET DIAMETER, ft:                            2.533
    CYCLONE GAS INLET LENGTH, ft:                                4.500
    CYCLONE GAS INLET WIDTH, ft:                                 1.896
    CYCLONE GAS OUTLET LENGTH, ft:                               3.448
    CYCLONE GAS OUTLET DIAMETR, ft:                              3.792
    GAS RATE, ft^3/s.:                                           516.70
    PARTICLE DENSITY, lb/ft^3:                                  62.430
    GAS DENSITY,  lb/ft^3:                                        .075
    GAS VISCOSITY, lb/ft.s.:                                   .128000E-04
    GAS TEMPERATURE, oF:                                        110.000
    PARTICLE SIZE (EQUIVALENT DIA.),ft.:                       .328100E-04
    VORTEX EXPONENT:                                             .7276
    RELAXATION TIME, s:                                        .291691E-03
    INLET FLUID VELOCITY, ft/s.:                                60.560
    SALTATION VELOCITY, ft/s.:                                  22.108
    CYCLONE CONFIGURATION FACTOR:                               89.728
    CYCLONE PRESSURE DROP, in H2O:                               7.834
    RATIO OF THE INLET TO THE SALTATION VELOCITIES:              2.739
    CYCLONE EFFICIENCY, %:                                      63.305
    EFFECTIVE NUMBER OF TURNS:                                   3.71
    CRITICAL PARTICLE DIAMETER, ft.:                            .643700E-04
    CRITICAL PARTICLE DIAMETER, microns:                        .196200E+02
    RATIO OF PARTICLE DIA. TO CRITICAL DIA.:                      .51
-----------------------------------------------------------------------------
```

Table 4-9
Dryer Parameters

Flow = 65 MM std ft^3/day	Desiccant H_2O cap = 8%
P = 700 psig	Desiccant density = 50 lb/ft^3
T = 80°F	Desiccant bed length = 15ft
Z = 0.9228	Heater outlet = 500°F
H_2O Cont = 47 lb/MM std ft^3	MW = 18
S = 15,500 lb/in^2	H_1 = 490 Btu/lb
E = 1.0	H_2 = 225 Btu/lb
Cycle = 12h	h = 2.0ft

From Figure 4-10,

Superficial gas velocity = 35 ft/min

Desiccant bed length = 15.0 ft

System pressure = 700 psig

The clean bed ΔP using Equation 4-79 is

$$\Delta P = 0.87\frac{\text{ft H}_2\text{O}}{\text{ft bed}}\left(\frac{0.4335\text{psi}}{\text{ft H}_2\text{O}}\right)(15.0\text{ ft bed})\left(\frac{18}{29}\right)^{0.9}$$

$$= 3.68\text{psi}$$

Table 4-10
Input Data and Computer Output for Gas Dryer Design

```
DATA45.DAT
---------------------
65.0    700.0  80.0
0.9228  12.0   47.0
15500.0  1.0   8.0
50.0    15.0   500.0
18.0    490.0  225.0


                                 GAS DRYER DESIGN
******************************************************************************
    GAS FLOW RATE, 10^6 std. ft^3/day:                          65.000
    DRYER OPERATING PRESSURE, psig.:                           700.000
    GAS FLOWING TEMPERATURE, oF:                                  80.0
    GAS COMPRESSIBILITY FACTOR:                                  .9228
    DRYING CYCLE, hr.:                                            12.0
    WATER CONTENT OF GAS, lb/10^6 std.ft^3:                        47.
    ALLOWABLE STRESS, psi:                                     15500.0
    JOINT EFFICIENCY:                                              1.0
    USEFUL DESIGN CAPACITY OF DESICCANT, (%):                      8.0
    DESICCANT DENSITY, lb/ft^3:                                   50.0
    HEATER OUTLET TEMPERATURE, oF:                               500.0
    MOLECULAR WEIGHT OF REGENERATION GAS:                         18.0
    ENTHALPY OF GAS BEFORE REGENERATION HEATER, Btu/lb:          490.0
    ENTHALPY OF GAS AFTER REGENERATION HEATER, Btu/lb:           225.0
    TOTAL WATER ADSORBED, lb/h.:                              1527.500
    DESICCANT VOLUME, ft^3.:                                  381.8750
    CALCULATED CROSS-SECTIONAL AREA, ft^2.:                    25.4583
    BED DIAMETER, ft.:                                      5.6934
    BED RADIUS, ft.:                                       34.1603
    BED LENGTH, ft.:                                         15.00
    ACTUAL GAS FLOW RATE, ft^3/min.:                           889.697
    SUPERFICIAL GAS VELOCITY, ft./min.:                         34.947
    DRYER SHELL THICKNESS, in.:                                 1.5857
    VESSEL WEIGHT, lb.:                                         24767.
    DESICCANT WEIGHT, lb.:                                      19094.
    TEMPERATURE OF DESICCANT BED, oF:                          487.500
    TOTAL HEAT REQUIRED TO REGENERATE DRYER, Btu:            .555954E+07
    LOSS FACTOR:                                                2.1282
    HEAT ADDED TO REGENERATION GAS:                          .118320E+08
    TOTAL REGENERATION GAS REQUIREMENT, lb:                  .446490E+05
    STANDARD CUBIC FEET OF REGENERATION GAS, std.ft^3:       .942590E+06
    MOMENTUM:                                                .305838E+05
---------------------------------------------------------------------------
```

$$\text{Fouled } \Delta P = 3.68 \times 1.6$$

$$= 5.89 \text{ psi}$$

The actual regeneration flow rate (lb/h) will depend upon the length of the heating cycle used.

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```
        PROGRAM PROG41

C       *********************************************************************
C       THIS PROGRAM USES THE WELL-KNOWN SOUDERS AND BROWN CORRELATION
C       COUPLED WITH LIQUID SURGE CAPACITY TO SIZE LIQUID-VAPOR SEPARATORS.
C       THE PROGRAM SIZES BOTH VERTICAL AND HORIZONTAL SEPARATORS
C       *********************************************************************
C       HL      =    LIQUID HEIGHT, ft.
C       SFac(SF)=    SEPARATION FACTOR
C       KV      =    VAPOR VELOCITY FACTOR FOR VERTICAL SEPARATORS
C       VM      =    MAXIMUM VAPOR VELOCITY, ft/s
C       WL      =    LIQUID FLOW RATE, lb/hr.
C       WV      =    VAPOR FLOW RATE, lb/hr.
C       DENL    =    LIQUID DENSITY, lb/ft^3.
C       DENV    =    VAPOR DENSITY, lb/ft^3
C       QV      =    VAPOR VOLUMETRIC FLOW, ft^3/s
C       D       =    VESSEL DIAMETER, ft
C       A       =    CROSS-SECTIONAL AREA OF VERTICAL SEPARATOR, ft^2
C       AV      =    MINIMUM CROSS-SECTIONAL AREA OF VERTICAL SEPARATOR, ft^2
C       QL      =    LIQUID VOLUMETRIC FLOW, ft^3/s
C       T       =    LIQUID SURGE TIME, min.
C       KH      =    VAPOR VELOCITY FACTOR FOR HORIZONTAL SEPARATORS
C       AT      =    TOTAL CROSS-SECTIONAL AREA OF HORIZONTAL VESSEL, ft^2
C       L       =    HORIZONTAL VESSEL LENGTH, ft
C       AL      =    CROSS-SECTIONAL AREA OF HORIZONTAL VESSEL OCCUPIED BY
C                    LIQUID PHASE, ft^2
C       X       =    ln(S.Fac)
C       *********************************************************************
C
C
        REAL KH, KV1, L
        COMMON B, D, E, F, G, PI

        COMMON/DATA1/ WL1, WV1, DENL1, DENV1, T1
        COMMON/DATA2/ SF1, KV1, VMAX1, D1
        COMMON/DATA3/ UMAX, UMIN, QL1, QV1, V, HL
        COMMON/DATA4/ WL2, WV2, DENL2, DENV2, RATIO
        COMMON/DATA5/ SF2, KH, QL2, QV2, VMAX2, D2, L, VESVOL, T2, CALT2


        OPEN (UNIT=3, FILE='DATA41.DAT', STATUS='OLD', ERR=18)
        OPEN (UNIT=1, FILE='PRN')

        PI = 3.1415927
C
C       CONSTANTS FOR VAPOR VELOCITY FACTOR

        B = -1.877478
        D = -0.814580
        E = -0.187074
        F = -0.014523
        G = -0.001015


 5      READ (3, *, ERR=19) I

        GO TO (11, 22),I

C       READ LIQUID FLOW RATE, WL1: lb/hr.
```

```
C       READ VAPOR FLOW RATE, WV1: lb/hr.
C       READ LIQUID DENSITY, DENL1: lb/ft^3.
C       READ VAPOR DENSITY, DENV1: lb/ft^3.
C       READ LIQUID SURGE TIME, T1: min.

 11     READ (3, *, ERR=19) WL1, WV1
        READ (3, *, ERR=19) DENL1, DENV1
        READ (3, *, ERR=19) T1

        GO TO 33

C       READ LIQUID FLOW RATE, WL2: lb/hr.
C       READ VAPOR FLOW RATE, WV2: lb/hr.
C       READ LIQUID DENSITY, DENL2: lb/ft^3.
C       READ VAPOR DENSITY, DENV2: lb/ft^3.
C       READ LIQUID SURGE TIME, T2: min.
C       READ LENGTH-TO-DIAMETER RATIO, RATIO.


 22     READ (3, *, ERR=19) WL2, WV2
        READ (3, *, ERR=19) DENL2, DENV2, T2
        READ (3, *, ERR=19) RATIO

        GO TO 44

 18     WRITE (*, 20)
 20     FORMAT (6X, 'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 21)
 21     FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

C       COMPUTE THE SIZING OF THE VERTICAL SEPARATOR

 33     CALL VERT

C       OUTPUT THE RESULTS OF THE VERTICAL SEPARATOR

        CALL OUTV

        GO TO 5

C       COMPUTE THE SIZING OF THE HORIZONTAL SEPARATOR

 44     CALL HORIZ

C       OUTPUT THE RESULTS OF THE HORIZONTAL SEPARATOR
        CALL OUTH

        GO TO 999

        CLOSE (3, STATUS='KEEP')
        CLOSE (1)

  999   STOP
        END

C       ***************************************************************
C       THIS PROGRAM SIZES VERTICAL LIQUID-VAPOR SEPARATORS
```

```
C       ***************************************************************
C
        SUBROUTINE VERT

        REAL KV1

        COMMON B, D, E, F, G, PI
        COMMON/DATA1/ WL1, WV1, DENL1, DENV1, T1
        COMMON/DATA2/ SF1, KV1, VMAX1, D1
        COMMON/DATA3/ UMAX, UMIN, QL1, QV1, V, HL

C       CALCULATE THE SEPARATION FACTOR

        SF1 = (WL1/WV1)*SQRT(DENV1/DENL1)
        X1 = ALOG(SF1)
        VAL1 = B+(D*X1)+(E*(X1**2))+(F*(X1**3))+(G*(X1**4))

C       CALCULATE THE VAPOR VELOCITY FACTOR, ft./s.

        KV1 = EXP(VAL1)

C       CALCULATE THE MAXIMUM VAPOR VELOCITY, ft./s.

        VMAX1 = KV1*SQRT((DENL1-DENV1)/DENV1)

C       CALCULATE THE VOLUMETRIC RATE, ft^3/sec.

        QV1 = WV1/(DENV1*3600.0)

        AV1 = QV1/VMAX1

C       CALCULATE THE DIAMETER OF THE VESSEL, ft.

        D1 = SQRT((4.0*AV1)/PI)
        AREA = (PI*D1**2)/4.0
C
C       CALCULATE THE VAPOR-LIQUID INLET NOZZLE VELOCITIES.

        DENM = (WL1+WV1)/((WL1/DENL1)+(WV1/DENV1))
        UMAX = 100.0/(DENM**0.5)
        UMIN = 60.0/(DENM**0.5)

C       CALCULATE THE LIQUID VOLUMETRIC RATE, ft^3/sec.

        QL1 = WL1/(DENL1*3600.)


C       CALCULATE THE REQUIRED VESSEL VOLUME, ft^3.

        V = (QL1*T1*60.0)

C       CALCULATE THE LIQUID HEIGHT, ft.

        HL = V/AREA

        RETURN
        END
C
C       ***************************************************************
C       THIS PROGRAM SIZES HORIZONTAL LIQUID-VAPOR SEPARATOR

C       ***************************************************************

        SUBROUTINE HORIZ

        REAL L, KH, KV2
        COMMON B, D, E, F, G, PI
        COMMON/DATA4/ WL2, WV2, DENL2, DENV2, RATIO
        COMMON/DATA5/ SF2, KH, QL2, QV2, VMAX2, D2, L, VESVOL, T2, CALT2
```

```
C       CALCULATE THE VAPOR-LIQUID SEPARATION FACTOR

        SF2 = (WL2/WV2)*SQRT(DENV2/DENL2)
        X2 = ALOG(SF2)
        VAL2 = B+(D*X2)+(E*(X2**2))+(F*(X2**3))+(G*(X2**4))
        KV2 = EXP(VAL2)
C
C       CALCULATE THE VAPOR VELOCITY FACTOR FOR HORIZONTAL SEPARATOR

        KH = 1.25*KV2

        VMAX2 = KH*SQRT((DENL2-DENV2)/DENV2)

C       CALCULATE THE LIQUID VOLUMETRIC RATE, ft^3/sec.

        QL2 = WL2/(DENL2*3600.0)

C       CALCULATE THE VAPOR VOLUMETRIC RATE, ft^3/sec.

        QV2 = WV2/(DENV2*3600.0)

C       CALCULATE THE VAPOR FLOW AREA, ft^2.

        AV2 = QV2/VMAX2

C       CALCULATE THE TOTAL CROSS-SECTIONAL AREA
C       OF HORIZONTAL VESSEL, ft^2.

        AT = AV2/0.2

C       CALCULATE THE DIAMETER, ft.

        D2 = SQRT((4.0*AT)/PI)

C       ASSUMING THE LENGTH TO DIAMETER RATIO = 3
C       THE LENGTH TO DIAMETER RATIO, (i.e. RATIO=L/D=3)

        L = RATIO*D2

C       THE SEPARATOR VAPOR AREA IS ASSUMED TO OCCUPY 20% OF THE TOTAL
C       CROSS-SECTIONAL AREA.  THEREFORE THE LIQUID AREA WILL OCCUPY 80% OF
C       THE TOTAL CROSS-SECTIONAL AREA.


C       CALCULATE THE FILL LIQUID VOLUME, ft^3.

        AL = 0.8*AT

C       CALCULATE THE VESSEL VOLUME, ft^3.

        VESVOL = AT*L

C       CALCULATE THE LIQUID SURGE TIME, min.

        CALT2 = (AL*L*DENL2*60.)/WL2

        RETURN
        END

C       ***********************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF THE VERTICAL SEPARATOR
C       ***********************************************************
C
        SUBROUTINE OUTV

        REAL KV1

        COMMON/DATA1/ WL1, WV1, DENL1, DENV1, T1
        COMMON/DATA2/ SF1, KV1, VMAX1, D1
        COMMON/DATA3/ UMAX, QL1, QV1, UMIN, V, HL


        WRITE (1, 100)
 100    FORMAT (///,25X, 'VERTICAL SEPARATOR SIZING',/,78(1H*))
```

```
        WRITE (1, 110) WL1, WV1, DENL1, DENV1, QL1, QV1, T1
 110    FORMAT (5X,'LIQUID FLOWRATE, lb/hr.:', T60, F10.0,/,
     1          5X,'VAPOR FLOWRATE, lb/hr.:', T60, F10.0,/,
     2          5X,'LIQUID DENSITY, lb/ft^3.:', T60, F9.3,/,
     3          5X,'VAPOR DENSITY, lb/ft^3.:',  T60, F9.3,/,
     4          5X,'LIQUID VOLUMETRIC RATE, ft^3/sec.:', T60, F9.4,/,
     5          5X,'VAPOR VOLUMETRIC RATE, ft^3/sec.:', T60, F9.4,/,
     6          5X,'LIQUID SURGE TIME, min.:', T60, F6.1)


        WRITE (1, 120) SF1, KV1, VMAX1, D1
 120    FORMAT (5X,'SEPARATION FACTOR:', T60, F8.4,/,
     1          5X,'VAPOR VELOCITY FACTOR:', T60, F8.3,/,
     2          5X,'MAXIMUM VAPOR VELOCITY, ft/s.:',T60, F8.3,/,
     3          5X,'VESSEL DIAMETER, ft:', T60,F8.3)

        WRITE (1, 130) UMIN, UMAX, V, HL
 130    FORMAT (5X,'MINIMUM VAPOR-LIQUID NOZZLE VELOCITY, ft/s.:', T60,
     1  F8.3,/,5X,'MAXIMUM VAPOR-LIQUID NOZZLE VELOCITY, ft/s.:',T60,
     2  F8.3,/,5X,'REQUIRED VESSEL VOLUME, ft^3:',T60,F8.3,/,
     3         5X,'LIQUID HEIGHT, ft.:',T60, F8.3)

        WRITE (1, 140)
 140    FORMAT (78(1H-))

        RETURN
        END


C       ************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF THE HORIZONTAL SEPARATOR
C       ************************************************************

        SUBROUTINE OUTH
        REAL L, KH

        COMMON/DATA4/ WL2, WV2, DENL2, DENV2, RATIO
        COMMON/DATA5/ SF2, KH, QL2, QV2, VMAX2, D2, L, VESVOL, T2, CALT2

        WRITE(1, 150)

 150    FORMAT(//,25X,'HORIZONTAL SEPARATOR SIZING',/78(1H*))


        WRITE (1, 160) WL2, WV2, DENL2, DENV2, QL2, QV2, T2, RATIO
 160    FORMAT (5X,'LIQUID FLOWRATE, lb/hr.:', T60, F10.0,/,
     1          5X,'VAPOR FLOWRATE, lb/hr.:', T60, F10.0,/,
     2          5X,'LIQUID DENSITY, lb/ft^3.:', T60, F9.3,/,
     3          5X,'VAPOR DENSITY, lb/ft^3.:', T60, F9.3,/,
     4          5X,'LIQUID VOLUMETRIC RATE, ft^3/sec.:', T60, F9.4,/,
     5          5X,'VAPOR VOLUMETRIC RATE, ft^3/sec.:', T60, F9.4,/,
     6          5X,'LIQUID SURGE TIME, min.:', T60, F9.3,/,
     7          5X,'LENGTH TO DIAMETER RATIO (L/D):', T60, F6.1)


        WRITE (1, 170) SF2, KH, QV2, VMAX2
 170    FORMAT (5X,'SEPARATION FACTOR:',T60,F8.3,/,
     1          5X,'VAPOR VELOCITY FACTOR:',T60,F8.3,/,
     2          5X,'VAPOR VOLUMETRIC RATE, ft^3/s.:', T60, F9.3,/,
     3          5X,'MAXIMUM VAPOR VELOCITY, ft/s.:',T60, F8.3)

        WRITE (1, 180) D2, L, VESVOL, CALT2
 180    FORMAT (5X,'VESSEL DIAMETER, ft.:',T60, F8.3,/,
     1          5X,'VESSEL LENGTH, ft.:', T60, F8.3,/,
     2          5X,'VESSEL VOLUME, ft^3.:', T60, F9.3,/,
     3          5X,'CALCULATED LIQUID SURGE TIME, min.:', T60, F8.3)

        WRITE (1, 190)
 190    FORMAT (78(1H-))

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
        PROGRAM PROG42

C       ********************************************************************
C       THIS PROGRAM CALCULATES THE SEGMENTAL AREA OF A CIRLCE COUPLED
C       WITH A MODIFIED DOOLITTLE FORMULA FOR DISHED HEADS TO CALCULATE
C       PARTIAL VOLUMES OF HORIZONTAL VESSELS.
C       THE PROGRAM WILL CALCULATE PARTIAL VOLUMES FOR HORIZONTAL
C       CYLINDRICAL VESSELS WITH FLAT, DISHED, ELLIPTICAL AND HEMISPHERICAL
C       HEADS, AND VERTICAL CYLINDRICAL TANKS.
C       ********************************************************************
C       CL    =     CHORD LENGTH OF SEGMENTAL AREA, in.
C       AC    =     AREA OF CHORD, in^2.
C       VHC   =     VOLUME OF HORIZONTAL CYLINDER, in^3.
C       VDH   =     VOLUME OF DISHED HEADS, in^3.
C       VELL  =     VOLUME OF ELLIPTICAL HEADS, in^3.
C       VHS   =     VOLUME OF HEMISPHERICAL HEADS, in^3.
C       VT    =     TOTAL VOLUME OF HORIZONTAL VESSEL, in^3.
C       D     =     VESSEL, TANK, OR CIRCLE DIAMETER, in.
C       H     =     CHORD OR LIQUID HEIGHT, in.
C       R     =     RADIUS OF VESSEL OR TANK, in.
C       L     =     VESSEL LENGTH, in.
C       VH    =     HEAD VOLUMES, in^3.
C       BBL   =     VOLUME IN BARRELS
C       AREA  =     CIRCLE AREA, in^2.
C       ********************************************************************

        REAL L1, L2, L3, L4, L5
        COMMON PI

        COMMON/DATA1/ D1, H1, L1
        COMMON/DATA2/ D2, H2, L2
        COMMON/DATA3/ D3, H3, L3
        COMMON/DATA4/ D4, H4, L4
        COMMON/DATA5/ D5, H5, L5

        COMMON/PROG1/ VHC, VHCCFT, VHCGAL, VHCBBL
        COMMON/PROG2/ VT, VTCFT, VTGAL, VTBBL
        COMMON/PROG3/ VTELL, VTECFT, VTEGAL, VTEBBL
        COMMON/PROG4/ VTHS, VTHCFT, VTHGAL, VTHBBL
        COMMON/PROG5/ VVT, VVCFT, VVGAL, VVBBL


        OPEN (UNIT=3, FILE='DATA42.DAT', STATUS='OLD', ERR=18)
        OPEN (UNIT=1, FILE='PRN')

        PI = 3.1415927

 5      READ (3, *, ERR=19) I

        GO TO (11, 22, 33, 44, 55), I

C       READ TANK DIAMETER, D1: in.
C       READ LIQUID DEPTH, H1: in.
C       READ TANK LENGTH, L1: in.

 11     READ (3, *, ERR=19) D1, H1, L1

        GO TO 66
```

```
C        READ TANK DIAMETER, D2: in.
C        READ LIQUID DEPTH, H2: in.
C        READ TANK LENGTH, L2: in.

 22      READ (3, *, ERR=19) D2, H2, L2

         GO TO 77

C        READ TANK DIAMETER, D3: in.
C        READ LIQUID DEPTH, H3: in.
C        READ TANK LENGTH, L3: in.

 33      READ (3, *, ERR=19) D3, H3, L3

         GO TO 88

C        READ TANK DIAMETER, D4: in.
C        READ LIQUID DEPTH, H4: in.
C        READ TANK LENGTH, L4: in.

 44      READ (3, *, ERR=19) D4, H4, L4

         GO TO 99

 55      READ (3, *, ERR=19) D5, H5, L5

         GO TO 111

 18      WRITE (*, 12)
 12      FORMAT (6X, ’DATA FILE DOES NOT EXIST’)
         GO TO 999

 19      WRITE (*, 13)
 13      FORMAT(6X, ’ERROR MESSAGE IN THE DATA VALUE’)
         GO TO 999

C        CALCULATE THE VOLUME OF THE TANK WITH FLAT HEADS

 66      CALL FLAT

C        PRINT THE RESULTS OF THE TANK WITH FLAT HEADS

         CALL OFLAT

         GO TO 5

C        CALCULATE THE VOLUME OF THE TANK WITH DISHED HEADS

 77      CALL DISHED

C        PRINT THE RESULTS OF THE TANK WITH DISHED HEADS

         CALL ODISH

         GO TO 5

C        CALCULATE THE VOLUME OF THE TANK WITH ELLIPTICAL HEADS

 88      CALL ELLIP
```

```
C       PRINT THE RESULTS OF THE TANK WITH ELLIPTICAL HEADS.

        CALL OELLIP

        GO TO 5

C       CALCULATE THE VOLUME OF THE TANK WITH HEMISPHERICAL HEADS

 99     CALL HEMISP

C       PRINT THE RESULTS OF THE TANK WITH HEMISPHERICAL HEADS.

        CALL OHEMIS

        GO TO 5

C       CALCULATE THE PARTIAL VOLUME OF A VERTICAL TANK

 111    CALL VERT

C       PRINT THE RESULTS OF THE PARTIAL VOLUME OF A VERTICAL
C       VESSEL

        CALL OVERT

        GO TO 999

        CLOSE (3, STATUS='KEEP')
        CLOSE (1)

  999   STOP
        END

C       *************************************************************
C       THIS PROGRAM CALCULATES THE PARTIAL VOLUME FOR A HORIZONTAL
C       CYLINDRICAL VESSEL WITH FLAT HEADS
C       *************************************************************

        SUBROUTINE FLAT

        REAL L1
        COMMON PI
        COMMON/DATA1/ D1, H1, L1
        COMMON/PROG1/ VHC, VHCCFT, VHCGAL, VHCBBL

        R1 = D1/2.
        CL1 = 2.*SQRT(D1*H1-(H1**2))
        VAL1 = (R1-H1)/R1
        VAL2 = (R1-H1)*SQRT(2.*R1*H1-(H1**2))
        AC1 = ((R1**2)*ACOS(VAL1))-VAL2
        AREA1 = (0.25*PI*D1**2)
        VHC = AC1*L1

C       CONVERT THE RESULTS TO FT^3, GALLONS AND BARRELS

        CALL CONVT (VHC, VHCCFT, VHCGAL, VHCBBL)

        RETURN
```

```
      END
C     *****************************************************************
C     THIS PROGRAM CALCULATES THE PARTIAL VOLUME FOR A HORIZONTAL
C     CYLINDRICAL VESSEL WITH DISHED HEADS
C     ****************************************************************

      SUBROUTINE DISHED

      REAL L2
      COMMON PI
      COMMON/DATA2/ D2, H2, L2
      COMMON/PROG2/ VT, VTCFT, VTGAL, VTBBL

      R2 = D2/2.
      CL2 = 2.*SQRT(D2*H2-(H2**2))
      VAL3 = (R2-H2)/R2
      VAL4 = (R2-H2)*SQRT(2.*R2*H2-(H2**2))
      AC2 = ((R2**2)*ACOS(VAL3))-VAL4
      VHC2 = AC2*L2
      VDH = 0.215483*H2*(1.5*D2-H2)
      VT = 2.*VDH+VHC2

C     CONVERT THE RESULTS TO CUBIC FEET, GALLONS AND BARRELS.

      CALL CONVT (VT, VTCFT, VTGAL, VTBBL)

      RETURN
      END

C     *****************************************************************
C     THIS PROGRAM CALCULATES THE PARTIAL VOLUME FOR A HORIZONTAL
C     CYLINDRICAL VESSEL WITH ELLIPTICAL HEADS
C     *****************************************************************

      SUBROUTINE ELLIP

      REAL L3
      COMMON PI
      COMMON/DATA3/ D3, H3, L3
      COMMON/PROG3/VTELL,VTECFT,VTEGAL,VTEBBL

      R3 = D3/2.
      CL3 = 2.*SQRT(D3*H3-(H3**2))
      VAL5 = (R3-H3)/R3
      VAL6 = (R3-H3)*SQRT(2.*R3*H3-(H3**2))
      AC3 = ((R3**2)*ACOS(VAL5))-VAL6
      VHC3 = AC3*L3
      VELL = 0.5236*(H3**2)*(1.5*D3-H3)
      VTELL = 2.*VELL+VHC3


C     CONVERT THE RESULTS TO CUBIC FEET, GALLONS AND BARRELS.

      CALL CONVT (VTELL, VTECFT, VTEGAL, VTEBBL)

      RETURN
      END

C     ***************************************************************
```

```
C       THIS PROGRAM CALCULATES THE PARTIAL VOLUME FOR A HORIZONTAL
C       CYLINDRICAL VESSEL WITH HEMISPHERICAL HEADS
C       ***************************************************************

        SUBROUTINE HEMISP

        REAL L4
        COMMON PI
        COMMON/DATA4/ D4, H4, L4
        COMMON/PROG4/ VTHS, VTHCFT, VTHGAL, VTHBBL

        R4 = D4/2.
        CL4 = 2.*SQRT(D4*H4-(H4**2))
        VAL7 = (R4-H4)/R4
        VAL8 = (R4-H4)*SQRT(2.*R4*H4-(H4**2))
        AC4 = ((R4**2)*ACOS(VAL7))-VAL8
        VHC4 = AC4*L4
        VELL4 = 0.5236*(H4**2)*(1.5*D4-H4)
        VHS = 2.*VELL4
        VTHS = 2.*VHS+VHC4


C       CONVERT THE RESULTS TO CUBIC FEET, GALLONS AND BARRELS.

        CALL CONVT (VTHS, VTHCFT, VTHGAL, VTHBBL)

        RETURN
        END

C       ***************************************************************
C       THIS PROGRAM CALCULATES THE PARTIAL VOLUME FOR A VERTICAL
C       CYLINDRICAL VESSEL
C       ***************************************************************

        SUBROUTINE VERT

        COMMON PI
        COMMON/DATA5/ D5, H5, L5
        COMMON/PROG5/ VVT, VVCFT, VVGAL, VVBBL

        VVT = 0.25*PI*(D5**2)*H5


C       CONVERT THE RESULTS TO CUBIC FEET, GALLONS AND BARRELS.

        CALL CONVT (VVT, VVCFT, VVGAL, VVBBL)

        RETURN
        END

C       ****************************************************************
C       THIS PROGRAM CONVERTS THE RESULTS TO CUBIC FEET, GALLONS, AND
C       BARRELS.
C       *****************************************************************


        SUBROUTINE CONVT (VOL, VLFT3, VLGAL, VLBAR)

        VLFT3 = VOL/1728.0
```

```
      VLGAL = VOL*0.004329

      VLBAR = VOL*0.00010307

      RETURN
      END

C     ****************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF THE TANK VOLUME WITH FLAT
C     HEADS
C     ****************************************************************

      SUBROUTINE OFLAT

      REAL L1
      COMMON/DATA1/ D1, H1, L1
      COMMON/PROG1/ VHC, VHCCFT, VHCGAL, VHCBBL

      WRITE (1, 100)
 100  FORMAT (//,25X, 'TANK VOLUME WITH FLAT HEADS',/,78(1H*))

      WRITE (1, 110) D1, H1, L1
 110  FORMAT (5X,'TANK DIAMETER, in.:', T60, F9.3,/,
     1        5X,'LIQUID DEPTH, in.:', T60, F9.3,/,
     2        5X,'TANK LENGTH, in.:', T60, F9.3)

      WRITE (1, 120) VHC, VHCCFT, VHCGAL, VHCBBL
 120  FORMAT (5X,'TANK VOLUME, in.^3:', T60, E14.6,/,
     1        5X,'TANK VOLUME, ft.^3:', T60, E14.6,/,
     2        5X,'TANK VOLUME, gal:', T60, E14.6,/,
     3        5X,'TANK VOLUME, bbl:', T60, E14.6)

      WRITE (1, 130)
 130  FORMAT (78(1H-))


      RETURN
      END

C     ****************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF THE TANK VOLUME WITH DISHED
C     HEADS.
C     ****************************************************************

      SUBROUTINE ODISH

      REAL L2
      COMMON/DATA2/ D2, H2, L2
      COMMON/PROG2/ VT, VTCFT, VTGAL, VTBBL

      WRITE (1, 140)
 140  FORMAT (//,25X,'TANK VOLUME WITH DISHED HEADS',/,78(1H*))

      WRITE (1, 150) D2, H2, L2
 150  FORMAT (5X,'TANK DIAMETER, in.:', T60, F9.3,/,
     1        5X,'LIQUID DEPTH, in.:', T60, F9.3,/,
     2        5X,'TANK LENGTH, in.:', T60, F9.3)
```

```
      WRITE (1, 160) VT, VTCFT, VTGAL, VTBBL
 160  FORMAT (5X,'TANK VOLUME, in^3:', T60, E14.6,/,
     1        5X,'TANK VOLUME, ft.^3:', T60, E14.6,/,
     2        5X,'TANK VOLUME, gal:', T60, E14.6,/,
     3        5X,'TANK VOLUME, bbl:', T60, E14.6)

      WRITE (1, 170)
 170  FORMAT (78(1H-))


      RETURN
      END

C     ***************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF THE TANK VOLUME WITH
C     ELLIPTICAL HEADS
C     ***************************************************************

      SUBROUTINE OELLIP

      REAL L3
      COMMON/DATA3/ D3, H3, L3
      COMMON/PROG3/ VTELL, VTECFT, VTEGAL, VTEBBL

      WRITE (1, 180)
 180  FORMAT (//,25X, 'TANK VOLUME WITH ELLIPTICAL HEADS',/,78(1H*))

      WRITE (1, 190) D3, H3, L3
 190  FORMAT (5X,'TANK DIAMETER, in.:', T60, F9.3,/,
     1        5X,'LIQUID DEPTH, in.:', T60, F9.3,/,
     2        5X,'TANK LENGTH, in.:', T60, F9.3)

      WRITE (1, 200) VTELL, VTECFT, VTEGAL, VTEBBL
 200  FORMAT (5X,'TANK VOLUME, in.^3:', T60, E14.6,/,
     1        5X,'TANK VOLUME, ft.^3:', T60, E14.6,/,
     2        5X,'TANK VOLUME, gal:', T60, E14.6,/,
     3        5X,'TANK VOLUME, bbl:', T60, E14.6)


      WRITE (1, 210)
 210  FORMAT (78(1H-))

      RETURN
      END
C     ***************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF THE TANK VOLUME FOR
C     HEMISPHERICAL HEADS.
C     ***************************************************************

      SUBROUTINE OHEMIS

      REAL L4
      COMMON/DATA4/ D4, H4, L4
      COMMON/PROG4/ VTHS, VTHCFT, VTHGAL, VTHBBL

      WRITE (1, 220)
 220  FORMAT (//,25X,'TANK VOLUME WITH HEMISPHERICAL HEADS',/,78(1H*))
```

```
      WRITE (1, 230) D4, H4, L4
  230 FORMAT (5X,'TANK DIAMETER, in.:', T60, F9.3,/,
     1        5X,'LIQUID DEPTH, in.:', T60, F9.3,/,
     2        5X,'TANK LENGTH, in.:', T60, F9.3)

      WRITE (1, 240) VTHS, VTHCFT, VTHGAL, VTHBBL
  240 FORMAT (5X,'TANK VOLUME, in.^3:', T60, E14.6,/,
     1        5X,'TANK VOLUME, ft.^3:', T60, E14.6,/,
     2        5X,'TANK VOLUME, gal:', T60, E14.6,/,
     3        5X,'TANK VOLUME, bbl:', T60, E14.6)

      WRITE (1, 250)
  250 FORMAT (78(1H-))

      RETURN
      END

C
C     ****************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF THE PARTIAL VOLUME FOR A
C     VERTICAL CYLINDRICAL VESSEL
C     ****************************************************************


      SUBROUTINE OVERT

      REAL L5
      COMMON/DATA5/ D5, H5, L5
      COMMON/PROG5/ VVT, VVCFT, VVGAL, VVBBL

      WRITE (1, 260)
  260 FORMAT (//,25X,'VERTICAL TANK VOLUME', /, 78(1H*))

      WRITE (1, 270) D5, H5, L5
  270 FORMAT (5X,'TANK DIAMETER, in.:', T60, F9.3,/,
     1        5X,'LIQUID DEPTH, in.:', T60, F9.3,/,
     2        5X,'TANK LENGTH, in.:', T60, F9.3)

      WRITE (1, 280) VVT, VVCFT, VVGAL, VVBBL
  280 FORMAT (5X,'TANK VOLUME, in.^3:', T60, E14.6,/,
     1        5X,'TANK VOLUME, ft.^3:', T60, E14.6,/,
     2        5X,'TANK VOLUME, gal:', T60, E14.6,/,
     3        5X,'TANK VOLUME, bbl:', T60, E14.6)

      WRITE (1, 290)
  290 FORMAT (78(1H-))

C     FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)

      RETURN
      END
```

```
      PROGRAM PROG43
C     ******************************************************************
C     A PROGRAM FOR PRELIMINARY VESSEL DESIGN.
C     THIS PROGRAM WILL ESTIMATE SHELL THICKNESS AND WEIGHT,
C     HEAD THICKNESS AND WEIGHT FOR CYLINDRICAL PRESSURE VESSELS.
C     IN ADDITION, HEAD THICKNESS AND WEIGHT ARE CALCULATED FOR
C     HEMISPHERICAL, ELLIPSOIDAL AND TORISPHERICAL HEADS. TOTAL VESSEL
C     WEIGHT IS CALCULATED (SHELL AND HEADS) EXCLUSIVE OF NOZZLES,
C     ATTACHMENTS AND VESSEL INTERNALS.
C     ******************************************************************
C     TKS   =     SHELL THICKNESS, in.
C     TKHH  =     HEMISPHERICAL HEAD THICKNESS, in.
C     TKELL =     ELLIPSOIDAL HEAD THICKNESS, in.
C     TKTOR =     TORISPHERICAL HEAD THICKNESS, in.
C     P     =     INTERNAL DESIGN PRESSURE, psig.
C     R     =     INSIDE RADIUS, in.
C     S     =     ALLOWABLE STRESS, lb/in^2.
C     E     =     JOINT EFFICIENCY
C     C     =     CORROSION ALLOWANCE, in.
C     ID    =     INSIDE DIAMETER OF SHELL OR HEAD, in.
C     RC    =     CROWN RADIUS OF TORISPHERICAL HEAD, in.
C     LN    =     SHELL LENGTH, ft.
C     DENV  =     DENSITY OF VESSEL MATERIAL, lb/ft^3.
C     OD    =     OUTSIDE DIAMETER OF HEAD, in.
C     HFAC  =     HEAD BLANK DIAMETER FACTOR
C     SF    =     STRAIGHT FLANGE LENGTH, in.
C     BD    =     HEAD BLANK DIAMETER, in.
C     WTH   =     WEIGHT OF HEAD, lb
C     WTS   =     WEIGHT OF VESSEL SHELL, lb.
C     TOTWT =     TOTAL VESSEL WEIGHT, lb.
C     ****************************************************************

      REAL LN1, LN2, LN3, ID1, ID2, ID3

      COMMON PI

      COMMON/DATA1/ ID1, LN1, P1, SF1, C1, DENS1, ES1, EH1, S1
      COMMON/RES1/ TKS1, TKH1, WTS1, WTH1, TOTWT1

      COMMON/DATA2/ ID2, LN2, P2, SF2, C2, DENS2, ES2, EH2, S2
      COMMON/RES2/ TKS2, TKHS2, WTS2, WTH2, TOTWT2

      COMMON/DATA3/ ID3, LN3, P3, SF3, C3, DENS3, ES3, EH3, S3, RC
      COMMON/RES3/ TKS3, TKHS3, WTS3, WTH3, TOTWT3

      OPEN (UNIT=3, FILE='DATA43.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT=1, FILE='PRN')

      PI = 3.1415927

 5    READ (3, *, ERR=19) I

      GO TO (11, 22, 33), I

C     READ INTERNAL DIAMETER, ID1: in.
C     READ SHELL LENGTH, LN1: in.
C     READ INTERNAL DESIGN PRESSURE, P1: psig.
C     READ STRAIGHT FLANGE LENGTH, SF1: in.
```

```
C       READ CORROSION ALLOWANCE, C1: in.
C       READ DENSITY OF VESSEL MATERIAL, DENS1: lb/ft^3.
C       READ JOINT EFFICIENCY OF SHELL, ES1
C       READ JOINT EFFICIENCY OF HEAD, EH1
C       READ ALLOWABLE STRESS, S1: lb/in^2.

 11     READ (3, *, ERR=19) ID1, LN1, P1
        READ (3, *, ERR=19) SF1, C1, DENS1
        READ (3, *, ERR=19) ES1, EH1, S1

        GO TO 44

C       READ INTERNAL DIAMETER, ID2: in.
C       READ SHELL LENGTH, LN2: in.
C       READ INTERNAL DESIGN PRESSURE, P2: psig.
C       READ STRAIGHT FLANGE LENGTH, SF2: in.
C       READ CORROSION ALLOWANCE, C2: in.
C       READ DENSITY OF VESSEL MATERIAL, DENS2: lb/ft^3.
C       READ JOINT EFFICIENCY OF SHELL, ES2:
C       READ JOINT EFFICIENCY OF HEAD, EH2:
C       READ ALLOWABLE STRESS, S2: lb/in^2.



 22     READ (3, *, ERR=19) ID2, LN2, P2
        READ (3, *, ERR=19) SF2, C2, DENS2
        READ (3, *, ERR=19) ES2, EH2, S2

        GO TO 55

C       READ INTERNAL DIAMETER, ID3: in.
C       READ SHELL LENGTH, LN3: in.
C       READ INTERNAL DESIGN PRESSURE, P3: psig.
C       READ STRAIGHT FLANGE LENGTH, SF3: in.
C       READ CORROSION ALLOWANCE, C3: in.
C       READ DENSITY OF VESSEL MATERIAL, DENS3: lb/ft^3.
C       READ JOINT EFFICIENCY OF SHELL, ES3:
C       READ JOINT EFFICIENCY OF HEAD, EH3:
C       READ CROWN RADIUS OF TORISPHERICAL HEAD, RC: in.


 33     READ (3, *, ERR=19) ID3, LN3, P3
        READ (3, *, ERR=19) SF3, C3, DENS3
        READ (3, *, ERR=19) ES3, EH3, S3, RC

        GO TO 66

 18     WRITE (*, 13)
 13     FORMAT (6X, 'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 14)
 14     FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

C       CALCULATE THE SHELL THICKNESS, WEIGHT AND HEAD THICKNESS FOR
C       HEMISPHERICAL HEADS.

 44     CALL HEMISP
```

```
C       PRINT THE RESULTS OF THE VESSEL WITH HEMISPHERICAL HEADS.

        CALL OHEMISP

        GO TO 5

C       CALCULATE THE SHELL THICKNESS, WEIGHT AND HEAD THICKNESS FOR
C       ELLIPSOIDAL HEADS.

 55     CALL ELLIP

C       PRINT THE RESULTS OF THE VESSEL WITH ELLIPSOIDAL HEADS.

        CALL OELLIP

        GO TO 5

C       CALCULATE THE SHELL THICKNESS, WEIGHT AND HEAD THICKNESS FOR
C       TORISPHERICAL HEADS.

 66     CALL TORIS

C       PRINT THE RESULTS OF THE VESSEL WITH TORISPHERICAL HEADS.

        CALL OTORIS

        GO TO 999

        CLOSE (3, STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END
C
C       ***************************************************************
C               VESSEL DESIGN WITH HEMISPHERICAL HEADS
C       ***************************************************************

        SUBROUTINE HEMISP

        REAL LN1,ID1,OD1
        COMMON PI
        COMMON/DATA1/ ID1, LN1, P1, SF1, C1, DENS1, ES1, EH1, S1
        COMMON/RES1/ TKS1, TKH1, WTS1, WTH1, TOTWT1


C       CALCULATE SHELL THICKNESS, in

        R1 = ID1/2.
        TKS1 = (P1*R1)/(S1*ES1-0.6*P1)+C1
        OD1 = ID1 + 2.0*TKS1

C       CALCULATE WEIGHT OF VESSEL SHELL, lb

        WTS1 = ((OD1+TKS1)*PI*LN1*TKS1*DENS1)/144.

C       CALCULATE WEIGHT OF HEAD, lb

        TKH1 = (P1*R1)/(2.*S1*EH1-0.2*P1)
```

```
        RAT1 = OD1/TKH1

        IF ((OD1/TKH1) .GE. 10.0 .AND. (OD1/TKH1) .LT. 18.0) THEN
        HFAC = 1.70
        ELSEIF ((OD1/TKH1) .GE. 18.0 .AND. (OD1/TKH1) .LT. 30.0) THEN
        HFAC = 1.65
        ELSEIF ((OD1/TKH1) .GT. 30.0 ) THEN
        HFAC = 1.60
        ENDIF

        BD1 = (OD1*HFAC+2.*SF1)/12.
        WTH1 = (0.25*(BD1**2)*PI*TKH1*DENS1*2.)/12.


C       CALCULATE TOTAL VESSEL WEIGHT

        TOTWT1 = WTS1 + WTH1

        RETURN
        END

C       ***************************************************************
C                   VESSEL DESIGN WITH ELLIPSOIDAL HEADS
C       ***************************************************************

        SUBROUTINE ELLIP

        REAL LN2,ID2,OD2
        COMMON PI
        COMMON/DATA2/ ID2, LN2, P2, SF2, C2, DENS2, ES2, EH2, S2
        COMMON/RES2/ TKS2, TKH2, WTS2, WTH2, TOTWT2

C       CALCULATE SHELL THICKNESS,  in

        R2 = ID2/2.
        TKS2 = (P2*R2)/(S2*ES2-0.6*P2)+C2
        OD2 = ID2 + 2.0*TKS2

C       CALCULATE WEIGHT OF VESSEL SHELL, lb

        WTS2 = ((OD2+TKS2)*PI*LN2*TKS2*DENS2)/144.

C       CALCULATE WEIGHT OF HEAD, lb

        TKH2 = (P2*ID2)/(2.*S2*EH2-0.2*P2)+C2

        RAT2 = OD2/TKH2
        IF ((OD2/TKH2) .GE. 10.0 .AND. (OD2/TKH2) .LT. 20.0) THEN
        HFAC = 1.30
        ELSEIF ((OD2/TKH2) .GT. 20.0) THEN
        HFAC = 1.24
        ENDIF


        BD2 = (OD2*HFAC+2.*SF2)/12.
        WTH2 = (0.25*(BD2**2)*PI*TKH2*DENS2*2.)/12.0


C       CALCULATE TOTAL WEIGHT
```

```
        TOTWT2 = WTS2 + WTH2

        RETURN
        END

C       ***************************************************************
C                       VESSEL DESIGN WITH TORISPHERICAL HEADS
C       ***************************************************************

        SUBROUTINE TORIS

        REAL LN3,ID3,OD3
        COMMON PI
        COMMON/DATA3/ ID3, LN3, P3, SF3, C3, DENS3, ES3, EH3, S3, RC
        COMMON/RES3/ TKS3, TKH3, WTS3, WTH3, TOTWT3

C       CALCULATE SHELL THICKNESS, in

        R3 = ID3/2.
        TKS3 = (P3*R3)/(S3*ES3-0.6*P3)+C3
        OD3 = ID3 + 2.0*TKS3

C       CALCULATE WEIGHT OF VESSEL SHELL, lb

        WTS3 = ((OD3+TKS3)*PI*LN3*TKS3*DENS3)/144.

C       CALCULATE WEIGHT OF HEAD, lb

        TKH3 = ((0.885*P3*RC)/(S3*EH3-0.1*P3))+C3

        RAT3 = OD3/TKH3

        IF ((OD3/TKH3) .GE. 20.0 .AND. (OD3/TKH3) .LT. 30.0) THEN
        HFAC = 1.15
        ELSEIF ((OD3/TKH3) .GE. 30.0 .AND. (OD3/TKH3) .LT. 50.0) THEN
        HFAC = 1.11
        ELSEIF ((OD3/TKH3) .GT. 50.0) THEN
        HFAC = 1.09
        ENDIF

        BD3 = (OD3*HFAC+2.0*SF3)/12.
        WTH3 = (0.25*(BD3**2)*PI*TKH3*DENS3*2.)/12.


C       CALCULATE TOTAL WEIGHT

        TOTWT3 = WTS3 + WTH3

        RETURN
        END


C       ***************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF THE VESSEL WITH
C       HEMISPHERICAL HEADS.
C       ***************************************************************

        SUBROUTINE OHEMISP

        REAL ID1, LN1
```

```
      COMMON/DATA1/ ID1, LN1, P1, SF1, C1, DENS1, ES1, EH1, S1
      COMMON/RES1/ TKS1, TKH1, WTS1, WTH1, TOTWT1

      WRITE (1, 100)
100   FORMAT (//,25X, 'VESSEL DESIGN WITH HEMISPHERICAL HEADS',
     *        /,78(1H*))

      WRITE (1, 110) ID1, LN1, P1
110   FORMAT (5X,'INTERNAL DIAMETER, in.:', T60, F9.3,/,
     1        5X,'SHELL LENGHT, ft.:', T60, F9.3,/,
     2        5X,'INTERNAL DESIGN PRESSURE, psig:', T60, F9.3)

      WRITE (1, 120) SF1, C1, DENS1
120   FORMAT (5X,'STRAIGHT FLANGE LENGTH, in.:', T60, F9.3,/,
     1        5X,'CORROSION ALLOWANCE, in.:', T60, F9.3,/,
     2        5X,'DENSITY OF VESSEL MATERIAL, lb/ft^3.:', T60, F9.3)


      WRITE (1, 130) ES1, EH1, S1
130   FORMAT (5X,'JOINT EFFICIENCY OF SHELL:', T60, F9.3,/,
     1        5X,'JOINT EFFICIENCY OF HEAD:', T60, F9.3,/,
     2        5X,'ALLOWABLE STRESS, lb/in^2.:', T60, F9.3)



      WRITE (1, 140) TKS1, TKH1, WTS1, WTH1, TOTWT1
140   FORMAT (5X,'CALCULATED SHELL THICKNESS, in.:', T60, F9.3,/,
     1        5X,'CALCULATED HEAD THICKNESS, in.:', T60, F9.3,/,
     2        5X,'WEIGHT OF VESSEL SHELL, lb:', T60, F12.2,/,
     3        5X,'WEIGHT OF VESSEL HEAD, lb:', T60, F12.2,/,
     4        5X,'TOTAL VESSEL WEIGHT, lb:', T60, F12.2)

      WRITE (1, 150)
150   FORMAT (78(1H-))


      RETURN
      END
C     ******************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF THE VESSEL WITH ELLIPSOIDAL
C     HEADS.
C     ******************************************************************

      SUBROUTINE OELLIP

      REAL ID2, LN2
      COMMON/DATA2/ID2, LN2, P2, SF2, C2, DENS2, ES2, EH2, S2
      COMMON/RES2/TKS2, TKH2, WTS2, WTH2, TOTWT2

      WRITE (1, 160)
160   FORMAT (//,25X, 'VESSEL DESIGN WITH ELLIPSOIDAL HEADS',
     1        /,78(1H*))

      WRITE (1, 170) ID2, LN2, P2
170   FORMAT (5X, 'INTERNAL DIAMETER, in.:', T60, F9.3,/,
     1        5X,'SHELL LENGTH, ft.:', T60, F9.3,/,
     2        5X,'INTERNAL DESIGN PRESSURE, psig.:', T60, F9.3)
```

```
      WRITE (1, 180) SF2, C2, DENS2
 180  FORMAT (5X,'STRAIGHT FLANGE LENGTH, in.:', T60, F9.3,/,
     1        5X,'CORROSION ALLOWANCE, in.:', T60, F9.3,/,
     2        5X,'DENSITY OF VESSEL MATERIAL, lb/ft^3.:',T60, F9.3)

      WRITE (1, 190) ES2, EH2, S2
 190  FORMAT (5X,'JOINT EFFICIENCY OF SHELL:', T60, F9.3,/,
     1        5X,'JOINT EFFICIENCY OF HEAD:', T60, F9.3,/,
     2        5X,'ALLOWABLE STRESS, lb/in^2.:', T60, F9.3)


      WRITE (1, 200) TKS2, TKH2, WTS2, WTH2, TOTWT2
 200  FORMAT (5X,'CALCULATED SHELL THICKNESS, in.:', T60, F9.3,/,
     1        5X,'CALCULATED HEAD THICKNESS, in.:', T60, F9.3,/,
     2        5X,'WEIGHT OF VESSEL SHELL, lb:', T60, F12.2,/,
     3        5X,'WEIGHT OF VESSEL HEAD, lb:', T60, F12.2,/,
     4        5X,'TOTAL VESSEL WEIGHT, lb:', T60, F12.2)


      WRITE (1, 210)
 210  FORMAT (78(1H-))


      RETURN
      END

C     ****************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF THE VESSEL WITH
C     TORISPHERICAL  HEADS.
C     ****************************************************************

      SUBROUTINE OTORIS

      REAL ID3, LN3
      COMMON/DATA3/ ID3, LN3, P3, SF3, C3, DENS3, ES3, EH3, S3, RC
      COMMON/RES3/ TKS3, TKH3, WTS3, WTH3, TOTWT3

      WRITE (1, 220)
 220  FORMAT (//,25X,'VESSEL DESIGN WITH TORISPHERICAL HEADS',
     1        /,78(1H*))

      WRITE (1, 230) ID3, LN3, P3
 230  FORMAT (5X,'INTERNAL DIAMETER, in.:', T60, F9.3,/,
     1        5X,'SHELL LENGTH, ft.:', T60, F9.3,/,
     2        5X,'INTERNAL DESIGN PRESSURE, psig.:', T60, F9.3)

      WRITE (1, 240) SF3, C3, DENS3
 240  FORMAT (5X,'STRAIGHT FLANGE LENGTH, in.:', T60, F9.3,/,
     1        5X,'CORROSION ALLOWANCE, in.:', T60, F9.3,/,
     2        5X,'DENSITY OF VESSEL MATERIAL, lb/ft^3.:', T60, F9.3)

      WRITE (1, 250) ES3, EH3, S3
 250  FORMAT (5X,'JOINT EFFICIENCY OF SHELL:', T60, F9.3,/,
     1        5X,'JOINT EFFICIENCY OF HEAD:', T60, F9.3,/,
     2        5X,'ALLOWABLE STREES, lb/in.^2:', T60, F9.3)


      WRITE (1, 260) TKS3, TKH3, WTS3, WTH3, TOTWT3
 260  FORMAT (5X,'CALCULATED SHELL THICKNESS, in.:', T60, F9.3,/,


     1        5X,'CALCULATED HEAD THICKNESS, ft.:', T60, F9.3,/,
     2        5X,'WEIGHT OF VESSEL SHELL, lb:', T60, F12.2,/,
     3        5X,'WEIGHT OF VESSEL HEAD, lb:', T60, F12.2,/,
     4        5X,'TOTAL VESSEL WEIGHT, lb:', T60, F12.2)


      WRITE (1, 270)
 270  FORMAT (78(1H-))

C     FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)

      RETURN
      END
```

```
      PROGRAM PROG44

C     ****************************************************************
C     THE PROGRAM CALCULATES CYCLONE EFFICIENCY BASED ON CYCLONE
C     DIMENSIONS AND ON FLUID AND PARTICLE CHARACTERISITICS.
C     IN ADDITION, THE PROGRAM CALCULATES THE CYCLONE PRESSURE DROP.
C     ****************************************************************
C     A1   =  CYCLONE GAS INLET LENGTH, ft
C     B    =  CYCLONE DUST-OUTLET DIAMETER, ft
C     B1   =  CYCLONE GAS INLET WIDTH, ft
C     DC   =  CYCLONE DIAMETER, ft
C     DE   =  CYCLONE GAS OUTLET DIAMETER, ft.
C     DENF =  GAS DENSITY, lb/ft^3.
C     DENP =  PARTICLE DENSITY, lb/ft^3.
C     DPI  =  PARTICLE SIZE EQUIVALENT, ft.
C     H    =  CYCLONE OVERALL HEIGHT, ft
C     H1   =  CYCLONE CYLINDRICAL HEIGHT, ft.
C     Q    =  TOTAL GAS FLOWRATE, ft^3./sec.
C     S    =  CYCLONE GAS OUTLET LENGTH, ft
C     T    =  TEMPERATURE, oF
C     VIS  =  FLUID VISCOSITY, lbm/ft.sec.
C
C     ****************************************************************
C

      REAL L, NH, NT

      COMMON/RES1/ L, D, NH, VI, VSA, RATIO, G, VE, RT, EFF, DELP
      COMMON/RES2/ NT, DPCRIT, DPMIC, RATIO1


      OPEN (UNIT=3, FILE='DATA44.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT=1, FILE='PRN')

C     READ CYCLONE OVERALL HEIGHT, H: ft.
C     READ CYCLONE CYLINDRICAL HEIGHT, H1: ft.
C     READ CYCLONE DIAMETER, DC: ft.
C     READ CYCLONE DUST-OUTLET DIAMETER, B: ft.
C     READ CYCLONE GAS INLET LENGTH, A1: ft.
C     READ CYCLONE GAS INLET WIDTH, B1: ft.
C     READ CYCLONE GAS OUTLET LENGTH, S: ft.
C     READ CYCLONE GAS OUTLET DIAMETER, DE: ft.
C     READ TOTAL GAS FLOWRATE, Q: ft^3/sec.
C     READ PARTICLE DENSITY, DENP: lb/ft^3.
C     READ GAS DENSITY, DENF: lb/ft^3.
C     READ GAS VISCOSITY, VIS: lb/ft.sec.
C     READ GAS TEMPERATURE, T: oF.
C     READ PARTICLE SIZE EQUIVALENT, DPI: ft.


      READ (3, *, ERR=19) H, H1, DC, B
      READ (3, *, ERR=19) A1, B1, S, DE
      READ (3, *, ERR=19) Q, DENP, DENF, VIS
      READ (3, *, ERR=19) T, DPI

      GO TO 10

 18   WRITE (*, 20)
 20   FORMAT (6X, 'DATA FILE DOES NOT EXIST')
```

```
      GO TO 999

 19   WRITE (*, 25)
 25   FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')

      GO TO 999


C     CALCULATE THE CYCLONE PRESSURE DROP AND EFFICIENCY


 10   CALL CALC (H,H1,DC,B,A1,B1,S,DE,Q,DENP,DENF,VIS,T,DPI)


C     PRINT THE RESULTS OF THE CYCLONE DESIGN.

      CALL OUTPUT (H,H1,DC,B,A1,B1,S,DE,Q,DENP,DENF,VIS,T,DPI)


      GO TO 999

      CLOSE (3, STATUS='KEEP')
      CLOSE (1)

 999  STOP
      END

C     ****************************************************************
C     THIS PROGRAM CALCULATES THE CYCLONE PRESSURE DROP AND EFFICIENCY
C     ****************************************************************

      SUBROUTINE CALC(H,H1,DC,B,A1,B1,S,DE,Q,DENP,DENF,VIS,T,DPI)
      PARAMETER (PI=3.1415927, GC=32.2)


      REAL L, NH, NT
      COMMON/RES1/ L, D, NH, VI, VSA, RATIO, G, VE, RT, EFF, DELP
      COMMON/RES2/ NT, DPCRIT, DPMIC, RATIO1

C     CALCULATE L- NATURAL LENGTH i.e. THE DISTANCE BELOW THE GAS
C     OUTLET WHERE THE VORTEX TURNS, ft.

      L = 2.3*DE*(((DC**2)/(A1*B1))**(1.0/3.0))

C     CALCULATE D-DIAMETER OF CENTRAL CORE AT POINT WHERE VORTEX TURNS

      D = DC-((DC-B)*((S+L-H1)/(H-H1)))

C     CALCULATE VOLUME AT NATURAL LENGTH EXCLUDING THE CORE, ft^3

      VN = (PI*(DC**2)*(H1-S))/4.0
      VN = VN+(PI*(DC**2)*(L+S-H1)*(1.0+(D/DC)+(D**2/DC**2)))/12.0
      VN = VN-(PI*(DE**2)*L)/4.0

C    CALCULATE THE VOLUME BELOW EXIT DUCT EXCLUDING THE CORE, ft^3

      VH = (PI*(DC**2)*(H1-S))/4.0
      VH = VH+(PI*(DC**2)*(H-H1)*(1.0+(B/DC)+(B**2/DC**2)))/12.0
      VH = VH-(PI*(DE**2)*(H-S))/4.0
```

```
C       CALCULATE VORTEX EXPONENT

        VE = 1.0-(1.0-(((12.0*DC)**0.14)/2.5))*(((T+460.0)/530.0)**0.3)

C       CALCULATE RELAXATION TIME,  RT in sec.

        RT = (DENP*(DPI)**2)/(18.0*VIS)


        VAL = S+L

        IF (VAL .GT. H) THEN
        VS = VH
        ELSEIF (VAL .LE. H) THEN
        VS = VN
        ENDIF

C       CALCULATE THE NUMBER OF INLET VELOCITY HEADS, NH

        NH = (16.0*A1*B1)/DE**2

C       CALCULATE THE INLET VELOCITY, VI:ft/s.

        VI = Q/(A1*B1)

C       CALCULATE THE CYCLONE PRESSURE DROP, in H2O

        DELP = (0.003*DENF*(VI**2)*NH)

C       CALCULATE SALTATION VELOCITY, VSA: ft/s.

        W = ((4.0*GC*VIS*(DENP-DENF))/(3.0*DENF**2))**(1.0/3.0)
        VAL1 = B1/DC
        VAL2 = (VAL1/(1.0-VAL1)**(1.0/3.0))
        VSA = 2.055*W*VAL2*(DC**0.067)*(VI**0.667)


C       CALCULATE THE OPTIMAL RATIO, VI/VSA

        RATIO = VI/VSA

C       CALCULATE CYCLONE CONFIGURATION FACTOR SPECIFIED BY THE
C       GEOMETRIC RATIOS THAT DESCRIBE THE CYCLONE'S SHAPE


        G = (2.0*(PI*(S-(A1/2.0))*((DC**2)-(DE**2)))+4.0*VS)*
     *      (DC/((A1**2)*(B1**2)))

C       CALCULATE CYCLONE EFFICIENCY

        EFF = 1.0-EXP(-2.0*((G*RT*Q*(VE+1.0))/(DC**3))**(0.5/(VE+1.0)))
        EFF = 100.0*EFF


C       CALCULATE THE EFFECTIVE NUMBER OF TURNS


        NT = (0.1079-(0.00077*VI)+(1.924*(10**(-6)))*(VI**2))
        NT = NT*VI
```

```
C       CALCULATE THE CRITICAL PARTICLE SIZE, ft.

        DPCRIT = (9.0*VIS*DC)/(4.0*PI*NT*VI*(DENP - DENF))
        DPCRIT = SQRT (DPCRIT)


C       CALCULATE THE CRITICAL PARTICLE SIZE, microns

        DPMIC = DPCRIT*0.3048*(10**6)


C       CALCULATE THE RATIO OF THE PARTICLE SIZE TO THE CRITICAL
C       PARTICLE SIZE, RATIO1

        RATIO1 = DPI/DPCRIT


C       USE THE RESULT TO DETERMINE THE PERCENTAGE REMOVAL OF THE
C       PARTICLES.


        RETURN
        END

C       ***********************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF THE CYCLONE DESIGN
C       ***********************************************************

        SUBROUTINE OUTPUT(H,H1,DC,B,A1,B1,S,DE,Q,DENP,DENF,VIS,T,DPI)

        REAL L, NH, NT

        COMMON/RES1/L,D,NH,VI,VSA,RATIO,G,VE,RT,EFF,DELP
        COMMON/RES2/NT, DPCRIT, DPMIC, RATIO1



        WRITE (1, 100)
 100    FORMAT(///,25X,'CYCLONE DESIGN',/78(1H*))

        WRITE (1, 110) H, H1, DC, B
 110    FORMAT (5X,'CYCLONE OVERALL HEIGHT, ft:', T60, F9.3,/,
     1          5X,'CYCLONE CYLINDRICAL HEIGHT, ft.:', T60, F9.3,/,
     2          5X,'CYCLONE DIAMETER, ft.:', T60, F9.3,/,
     3          5X,'CYCLONE DUST-OUTLET DIAMETER, ft:', T60, F9.3)

        WRITE (1, 120) A1, B1, S, DE
 120    FORMAT (5X,'CYCLONE GAS INLET LENGTH, ft:', T60, F9.3,/,
     1          5X,'CYCLONE GAS INLET WIDTH, ft:', T60, F9.3,/,
     2          5X,'CYCLONE GAS OUTLET LENGTH, ft:', T60, F9.3,/,
     3          5X,'CYCLONE GAS OUTLET DIAMETR, ft:', T60, F9.3)

        WRITE (1, 130) Q, DENP, DENF, VIS
 130    FORMAT (5X,'GAS RATE, ft^3/s.:', T60, F10.2,/,
     1          5X,'PARTICLE DENSITY, lb/ft^3:', T60, F9.3,/,
     2          5X,'GAS DENSITY,  lb/ft^3:', T60, F9.3,/,
     3          5X,'GAS VISCOSITY, lb/ft.s.:', T60, E12.6)

        WRITE (1, 140) T, DPI, VE, RT
```

```
 140     FORMAT (5X, 'GAS TEMPERATURE, oF:', T60, F9.3,/,
    1            5X, 'PARTICLE SIZE (EQUIVALENT DIA.),ft.:',T60,E12.6,/,
    2            5X, 'VORTEX EXPONENT:', T60, F9.4,/,
    3            5X, 'RELAXATION TIME, s:', T60, E12.6)

         WRITE (1, 150) VI, VSA, G, DELP
 150     FORMAT (5X, 'INLET FLUID VELOCITY, ft/s.:', T60, F9.3,/,
    1            5X,'SALTATION VELOCITY, ft/s.:', T60, F9.3,/,
    2            5X,'CYCLONE CONFIGURATION FACTOR:', T60, F9.3,/,
    3            5X,'CYCLONE PRESSURE DROP, in H2O:', T60, F9.3)

         WRITE (1, 160) RATIO,  EFF
 160     FORMAT (5X, 'RATIO OF THE INLET TO THE SALTATION VELOCITIES:',
    1            T60, F9.3,/,5X,'CYCLONE EFFICIENCY, %:', T60, F9.3)


         WRITE (1, 170) NT, DPCRIT, DPMIC, RATIO1
 170     FORMAT (5X,'EFFECTIVE NUMBER OF TURNS:', T60, F8.2,/,
    1            5X,'CRITICAL PARTICLE DIAMETER, ft.:', T60, E14.6,/,
    2            5X,'CRITICAL PARTICLE DIAMETER, microns:',T60,E14.6,/,
    3            5X,'RATIO OF PARTICLE DIA. TO CRITICAL DIA.:',T60,F8.2)


         WRITE (1, 180)
 180     FORMAT (78(1H-))

C        FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

         WRITE (1, *) CHAR(12)

         RETURN
         END
```

```
      PROGRAM PROG45
C     ********************************************************************
C     THE DESIGN OF A GAS DRYER.
C     THIS PROGRAM WILL PROVIDE A PRELIMINARY DESIGN FOR A SOLID-
C     DESICCANT DRYER USED FOR THE REMOVAL OF MOISTURE FROM GAS STREAMS.
C     THE PROGRAM WILL CALCULATE WATER PICKUP, DESICCANT VOLUME, DESICCANT
C     BED (TOWER) DIAMETER, GAS VELOCITY THROUGH THE BED, VESSEL WEIGHT,
C     DRYER REGENERATION REQUIREMENTS AND MOMENTUM FOR MAXIMUM DOWNFLOW
C     VELOCITIES.
C     *******************************************************************
C     H2OL    =       TOTAL WATER ADSORBED, lb/hr.
C     FLOW    =       GAS FLOW RATE,  10^6 std ft^3/day.
C     CYCLE   =       DRYING CYCLE, hr.
C     H2OC    =       WATER CONTENT OF GAS, lb/10^6 std ft^3.
C     DESVOL  =       DESICCANT VOLUME, ft^3.
C     DDEN    =       DESICCANT DENSITY, lb/ft^3.
C     AREA1   =       CALCULATED AREA BASED ON DESICCANT VOLUME, ft^3.
C     BL      =       DESICCANT BED LENGTH, ft.
C     BD      =       CALCULATED BED DIAMETER USING AREA1, ft.
C     AREA    =       ACTUAL DESSICANT BED AREA USING BD CALCULATED OR
C                     MODIFIED BY THE USER, ft^2.
C     Q       =       ACTUAL GAS FLOW RATE AT FLOWING CONDITIONS, ft^3/min.
C     T       =       GAS FLOWING TEMPERATURE oF.
C     P       =       DRYER OPERATING PRESSURE, psig.
C     Z       =       COMPRESSIBILITY FACTOR
C     VEL     =       GAS VELOCITY, ft/min.
C     TC      =       DRYER SHELL THICKNESS, in.
C     H       =       ADDITIONAL SHELL HEIGHT FOR DESICCANT SUPPORTS
C                     AND DISTRIBUTOR, ft.
C     R       =       RADIUS OF DESICCANT BED, ft.
C     S       =       ALLOWABLE STRESS, lb/in^2.
C     E       =       JOINT EFFICIENCY.
C     THEAT   =       TOTAL HEAT REQUIRED TO REGENERATE DRYER (IDEAL), Btu.
C     WS      =       STEEL WEIGHT OF SHELL AND HEADS, lb.
C     WD      =       DESICCANT WEIGHT, lb.
C     TB      =       TEMPERATURE OF DESICCANT BED, oF.
C     HT      =       HEATER TEMPERATURE, oF.
C     F       =       LOSS FACTOR FOR NON-STEADY STATE HEATING.
C     REGENH  =       HEAT ADDED TO REGENERATION GAS TO REGENERATE
C                     DESICCANT BED.
C     H1,H2   =       ENTHALPY OF REGENERATION GAS BEFORE
C                     AND AFTER REGENERATION, Btu/lb
C     REGENG  =       TOTAL REGENERATION GAS REQUIREMENT, lb
C     MW      =       MOLECULAR WEIGHT OF REGENERATION GAS
C     SCF     =       STANDARD CUBIC FEET OF REGENERATION GAS
C     PICKUP  =       DESICCANT WATER CAPACITY, %
C     ***********************************************************************

      REAL MW, MOMEN

      COMMON/DRY1/ FLOW, P, T
      COMMON/DRY2/ Z, CYCLE, H2OC
      COMMON/DRY3/ S, E, PICKUP
      COMMON/DRY4/ DDEN, BL, HT
      COMMON/DRY5/ MW, H1, H2

      COMMON/RES1/ H2OL, DESVOL, AREA1
      COMMON/RES2/ BD, R, Q, VEL
```

```
      COMMON/RES3/ TC, VESWT, WD
      COMMON/RES4/ TB, THEAT, F
      COMMON/RES5/ REH, REG, SCF, MOMEN

      OPEN (UNIT=3, FILE='DATA45.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT=1, FILE='PRN')

C     READ GAS FLOW RATE, FLOW: 10^6 std ft^3/day.
C     READ DRYER OPERATING PRESSURE, P: psig.
C     READ GAS FLOWING TEMPERATURE, T: oF.
C     READ GAS COMPRESSIBILITY FACTOR, Z.
C     READ DRYING CYCLE, CYCLE: hr.
C     READ WATER CONTENT OF GAS, H2OC: lb/MM std ft^3.
C     READ ALLOWABLE STRESS, S: lb/in^2.
C     READ JOINT EFFICIENCY, E: 1.0
C     READ DESICCANT WATER CAPACITY, PICKUP: %
C     READ DESCICCANT DENSITY, DDEN: lb/ft^3.
C     READ DESICCANT BED LENGTH, BL: ft.
C     READ HEATER TEMPERATURE, HT: oF.
C     READ MOLECULAR WEIGHT OF REGENERATING GAS, MW:
C     READ ENTHALPY OF REGENERATION GAS BEFORE REGENERATION HEATER,
C     H1: Btu/lb.
C     READ ENTHAPLY OF REGENERATION GAS AFTER REGENERATAION HEATER,
C     H2: Btu/lb.

      READ (3, *, ERR=19) FLOW, P, T
      READ (3, *, ERR=19) Z, CYCLE, H2OC
      READ (3, *, ERR=19) S, E, PICKUP
      READ (3, *, ERR=19) DDEN, BL, HT
      READ (3, *, ERR=19) MW, H1, H2


      GO TO 10
 18   WRITE (*, 11)
 11   FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
      GO TO 999

 19   WRITE (*, 12)
 12   FORMAT (6X, 'DATA FILE DOES NOT EXIST')
      GO TO 999

C     CALCULATE THE REQUIREMENTS FOR A GAS DRYER


 10   CALL DRYER

C     PRINT THE RESULTS.

      CALL OUTPUT

      CLOSE (UNIT=3, STATUS='KEEP')
      CLOSE (1)
 999  STOP
      END

C
C     ****************************************************************
C     THIS PROGRAM SIZES THE GAS DRYER WITH THE GIVEN DATA VALUES
C     ****************************************************************
```

```
        SUBROUTINE DRYER

        PARAMETER (PI=3.1415927)
        REAL MW, MOMEN

        COMMON/DRY1/ FLOW, P, T
        COMMON/DRY2/ Z, CYCLE, H2OC
        COMMON/DRY3/ S, E, PICKUP
        COMMON/DRY4/ DDEN, BL, HT
        COMMON/DRY5/ MW, H1, H2

        COMMON/RES1/ H2OL, DESVOL, AREA1
        COMMON/RES2/ BD, R, Q, VEL
        COMMON/RES3/ TC, VESWT, WD
        COMMON/RES4/ TB, THEAT, F
        COMMON/RES5/ REH, REG, SCF, MOMEN


C       CALCULATE TOTAL WATER ADSORBED, H2OL.

        H2OL = (FLOW*CYCLE*H2OC)/24.0


C       CALCULATE DESICCANT VOLUME, DESVOL

        DESVOL = (H2OL*100.0)/(PICKUP*DDEN)


C       CALCULATE DESICCANT CROSS-SECTIONAL AREA, AREA1.

        AREA1 = DESVOL/BL

C       CALCULATE BED DIAMETER, BD.

        BD = SQRT((4.0*AREA1)/PI)


C       CALCULATE THE BED AREA, AREA.

        AREA = (PI*BD**2)/4.

        T1 = T+460.
        R = (12.*BD)/2.
        P1 = P+14.7

C       CALCULATE THE ACTUAL GAS FLOW RATE AT FLOWING CONDITIONS, ft^3/min.

        Q = (FLOW*T1*Z*19.6314)/P1


C       CALCULATE THE SUPERFICIAL GAS VELOCITY, ft./min.

        VEL = Q/AREA

C       CALCULATE THE DRYER SHELL THICKNESS, in.

        TC = (P*R)/(S*E-0.6*P)


C       ASSUME H=2.0 ft. ADDITIONAL SHELL HEIGHT FOR DESICCANT SUPPORT AND
```

```
C       DISTRIBUTOR.

        H = 2.0

        R1 = BD/2.0

C       CALCULATE THE VESSEL WEIGHT., lb.


        VESWT = (480.*PI*BD*(TC/12.0)*(BL+H+R1)*1.1)
        TB = 0.75*HT+0.25*(HT-50.)

        WD = DDEN*DESVOL

        THEAT = 1.05*(VESWT*0.12*(TB-T)+WD*0.25*(TB-T)+H2OL*1400.)
        F = ALOG((HT-T)/50.)

C       CALCULATE TOTAL REGENERATION GAS REQUIREMENT AND STANDARD CUBIC
C       FEET OF REGENERATION GAS


        REH = THEAT*F
        REG = REH/(H1-H2)
        SCF = (REG*380.0)/MW

C       CALCULATE ALCOA'S MOMENTUM FOR MAXIMUM DOWNFLOW
C       VELOCITIES i.e. DESICCANT ATTRITION SHOULD NOT BE A PROBLEM
C       IF THE MOMEMTUM IS EQUAL TO OR LESS THAN 30,000.
C       MOMENTUM = (V)(MOL.WT) (P. Atms)

        MOMEN = VEL*MW*(P1/14.7)

        RETURN
        END


C       ****************************************************************
C       THIS PROGRAM PRINTS THE OUTPUT OF THE RESULTS
C       *****************************************************************

        SUBROUTINE OUTPUT

        REAL MOMEN, MW

        COMMON/DRY1/ FLOW, P, T
        COMMON/DRY2/ Z, CYCLE, H2OC
        COMMON/DRY3/ S, E, PICKUP
        COMMON/DRY4/ DDEN, BL, HT
        COMMON/DRY5/ MW, H1, H2

        COMMON/RES1/ H2OL, DESVOL, AREA1
        COMMON/RES2/ BD, R, Q, VEL
        COMMON/RES3/ TC, VESWT, WD
        COMMON/RES4/ TB, THEAT, F
        COMMON/RES5/ REH, REG, SCF, MOMEN

C
        WRITE (1, 100)
 100    FORMAT (///,35X, 'GAS DRYER DESIGN',/1H ,78(1H*))
```

```
      WRITE (1, 110) FLOW, P, T
110   FORMAT (5X, 'GAS FLOW RATE, 10^6 std. ft^3/day:',  T60, F12.3,/,
     *        5X,'DRYER OPERATING PRESSURE, psig.:', T60, F12.3,/,
     *        5X,'GAS FLOWING TEMPERATURE, oF:', T60, F12.1)

      WRITE (1, 120) Z, CYCLE, H2OC
120   FORMAT (5X,'GAS COMPRESSIBILITY FACTOR:', T60, F12.4,/,
     *        5X,'DRYING CYCLE, hr.:', T60, F12.1,/,
     *        5X,'WATER CONTENT OF GAS, lb/10^6 std.ft^3:',T60,F12.0)

      WRITE (1, 130) S, E, PICKUP
130   FORMAT (5X,'ALLOWABLE STRESS, psi:', T60, F12.1,/,
     *        5X,'JOINT EFFICIENCY:', T60, F12.1,/,
     * 5X,'USEFUL DESIGN CAPACITY OF DESICCANT, (%):', T60, F12.1)

      WRITE (1, 140) DDEN, HT
140   FORMAT (5X, 'DESICCANT DENSITY, lb/ft^3:', T60, F12.1,/,
     *        5X, 'HEATER OUTLET TEMPERATURE, oF:', T60, F12.1)

      WRITE (1, 150) MW, H1, H2
150   FORMAT (5X, 'MOLECULAR WEIGHT OF REGENERATION GAS:',T60,F12.1,/,
     *5X,'ENTHALPY OF GAS BEFORE REGENERATION HEATER, Btu/lb:',T60,
     *F12.1,/,5X,'ENTHALPY OF GAS AFTER REGENERATION HEATER, Btu/lb:',
     *T60, F12.1)


      WRITE (1, 160) H2OL, DESVOL, AREA1
160   FORMAT (5X,'TOTAL WATER ADSORBED, lb/h.:', T60, F12.3,/,
     *        5X,'DESICCANT VOLUME, ft^3.:', T60, F12.4,/,
     *        5X,'CALCULATED CROSS-SECTIONAL AREA, ft^2.:', T60, F12.4)

      WRITE (1, 170) BD, R, BL, Q, VEL
170   FORMAT (5X,'BED DIAMETER, ft.:', T60, F8.4,/,
     *        5X,'BED RADIUS, ft.:', T60, F8.4,/,
     *        5X,'BED LENGTH, ft.:', T60, F8.2,/,
     *        5X,'ACTUAL GAS FLOW RATE, ft^3/min.:', T60, F12.3,/,
     *        5X,'SUPERFICIAL GAS VELOCITY, ft./min.:', T60, F12.3)

      WRITE (1, 180) TC, VESWT, WD
180   FORMAT (5X,'DRYER SHELL THICKNESS, in.:', T60, F12.4,/,
     *        5X,'VESSEL WEIGHT, lb.:', T60, F12.0,/,
     *        5X,'DESICCANT WEIGHT, lb.:', T60, F12.0)

      WRITE (1, 190) TB, THEAT, F
190   FORMAT (5X,'TEMPERATURE OF DESICCANT BED, oF:', T60, F12.3,/,
     *        5X,'TOTAL HEAT REQUIRED TO REGENERATE DRYER, Btu:', T60,
     *        E14.6,/, 5X, 'LOSS FACTOR:', T60, F12.4)

      WRITE (1, 200) REH, REG, SCF, MOMEN
200   FORMAT (5X,'HEAT ADDED TO REGENERATION GAS:', T60, E14.6,/,
     *        5X,'TOTAL REGENERATION GAS REQUIREMENT, lb:',T60, E14.6,
     *      /,5X,'STANDARD CUBIC FEET OF REGENERATION GAS, std.ft^3:',
     *     T60, E14.6,/,5X,'MOMENTUM:', T60, E14.6)


      WRITE (1, 210)
210   FORMAT (76(1H-))

C     FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.


      WRITE (1, *) CHAR(12)

      RETURN
      END
```

CHAPTER 5

Instrument Sizing

INTRODUCTION

Instruments are used to monitor the pertinent process variables during plant operation. They may be part of automatic control loops or used for the manual monitoring of the process operation. Instruments that monitor critical process variables are fitted with automatic alarms to alert the operators to critical and hazardous situations. Miller [1] and Perry [2] provide details of process instruments and control equipment.

This chapter considers orifice sizing for liquid and gas flows, control valve design for liquid, vapor, steam services, and two-phase flow. The chapter further reviews relief valve sizing for vapor, steam, liquid, air, and fire conditions. The effect of the pressure drop (ΔP) on pipework design, noise suppression, discharge reactive forces, and relief valve location is considered. In addition, the chapter discusses two-phase flow relief sizing involving runaway reactions. For all the sizing procedures, the chapter develops the engineering equations for ease in preparing computer programs.

Orifice Sizing For Liquid and Gas Flows

In process design, an orifice or a nozzle is usually sized for known flow rate and pressure drop (ΔP). Nozzles and orifices are used to restrict the flow of fluids. Thus, a reduction in cross-sectional area can cause significant changes in the pressure and temperature of a compressible fluid as it flows through the constriction. The magnitude of the change depends on the linear velocity of the fluid or the Mach number at the constriction. An orifice is usually designed to develop a full-scale pressure differential at maximum flow. Alternatively, it can be designed to a square-edged or sharp-edged cut.

A square-edged or sharp-edged orifice is a clean cut square-edge hole with straight walls perpendicular to the flat upstream face of a thin plate placed crosswise of the channel. The stream issuing from such an orifice attains its minimum cross section (vena-contracta) at a distance downstream of the orifice. This varies with the ratio, β, of the orifice to the pipe diameter. All measurements of the distance from the orifice are made from the upstream face of the plate for the corner, radius, pipe, and vena contracta taps.

Corner Taps. Static holes are drilled, one in the upstream and the other in the downstream flange. The opening is as close as possible to the orifice plate.

Radius Taps. Static holes are located one pipe diameter upstream and one-half diameter downstream from the plate.

Pipe Taps. Static holes are located $2\frac{1}{2}$ pipe diameters upstream and 8 pipe diameters downstream from the plate.

Vena-Contracta Taps. The upstream static hole is $\frac{1}{2}$ to 2 pipe diameters from the plate; the downstream tap is located at the position of minimum pressure.

Flange Taps. Static holes are located 1 inch upstream and 1 inch downstream of the plate.

Figure 5-1 shows the locations and names of the orifice taps. The true mass flow rate for both liquids and gases is obtained by multiplying the theoretical mass flow equation by the discharge coefficient, the gas expansion factor, and the thermal-expansion factor. This is expressed as:

$$W_{\text{true}} = 0.52502\left(\frac{C_D Y d^2 F_a}{\sqrt{1-\beta^4}}\right)(\rho\Delta P)^{0.5} \qquad (5\text{-}1)$$

where the coefficient of discharge, C_D, is

$$C_D = \frac{\text{true flow rate}}{\text{theoretical flow rate}} \qquad (5\text{-}2)$$

C_D for a given orifice type is a function of the Reynolds number (N_{Re}) and the diameter ratio β. C_D is constant at Reynolds number greater than 30,000. For square-edged or sharp-edged concentric circular

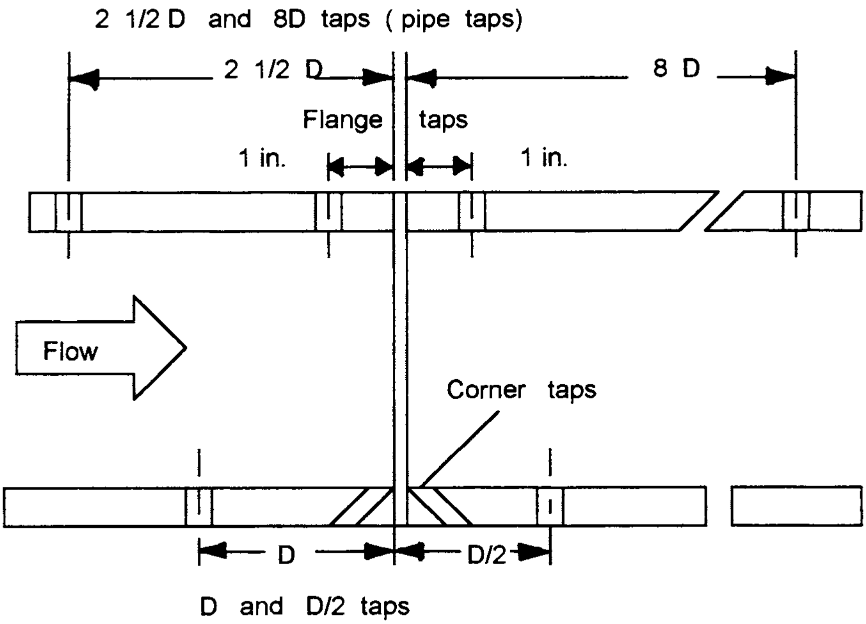


Figure 5-1. Orifice pressure tap locations. 2 1/2D and 8D pipe taps are not recommended in ISO 5167 or ASME fluid meters. D and D/2 taps are now used in place of vena-contracta taps.

orifices, C_D falls between 0.595 and 0.62. The discharge coefficient corrects the theoretical equation for the influence of velocity profile (N_{Re}), assuming no energy loss between the taps and pressure-tap location.

The thermal expansion factor F_a: The material of primary element and pipe expands or contracts with temperature. The pipe and bore diameters are measured at room temperature, but will be larger or smaller when used at other temperatures. F_a is introduced to correct for these differences.

The Expansion Factor Y. This corrects for density changes between taps. Y depends on the adiabatic exponent ($k = C_p/C_v$), absolute pressure ratio ($\Delta P/P_1$), and the ratio, β, between restriction diameter and the inside pipe diameter. For liquid flow, Y = 1.0. For gas flow, Buckingham derived the equation [3]:

$$Y = 1 - (0.41 + 0.35\beta^4)\frac{\Delta P}{Pk} \tag{5-3}$$

Orifice Sizing For Liquid Flows

For liquid sizing, Y=1.0, and the following assumptions are $F_a = 1.0$, $C_D = 0.62$ [4]

Equation 5-1 is re-arranged in the form

$$\frac{\sqrt{1-\beta^4}}{d^2} = \frac{0.52502(C_D)}{W_{\text{true}}}(\rho\Delta P)^{0.5} \tag{5-4}$$

where

$$Z = \frac{0.52502(C_D)}{W_{\text{true}}}(\rho\Delta P)^{0.5} \tag{5-5}$$

and

$$\beta = \frac{d}{D} \tag{5-6}$$

Equation 5-4 is expressed by

$$\frac{1}{d^2}\left[1-\left(\frac{d}{D}\right)^4\right]^{0.5} = Z \tag{5-7}$$

squaring both sides of Equation 5-7

$$\frac{1}{d^4}\left[1-\left(\frac{d}{D}\right)^4\right] = Z^2 \tag{5-8}$$

$$\frac{1}{d^4} - \frac{1}{D^4} = Z^2 \tag{5-9}$$

$$\frac{1}{d^4} = Z^2 + \frac{1}{D^4} \tag{5-10}$$

The orifice size, d, is expressed by

$$d = \left(\frac{D^4}{1 + D^4 Z^2}\right)^{0.25} \tag{5-11}$$

Orifice Sizing For Gas Flows

Using Equations 5-1 and 5-3
That is,

$$W_{\text{true}} = 0.52502\left(\frac{C_D Y d^2 F_a}{\sqrt{1-\beta^4}}\right)(\rho\Delta P)^{0.5} \tag{5-1}$$

and

$$Y = 1 - (0.41 + 0.35\beta^4)\frac{\Delta P}{Pk} \tag{5-3}$$

The following substitutions are made:

$$y = \beta^4 \tag{5-12}$$

$$l = \frac{W_{\text{true}}}{0.52502(D^2)(\rho\Delta P)^{0.5}} \tag{5-13}$$

$$n = 1 - 0.41\frac{\Delta P}{P.k} \tag{5-14}$$

$$t = 0.35\frac{\Delta P}{P.k} \tag{5-15}$$

Equation 5-1 and Equation 5-3 are modified and combined to give

$$l = \frac{(ny^{1/2} - ty^{3/2})}{(1-y)^{1/2}} \tag{5-16}$$

Squaring both sides and dividing by t^2, Equation 5-16 is expressed in cubic form as:

$$y^3 - \frac{2n.y^2}{t} + \frac{n^2 + l^2}{t^2}y - \frac{l^2}{t^2} = 0 \tag{5-17}$$

Equation 5-17 is solved for y by finding roots of the cubic equation using the following substitutions.

Let

$$p = \frac{2n}{t} \tag{5-18}$$

$$q = \left(\frac{n^2 + l^2}{t^2}\right) \tag{5-19}$$

$$r = -\frac{l^2}{t^2} \tag{5-20}$$

$$y^3 - 2py^2 + qy - r = 0 \tag{5-21}$$

and

$$a = \frac{3q - p^2}{3}$$

$$= \frac{3l^2 - n^2}{3t^2} \tag{5-22}$$

$$b = \frac{(2p^3 - 9pq + 27r)}{27}$$

$$= -\frac{(2n^3 + 18nl^2 + 27tl^2)}{27t^3} \tag{5-23}$$

The solution to Equation 5-17 yielding a real number is:

$$y = \left\{-\frac{b}{2} + \left(\frac{b^2}{4} + \frac{a^3}{27}\right)^{1/2}\right\}^{1/3}$$

$$+ \left\{-\frac{b}{2} - \left(\frac{b^2}{4} + \frac{a^3}{27}\right)^{1/2}\right\}^{1/3} - \frac{2n}{3t} \tag{5-24}$$

the orifice diameter, d, is expressed by

$$d = Dy^{1/4} \tag{5-25}$$

Conversions:

$$\Delta P = 0.03613(h_w) \tag{5-26}$$

$$W_{true} = \left(\frac{Q.\rho}{60.0}\right) \tag{5-27}$$

The orifice sizing applies to corner, flange, vena-contracta and 1/2-diameter taps.

Nomenclature

C_D = coefficient of discharge
d = orifice diameter for full scale ΔP, inch
D = internal pipe diameter, inch
F_a = area thermal-expansion factor. Takes into account the expansion of the orifice with temperature changes
h_w = full-scale orifice pressure differential, in. H_2O at 68°F
k = specific heat ratio (constant pressure to constant volume C_p/C_v)
P = upstream pressure, psia
ΔP = full-scale orifice pressure-differential, psi
Q = full-scale flow rate at upstream conditions, ft^3/min
W_{true} = true full-scale flow rate, lb/s
Y = expansion factor
β = d/D, ratio of orifice diameter to pipe I.D.
ρ = upstream fluid density, lb/ft^3

CONTROL VALVE SIZING

Introduction

Valves and piping represent about 25 percent of the total capital expenditure for materials and equipment in the chemical process industries (CPI). These industries employ valves in a wide range of flowing media from granula solids to industrial wastes. The most important characteristics in the selection of valves are viscosity, corrosiveness, and abrasiveness. In addition, a designer must consider the process parameters. These may be predictable short-term upset conditions, handling more than one fluid with the same valve, or potentially high pressures resulting from a fluid being entrapped in a valve body that then vaporizes due to heat gain. Selecting the right control valve for an application involves four basic styles of throttling: cage-style globe valves, ball valves, eccentric-disk valves, and butterfly valves. Globe valves are the standards of the control valves. These may be hand operated or power actuated types for automatic control. The common feature of these valves is their internal construction, which consists of a disc or plug reciprocating within the valve body. Figure 5-2A shows a typical globe valve, and Figure 5-2B shows a globe valve with cage-style trim.

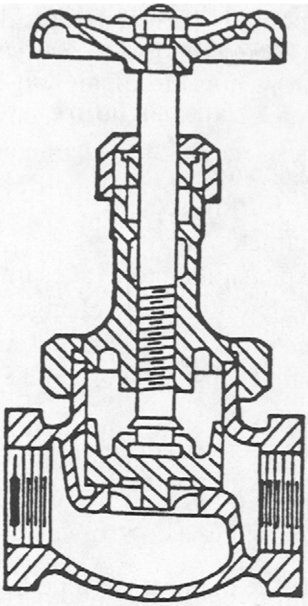


Figure 5-2A. A globe valve.

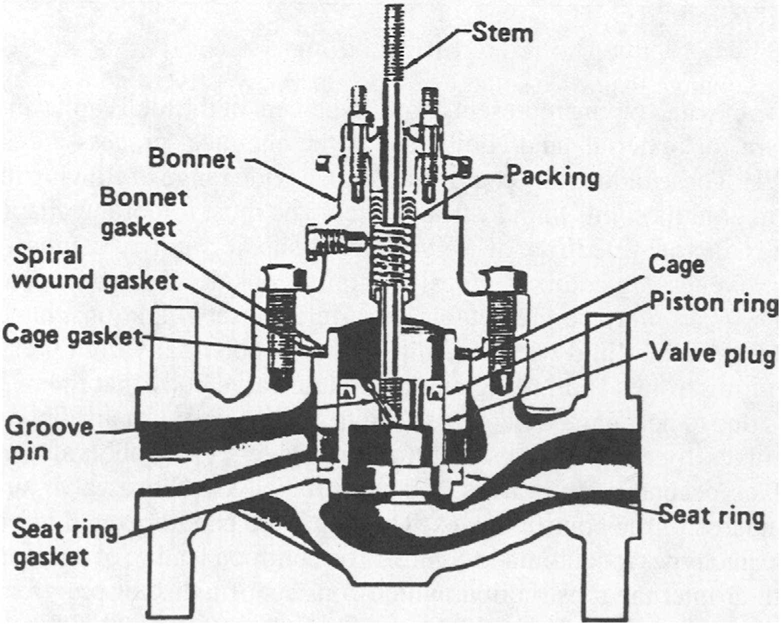


Figure 5-2B. A globe valve with cage-style trim.

Langford [5] has reviewed the installation, maintenance and troubleshooting of control valves, while Driskell [6] studied the various aspects of two-phase flow, non-turbulent, non-Newtonian and flashing liquids. Recently, Collins [7] listed the main basic conditions for selecting control valves. These include (1) characteristics of the controlled fluid, (2) system pressures, (3) maximum differential pressure, (4) fluid operating temperature and range, (5) line size, (6) valve size, (7) valve type, (8) valve C_v, (9) allowable leakage, (10) end connections, (11) valve environment (outside temperature and range), (12) seat material, body material, (13) actuation medium, (14) flow characteristics, and (15) rangeability.

Correctly sized control valves achieve a high quality of control. A valve that is too small will not allow the required flow, and a valve that is too large will cost more than a correctly sized smaller valve and the flow will be uncontrollable because its full control range will not be used. The procedure for sizing a control valve is [8]:

1. Calculate the required valve sizing coefficient, C_v, based on process data and manufacturers' valve data.
2. Consult valve manufacturers' table of C_v against size. Then select the smallest valve with a C_v rating greater than or equal to the required C_v.
3. Check that the reducers required installing the valve will not change the valve selection. Choose a new valve with a greater C_v if necessary.
4. Check that the flow through the valve is not choked.

When the liquid flow is turbulent, and the effects of choked flow and reducers are ignored, the expression for C_v reduces to

$$C_v = \frac{q}{K_D}\left(\frac{SpGr_f}{\Delta P}\right)^{0.5} \tag{5-28}$$

Pressure Drop For Sizing

The pressure drop (ΔP_{sizing}) used for sizing the control valve is the actual pressure drop across the valve at the sizing flow rate. This is obtained by starting with the system pressure drop (ΔP_{system}). The pressure drop at the sizing flow rate of all pipe, fittings, and equipment in the flow system is subtracted from ΔP_{system}. The remainder is the actual pressure drop across the control valve at the sizing flow rate.

Choked Flow

As the flow of liquid passes the point of greatest restriction inside the control valve, its velocity reaches a maximum and its pressure falls to a minimum. If the pressure falls below the vapor pressure of the liquid, vapor bubbles form within the valve. Increasing ΔP_{sizing} across the valve beyond the point where vapor bubbles form would not alter the flow. This suggests choked flow. The ΔP at which choked flow begins is called the terminal, ΔP_T. ΔP_T is used instead for sizing the control valve when ΔP_{sizing} across the valve is greater than ΔP_T.

Flashing and Cavitation

Choked flow produces either flashing or cavitation. Flashing occurs when the pressure downstream of the valve is below the vapor pressure of the liquid, ΔP_v. Pipe and internal valve erosion often occur because the velocity of flashing the vapor-liquid stream is higher than the inlet liquid velocity. A cavitation will occur if the downstream pressure is above the liquid's vapor pressure. This results in the collapse of the vapor bubbles as they leave the point of greatest restriction in the valve. The shock waves and noise caused by the collapsing bubbles cause rapid and severe damage to the valve or piping.

CONTROL VALVE SIZING FOR LIQUID, GAS, STEAM, AND TWO-PHASE FLOW

The valve flow coefficients,C_v for a given valve depend on the internal dimensions of the valve and the smoothness of the valve's internal surface. Control valve manufacturers establish the C_v for their valves through a series of tests using water or air at a given pressure differential across the valve. Manufacturers define C_v as the capacity index. This indicates the flow of water (gpm at 60°F) that will pass through a completely open valve under a pressure differential between the inlet and outlet flanges. Control valve coefficients for single and double seated valves are given in Table 5-1 [9].

Liquid Sizing

The equation for sizing valve for liquid service is given by

$$C_v = Q_l \left(\frac{SpGr_l}{P_1 - P_2} \right)^{0.5} \tag{5-29}$$

Table 5-1
Flow Coefficients for Control Valves

	Flow Coefficient	C_V
Size, in.	Single-Seat	Double-Seat
3/4	—	8
1	9	12
1 1/4	14	18
1 1/2	21	28
2	36	48
2 1/2	54	72
3	75	110
4	124	195
6	270	450
8	480	750
10	750	1160
12	1080	1620
14	1470	2000
16	1920	2560

Alternatively, for a given C_v, the liquid flow rate can be defined by

$$Q_l = C_v \left(\frac{P_1 - P_2}{SpGr_l} \right)^{0.5} \qquad (5\text{-}30)$$

Equation 5-29 is valid for liquid flowing below its saturation temperature in the turbulent zone with a viscosity value that is close to that of water and size of pipe. Also, the control valve must be the same. Equation 5-29 can also be applied, if the vapor pressure of the liquid at the flowing temperature is equal to or less than one-half the upstream pressure. For this case, the vapor pressure of the liquid is substituted for downstream pressure, P_2, and the valve coefficient is calculated. The calculated C_v must be corrected by a critical flow factor, C_f, where $C_v$corr is defined by

$$C_v\text{corr} = \frac{C_v\text{calc}}{C_f} \qquad (5\text{-}31)$$

The value of C_f is between 0.85 and 0.98. Flow capacity of a control valve placed between pipe reducers is slightly decreased. In subcritical flow, this is accounted for by a correction factor, R. In critical flow, the correction factor is C_{fr}. This replaces C_f in the sizing calculations. In addition, R, C_f, and C_{fr} depend on the ratio between pipe size and valve size. Table 5-2 lists values of R, C_f, and C_{fr} for single-seated and double-seated control valves [9].

Gas Sizing

The following equations are used for sizing control valves for gas and steam conditions. These equations apply to both subcritical and critical flow conditions [10].

For subcritical condition, C_v, is defined by

$$C_v = \frac{Q_g\left\{(SpGr_g)(T)\right\}^{0.5}}{1360\left\{(P_1 - P_2)(P_2)\right\}^{0.5}} \tag{5-32}$$

Table 5-2
Correction Factors for Control Valve Flow Coefficient

		Single	Seat	Double	Seat
Condition	Factor	Equal-Percentage	V-Port	Equal-Percentage	V-Port
Critical flow line size control valve	C_f	0.98 or .85	0.98	0.98	0.98
Critical flow (control valve between pipe reducers)	C_{fr}	0.86	0.94	0.86	0.94
Subcritical flow D/d = 1.5	R	0.96	0.96	0.96	0.94
Subcritical flow D/d = 2 (Control valve between pipe reducers)	R	0.94	0.94	0.94	0.94

The gas flow rate is computed for a given C_v, and is defined by

$$Q_g = \frac{C_v(1360)\{(P_1 - P_2)(P_2)\}^{0.5}}{\{(SpGr_g)(T)\}^{0.5}} \tag{5-33}$$

Critical Condition

For critical flow, the downstream pressure of the control valve is less than one-half the upstream pressure. Therefore, the term $\{(P_1 - P_2)(P_2)\}^{0.5}$ reduces to $0.5P_1$ in Equations 5-32 and 5-33. C_v is then defined by

$$C_v = \frac{Q_g\{(SpGr_g)(T)\}^{0.5}}{1360(0.5P_1)} \tag{5-34}$$

The gas flow rate is:

$$Q_g = \frac{C_v(1360)(0.5P_1)}{\{(SpGr_g)(T)\}^{0.5}} \tag{5-35}$$

Steam Sizing

The following equations are used to size control valves for saturated and superheated steam flow. For saturated steam flow, a value of zero is used for °F superheat.

Subcritical Condition. The control valve coefficient, C_v, is defined by

$$C_v = \frac{(W)(K)}{3\{(P_1 - P_2)(P_2)\}^{0.5}} \tag{5-36}$$

The steam flow rate, W, is defined by

$$W = \frac{(3)(C_v)\{(P_1 - P_2)(P_2)\}^{0.5}}{K} \tag{5-37}$$

Critical Condition. The control valve coefficient and the steam flow rate are expressed as:

$$C_v = \frac{(W)(K)}{1.5P_1} \tag{5-38}$$

and

$$W = \frac{1.5(P_I)(C_v)}{K} \tag{5-39}$$

where

$$K = 1 + (0.0007 \times {}^\circ F \text{ superheat}) \tag{5-40}$$

Two-Phase Flow

Sizing a control valve for liquid-gas mixtures introduces incorrect valve coefficient, C_v, if C_v for each of the two fractions is calculated separately, and then added. This method assumes that the liquid and gas are passing through the valve orifice independently and at greater different velocities.

Driskell [6] has given a plausible assumption that the two fluids travel through the throttling orifice as a homogeneous mixture at approximately the same velocity. He applied the gas expansion factor to the gas fraction only, and not to the total mixture. C_v for liquid-gas mixtures can be expressed as follows:

Divide the specific volume of the inlet gas, v_g, by the square of the expansion factor Y. This gives an effective incompressible specific volume, while the liquid specific volume, v_l, is unaffected.

That is,

$$\frac{v_g}{Y^2} + v_l \tag{5-41}$$

where $v_g = 1/\rho_g$ and $v_l = 1/\rho_l$

Add the effective volumes of the two fluids in proportion to their mass fraction, f, in the mixture to obtain the effective specific volume of the stream, v_e.

$$v_e = \frac{f_g \cdot v_g}{Y^2} + f_l \cdot v_l \tag{5-42}$$

where the expansion factor is:

$$Y = 1 - \frac{x}{(3F_k x_T)} \tag{5-43}$$

and

$x = \Delta P/P_1$
x_T = pressure drop ratio factor (from manufacturer)
F_k = ratio of specific heats factor (k/1.40)
k = ratio of specific heats (C_p/C_v)
$\Delta P = P_1 - P_2$, psi
P_1 = inlet pressure, psia
P_2 = outlet pressure, psia

The valve coefficient, C_v, is:

$$C_v = \frac{W}{63.3\left(\frac{\Delta P}{v_e}\right)^{0.5}} \tag{5-44}$$

Alternatively, for a given C_v, the flow rate in lb/h is:

$$W = 63.3(C_v)\left(\frac{\Delta P}{v_e}\right)^{0.5} \tag{5-45}$$

Installation

Control valves form an important equipment item in process plants, and therefore, a lot of money can be saved by ensuring that the right valves are installed. Selecting the right control valve for any application starts with defining the valve's functions. For example, if an on-off interlock valve is to be used, then the primary criteria for selection are reliability and simplicity. If very fast and precise modulation is required, such as for a compressor antisurge vent, a high quality valve is chosen.

Factors that affect the selection of control valves are:

- ***Defining the type of fluid.*** This includes the physical properties (density and viscosity), corrosive properties, and the nominal pressures, temperatures and flow rate. In the case of fluids, it is necessary to know the vapor pressures to check for flashing and cavitation. Also a high temperature increase can severely damage some types of gaskets and packings.
- ***The valve size.*** This can be defined using standard calculation methods. The operating conditions and calculations may eliminate cer-

tain valve styles from consideration. Cavitation is more evident with the high-recovery rotary type valves and sometimes can be avoided by selecting a globe valve. In addition, a valve that is too small will not permit the required amount of flow. Alternatively, a valve that is too large will be expensive and may create trim wear and control problems.

- ***Access for maintenance.*** This must be provided during the design phase, retained during construction, and considered during the revision stage. Maintenance can be both problematic and expensive if a valve is difficult to reach or to work on. A substantial change in the fluid-momentum (e.g., a flow through an angle valve or a large fluid-velocity change) causes high reaction forces. This can cause serious damage to the valves. The valve should be installed between one and three feet above the grade or platform to control the process.
- ***Excessive stress on a valve body.*** This can cause leakage and prevent normal operation of the moving parts resulting in the breakage of the flange or valve body. Poor pipe alignment is the most probable cause of excess stress. Also, heavy valves require support in order to reduce the stress and to make removal and reinstallation easier.

Noise

Cavitation refers to the formation and subsequent collapse of vapor bubbles in the flowing liquid stream at a point of higher pressure. This causes erosion of the valve parts. It generates extremely high pressure shock waves that hammer against the valve outlet and piping. Pressures in these collapsing cavities can be as high as 500,000 psi in magnitude, and often result in severe and rapid damage to the valve and piping.

Noise from control valves is often caused by pressures, flows, and temperatures involving compressible flow. Valves control flow by causing turbulence, thereby converting much of the energy to heat and a small fraction to sound. The control valve manufacturers have developed noise reducing valve trims and high-capacity valve configuration. Langford [5] suggested that noise may be reduced by as much as 20 dB by installing acoustic insulation at the valve and downstream, or alternatively by using heavier wall pipe downstream.

Nomenclature

C_v = capacity coefficient for fully open control valve
f_g = mass fraction in the gas phase

f_l = mass fraction in the liquid phase
F_k = ratio of specific heats factor (k/1.40)
k = ratio of specific heats (C_p/C_v)
K = superheat correction factor
K_D = coefficient of discharge
P_1 = inlet pressure, psia
P_2 = outlet pressure, psia
ΔP = pressure drop, psi
q = fluid flow rate
Q_l = liquid flow rate, gpm
Q_g = gas flow rate,ft^3/h at 14.7 psia and 60°F
$SpGr_f$ = specific gravity of fluid
$SpGr_l$ = specific gravity of liquid
$SpGr_g$ = specific gravity of gas = M Wt of gas/M Wt of air
T = flowing temperature, °R (°F + 460)
V_e = effective specific volume of the stream
V_g = specific volume of the inlet gas
V_l = specific volume of the inlet liquid
X_T = pressure drop ratio factor (from manufacturer)
W = steam flow, lb/h

RELIEF VALVE SIZING

Introduction

Safety relief valves serve a valuable function in protecting against overpressure of pipework and process equipment. This may occur due to operational malfunction, such as equipment failure, fire or human error. Proper sizing of a relief system is therefore essential. This requires the determination of proper relieving conditions (e.g., flows, pressures ,and temperatures) so that relief valves and their associated pipework can be properly sized for the worst scenario. Designers are responsible to obviate all conceivable conditions, and good judgment must be exercized in setting the relief requirements (set pressure, for example) in all design facets during hazard and operability studies. Here, five relief conditions are considered [11]:

- gas or vapor
- steam
- liquid

- air
- fire

In addition, noise suppression, preferred location of relief valves, and pressure drop requirements for stable operation involving inlet pipe to the valve and tail pipe are reviewed.

Typical Relief Valves

There are two main types of safety relief valves. The conventional type is shown in Figure 5-3. A balanced safety relief valve shown in Figure 5-4 is designed to limit the effect of back pressure on opening pressure, closing pressure, lift capacity, and relieving capacity. The balanced valves are mainly the piston type and the bellows type.

Because of its design, a conventional relief valve encounters any back pressure accumulated in the discharge header so that the relieving pressure is affected. For example, a relief valve set at 450 psig relieving into a closed header system with 10 psig back pressure caused by loads from other units will not open until the vessel is at 460 psig. Normal practice allows only 10 percent of the set pressure "buildup" in a unit for most emergencies. Conventional relief valves, therefore, may often force the designer to increase the header size to limit back pressure. The balanced relief valve does not encounter the accumulated pressure and can relieve at design rates even when back pressure is 30–50 percent of its set pressure. Therefore, for services with high back pressure in the header, the balanced relief valve is much preferred.

Gas or Vapor Sizing

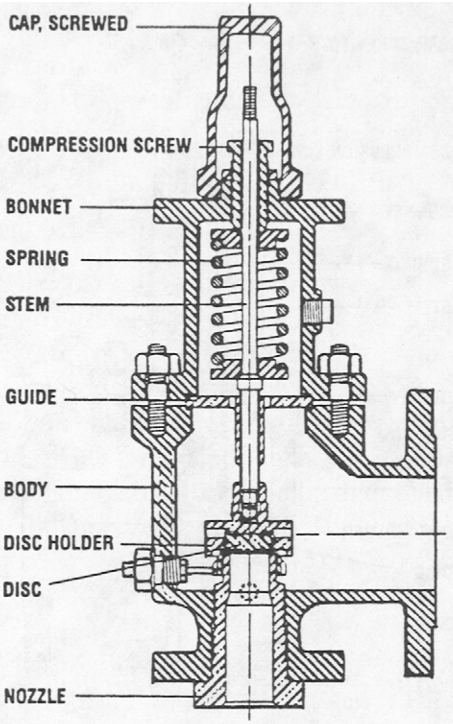
The expression used to determine the relief area for vapor discharge when the back pressure is less than the critical flow pressure is:

$$A = \frac{W}{(C)(K)(P)(K_b)}\left[\frac{T.Z}{M_w}\right]^{0.5} \tag{5-46}$$

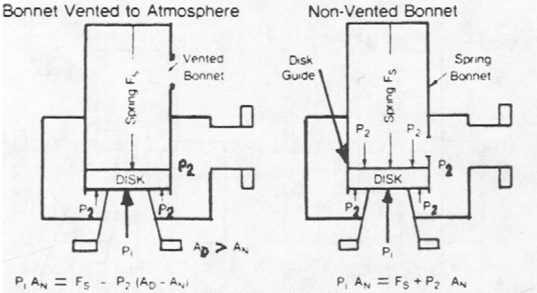
where C can be expressed as:

$$C = 520\left[k\left(\frac{2}{k+1}\right)^{\frac{(k+1)}{(k-1)}}\right]^{0.5} \tag{5-47}$$

CONVENTIONAL SAFETY-RELIEF VALVE



Valve Cross Section



$P_1 A_N = F_S - P_2 (A_D - A_N)$

Back Pressure Decreases Set Pressure

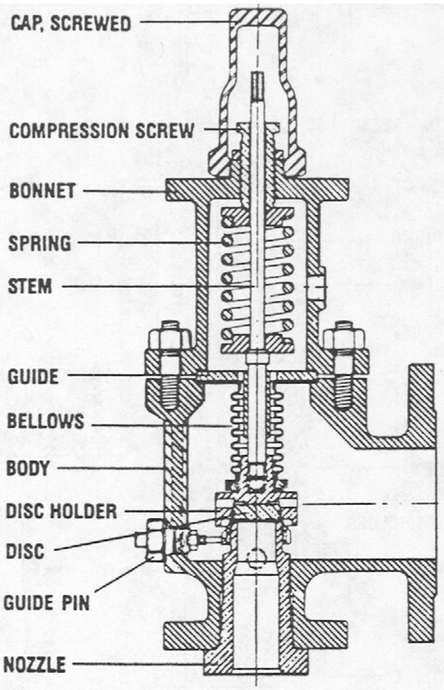
$P_1 A_N = F_S + P_2 A_N$

Back Pressure Increases Set Pressure

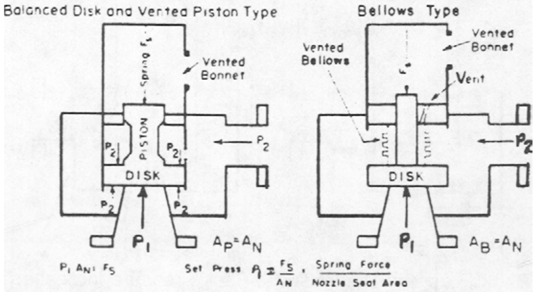
Effect of Back Pressure on Set Pressure of Conventional Safety-Relief Valves

Figure 5-3. Conventional safety relief valve. (Reprinted courtesy of the American Petroleum Institute.)

BALANCED SAFETY-RELIEF VALVE



Bellows Valve Cross Section



NOTE: Back pressure has very little effect on set pressure.

Effect of Back Pressure on Set Pressure of Balanced Safety-Relief Valves

Figure 5-4. Balanced safety-relief valve. (Reprinted courtesy of the American Petroleum Institute.)

The values of k for some gases are given in Chapter Three. K_b is the back pressure correction factor due to back pressure and is dependent on the type of relief used. Figure 5-5 gives K_b for conventional spring reliefs and Figure 5-6 for balanced bellows reliefs, repectively.

Steam Sizing

The equation for steam service is a modification of Napier steam flow given in the ASME Boiler and Pressure Vessel Code. ASME Power Boiler Code applications permit 3 percent overpressure. The equation for steam relief is [12]:

$$A = \frac{W}{(51.5)(P_1)(K_d)(K_N)(K_{SH})} \tag{5-48}$$

Liquid Sizing

The requisite orifice area for a safety relief valve used in liquid service (nonviscous) requiring liquid capacity certification is:

$$A = \frac{W}{(38)(K_d)(K_w)(K_v)}\left(\frac{SGL}{P_1 - P_2}\right)^{0.5} \tag{5-49}$$

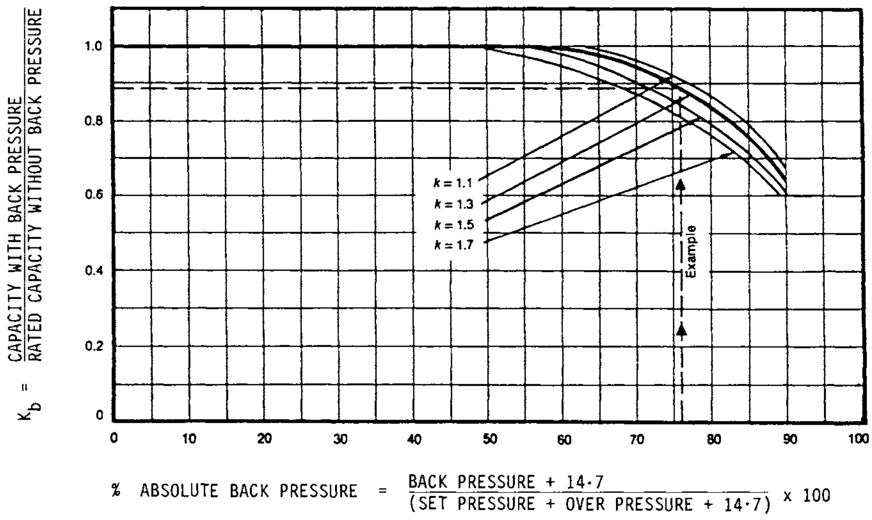


Figure 5-5. Constant back pressure sizing factor, K_b, for conventional safety relief valves in vapor or gas service. (API Recommended Practice 520, Sizing, Selection and Installation of Pressure Relieving Devices in Refineries, Part 1, 5th ed., 1990. Reprinted courtesy of the American Petroleum Institute.)

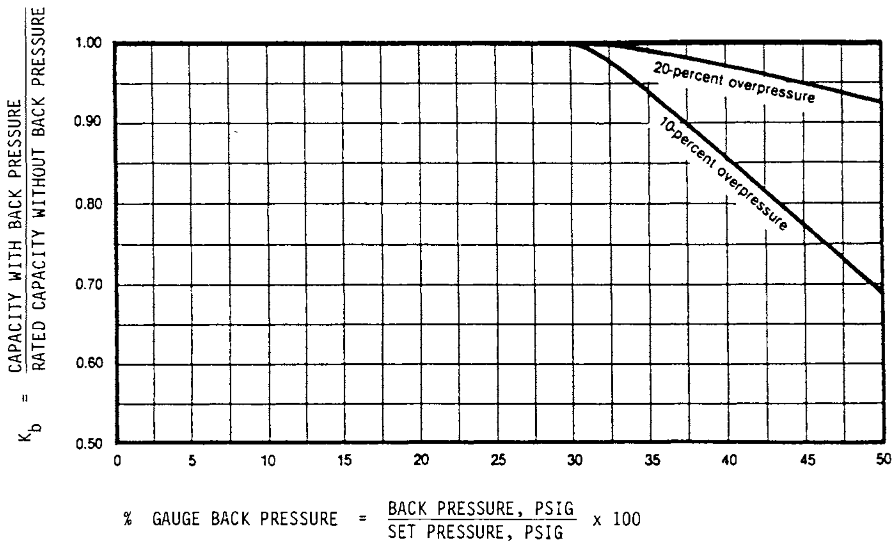


Figure 5-6. Back pressure sizing factor, K_b, for balanced-bellows pressure relief valves in vapor or gas service. (API Recommended Practice 520, Sizing, Selection and Installation of Pressure Relieving Devices in Refineries, Part 1, 5th ed., 1990. Reprinted courtesy of the American Petroleum Institute.)

K_w is the capacity correction factor due to back pressure on balanced-bellow relief valves. If the back pressure is atmospheric $K_w = 1$. This correction factor is given is Figure 5-7. When sizing a relief valve for viscous liquid service, the orifice area is first calculated for nonviscous service to obtain a preliminary discharge area. The next standard orifice size is used to calculate the Reynolds number. The K_v factor is then calculated and applied to correct the preliminary required discharge area. The Reynolds number is expressed as [10]:

$$\mathrm{Re} = \frac{Q(2800)(SGL)}{\mu(ADES)^{0.5}} \tag{5-50}$$

where

$$\begin{aligned} K_v &= -2.38878 + 1.2502(\ln \mathrm{Re}) + 0.1751(\ln \mathrm{Re})^2 \\ &\quad + 0.01087(\ln \mathrm{Re})^3 - 0.00025(\ln \mathrm{Re})^4 \end{aligned} \tag{5-51}$$

Air Sizing

The required orifice area for a relief valve sizing for air at constant back pressure is:

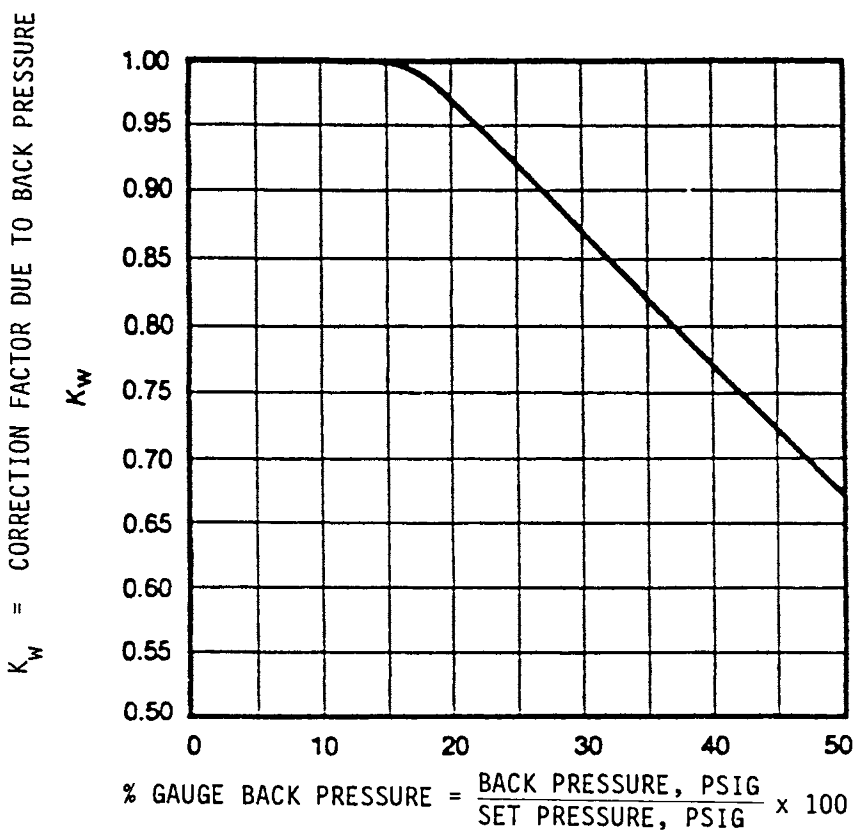


Figure 5-7. Capacity correction factor, K_w, due to back pressure on balanced-bellows pressure relief valves in liquid service. (API Recommended Practice 520, Sizing, Selection and Installation of Pressure Relieving Devices in Refineries, Part 1, 5th ed., 1990. Reprinted courtesy of the American Petroleum Institute.)

$$A = \frac{(V_a)(T)^{0.5}}{(418)(K_d)(P)(K_b)} \tag{5-52}$$

Fire Sizing

In the case of a fire, there is a pressure buildup and the required relief capacity can be determined provided that the heat absorbed can be estimated. API 520 gives recommendations for heat of absorption during vapor relief [12}. Not all the causes will happen simultaneously, but the pressure relief or safety relief should be sized for conditions that require the greatest relief.

Inconsistencies for sizing relief valves for fire emergencies arise among published codes. This is because of varying interpretations of the heat flux caused by fire exposure. These variations are based on the area in which the heat flux applies and the protection factors used to characterize the installations. Crozier [13] has summarized these variations and evaluated the pertinent correlations. Here, the API 520 correlation is used because it contains an implied protection factor of 0.5 for good drainage.

Liquid in liquid-filled vessels exposed to direct or radiated heat from a fire will vaporize. The heat required to accomplish this will limit the shell temperature of the tank to only a slight rise. The amount of liquid vaporized depends on the rate of heat input from the fire and the relieving temperature. This can be determined by calculating the heat input to the wetted surface of the vessel and dividing this by the latent heat of vaporization.

$$Q_r = 21{,}000(FI)(A_w)^{0.82} \tag{5-53}$$

and

$$W = \frac{Q_r}{\lambda} \tag{5-54}$$

The vapor to be relieved is the vapor in equilibrium with the liquid (that is, saturated vapor at the conditions existing when the valve is relieving at the rated capacity). Table 5-3 shows environmental factors for bare and insulated vessels.

For a multicomponent mixture, λ_{mix} can be determined from

$$\lambda_{mix} = \sum_{i=1}^{n} \frac{\lambda_i y_i M_i}{M} \tag{5-55}$$

To determine y_i, it is necessary to know the equilibrium liquid-phase mole fraction, x_i, at the bubble point corresponding to the accumulated relieving pressure.

The wetted surface area depends on the diameter and length of the vessel. For working storage tanks, the wetted surface is obtained on the average inventory. Surge drums usually operate about half full; thus the wetted surface will be calculated at 50 percent of the total vessel surface.

Table 5-3
Environmental Factor

Type of Equipment	Factor
Bare vessel	1.0
Insulated vessel (These arbitrary insulation conductance values are in Btu/hrft^2 °F	
4	0.3
2	0.15
1	0.075
0.67	0.05
0.5	0.0376
0.4	0.03
0.33	0.026
Water-application facilities on bare vessel	1.0
Depressurizing and emptying facilities	1.0
For approved water spray with approved insulation	0.15
For drainage	0.5
For approved water spray	0.3

Effect of Back Pressure

The maximum allowable back pressure (gauge) for a conventional safety relief valve is 10% of the set pressure (gauge). If the maximum allowable back pressure is exceeded during any relief situation, the size of the relief lines or headers should be increased until the back pressures are sufficiently reduced.

Noise Suppression

Expansion of gas or vapor usually gives rise to an unacceptable noise level. However, this is not a problem with liquid relief. There are two sources of noise:

1. Noise due to turbulence at the point where the gas mixes with the atmosphere. Suppression of this type of noise involves the fitting of a silencer.
2. Noise due to pressure letdown (that is, relief valve) when sonic or near sonic velocities are generated. This is transmitted through the wall of pipe and, if the discharge is short, it is transmitted through the open end. Noise from this can be reduced by lengthening the discharged pipe and by insulation. Suppression of the noise can also be overcome by fitting a silencer. Such silencers are often installed in an exposed environment and are likely to accumulate dirt, vapor, or products from minor leakage of safety devices.

Effect of Pressure Drop (ΔP) on Pipework

The pipework should be designed with the following considerations:

- The frictional ΔP through the inlet pipework, inlet fittings, and valves at the maximum possible relief rate should not exceed 3% of the set gauge pressure (psig). The calculation of ΔP should include the entrance loss of the inlet pipework. The discharge pipework must be such that ΔP is less than 10% of the relieving pressure (that is, set pressure plus overpressure in gauge). The discharge pipework should withstand the internal pressure and high velocities, the reaction forces, and the sudden transient loading that occur when a relief device suddenly comes into operation.
- The inlet pipework should be of a size at least equal to the relief valve, with its length minimized to reduce ΔP. It should also be equal to the bending moments resulting from the forces that develop when the valve or disc is discharging at full capacity.
- A relief device should be installed vertically and preferably on a nozzle at the top of the equipment (for example, vessel) or on a tee connected to a pipeline. When discharging a gas or vapor, the fluid reaches sonic velocity when passing through a relief device. Thus, the gas flow rate or ΔP can be determined by a method as described in Chapter Three.

For liquid discharges, the design of the pipework may be complex. If the liquid is subcooled, the discharge pipework is sized by standard liquid pressure formulae. If the liquid in the equipment is at or near its saturation pressure, the relief device and discharge pipework should be sized for two-phase flow. As the liquid flows through the relief valve, the ΔP will cause it to flash. Therefore, the size of the valve and discharge pipework must be increased to accommodate the larger volume. Further flashing in the downstream piping will increase the gas-liquid mixture through the two-phase regimes. If this is not arrested, slug flow will develop along the pipeline resulting in the mechanical damage to the pipework.

Discharge Reactive Forces

The total stress imposed on a safety valve or its piping is a result of the sum of the following:

- internal pressure
- dead weight of piping
- thermal expansion or contraction of either the discharge line
- the equipment upon which the valve is mounted
- the bending moment caused by the reaction thrust at the discharge

The discharge reactive force is based on the assumption that critical flow of the gas or vapor is obtained at the outlet of the relief device and the discharge is horizontal to the atmosphere. For any gas or vapor, the reactive force can be expressed as:

$$F = \frac{W\left[\dfrac{kT}{(k+1)M_w}\right]^{0.5}}{366} \qquad (5\text{-}56)$$

Relief Valve Location

The location of a relief device often influences its size and material of construction. Relief devices must be sited so that the risk of blockage by debris is minimized. It is poor practice to mount relief valves at the end of long horizontal pipe through which there is no flow. The possibility of liquid phase entering a vapor relief system must also be avoided. Locating a relief device upstream of equipment that has ΔP due to flow allows the relief valve to be smaller because increased ΔP is available. Reduced costs of a relief system may be obtained by installing relief valves in a more conducive position with regard to temperature and corrosion. Figure 5-8 shows alternative positions. Position 1 is preferred when the relief valve is tied into a closed relief system because of ease of maintenance. It assures a relatively short line to the relief header and

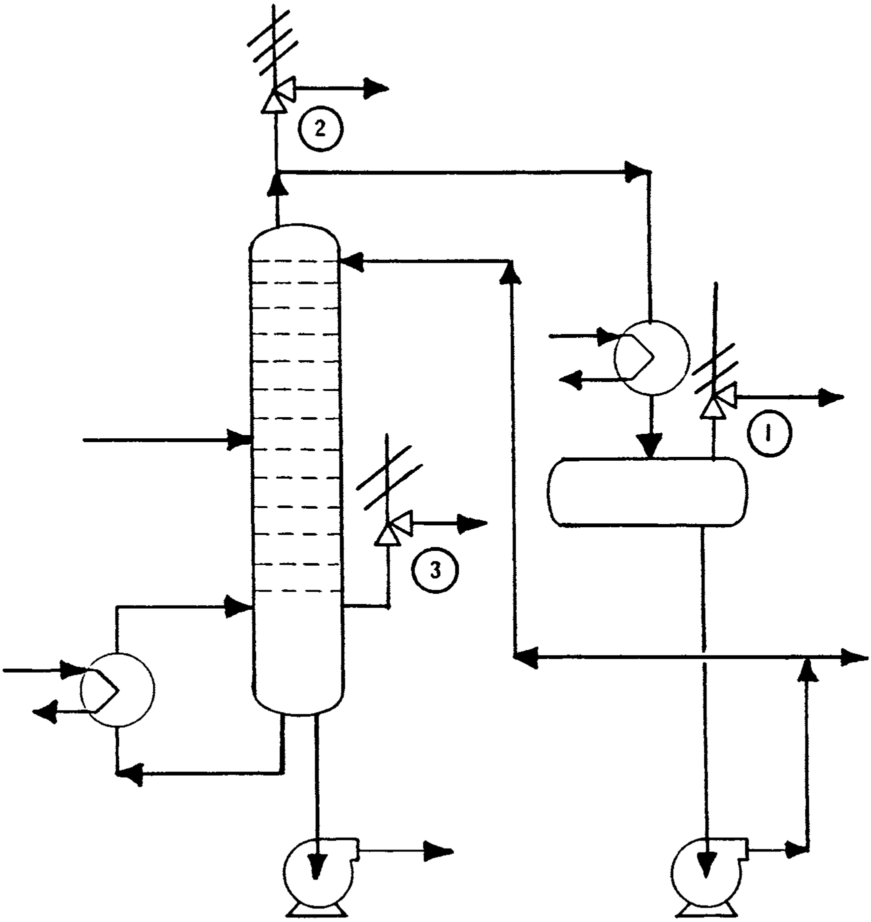
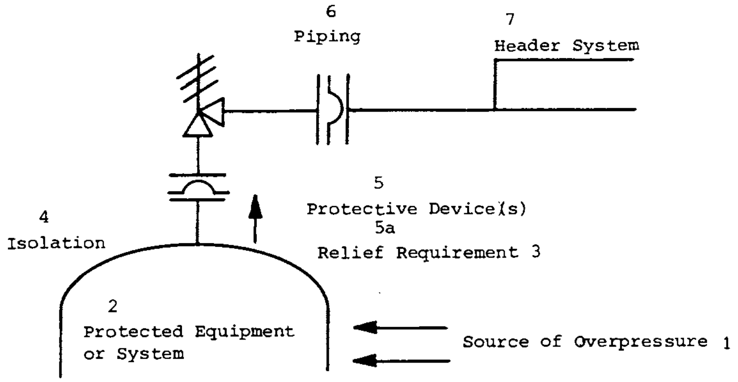


Figure 5-8. Alternative positions for a relief valve.

lower temperature for relief when air fan coolers are used. Position 2 is preferred for relief to atmosphere. Position 3 is used on low pressure towers designed for the same top and bottom pressure. Figure 5-9 illustrates key areas for design verification of relief system. Manufacturers' orifice areas and corresponding valve sizes are shown in Table 5-4.

Nomenclature

A = valve discharge area, sq in.
A_w = wetted surface area of the vessel, sq ft
ADES = next largest valve orifice, sq. in, from the manufacturer's standard orifice area



KEY AREA	BASIC CONSIDERATIONS
1. Sources of Overpressure	Which have been considered?
2. Equipment or System protected by Relief stream	(i) All equipment is identified. (ii) Design press. and temp. limits cannot be exceeded. Design codes for protected equipment and devices are compatible.
3. Require Relief Rate	What is it?
4. Isolation	Is any fitted? If so, how is continuity assured?
5. Protective Device(s)	Under or oversized? Suitability of device(s).
5a. Devices in Series	Correct ΔP maintained across devices. Interspace monitored/alarmed
6. Piping	Correctly sized. Pressure drop O.K. Supports O.K for reaction loads. Suitable for fluid. Drainage/blockage.
7. Headers or Common Vents	Is there one? Sized for all streams. Back pressure O.K. Damage to/from other streams.

Figure 5-9. Pressure relief design verification.

Table 5-4
Orifice Sizes for Relief Valves

Orifice Designation	Orifice Area (sq. in.)	Valve Size (in.)
D	0.110	1–2
E	0.196	1–2
F	0.307	1.5–2
G	0.503	1.5–2.5
H	0.785	1.5–3 or 2–3
J	1.287	2–3 or 2.5–4
K	1.838	3–4
L	2.853	3–4 or 4–6
M	3.600	4–6
N	4.340	4–6
P	6.379	4–6
Q	11.050	6–8
R	16.000	6–8 or 6–10
T	26.000	8–10

C = coefficient determined by ratio of specific heats of the gas or vapor at standard conditions
F = reaction force at the point of discharge to the atmosphere, lb
FI = factor for insulation (for non-insulated vessel FI is 1.0)
K = effective coefficient factor due to backpressure (0.975 for vapor flow)
K_b = capacity correction factor due to backpressure is 1.0, when backpressure is 55% of absolute relieving pressure
K_d = coefficient of discharge (0.953)
K_N = correction factor for Napier equation, K_N, is 1.0, where $P \leq 1515$ psia
K_p = overpressure correction factor for direct spring-operated valves only, K_p is 1.0
K_{SH} = correction factor due to amount of superheat in the steam. Values range from 0.88 (maximum superheat) to 1.0 for saturated steam.
K_v = viscosity correction factor
K_w = backpressure correction factor for balanced-bellows spring-operated valves only (K_w is 1.0)
k = ratio of specific heat capacities (C_p/C_v)

M = molecular weight
M_w = molecular weight of vapor (or process fluid)
P = upstream relieving pressure, psia
P_b = total backpressure, psig
P_i = set pressure at which relief valve begins to open, psig
Q = flow rate, in U.S. gallons per min
Q_r = rate of heat input due to fire, Btu/hr
SGL = specific gravity of liquid at flowing temperature referred to water as 1.0 at 70°F
T = absolute temperature of inlet vapor °R(°F + 460)
V_a = required air capacity, standard ft^3/min
W = flow of any gas or vapor, lb/hr
Z = compressibility factor
λ = latent heat of vaporization at the boiling point of the liquid, Btu/ib
μ = absolute viscosity at the flowing temperature, cP

TWO-PHASE FLOW RELIEF SIZING FOR RUNAWAY REACTION

Introduction

Many methods have been used to size relief systems: area/volume scaling, mathematical modeling using reaction parameters and flow theory, and empirical methods by the Factory Insurance Association (FIA). The Design Institute for Emergency Relief Systems (DIERS) of the AIChE has carried studies of sizing reactors undergoing runaway reactions. Intricate laboratory equipment and analysis have resulted in better vent sizes.

A selection of relief venting as the basis of safe operation is based upon the following considerations [14]:

- compatibility of relief venting with the design and operation of the plant/process
- identifying the worst scenarios
- type of reaction
- means of measuring the reaction parameters during the runaway reaction
- relief sizing procedure
- design of the relief system including discharge ducting and safe discharge area

Runaway Reactions

A runaway reaction occurs when an exothermic system becomes uncontrollable. The reaction leads to a rapid increase in the temperature and pressure, which if not relieved can rupture the containing vessel. A runaway reaction happens because the rate of reaction and therefore the rate of heat generation increases exponentially with temperature. Alternatively, the rate of cooling increases only linearly with temperature. Once the rate of heat generation exceeds available cooling, the rate of increase in temperature becomes progressively faster. Runaway reactions nearly always result in two-phase flow reliefs. Runaway reactions are generally classified into three systems.

Vapor Systems

Boiling is attained before potential gaseous decomposition, that is, the heat of reaction is removed by the latent heat of vaporization. The reaction is tempered, and the total pressure in the reactor is equal to the vapor pressure. The principal parameter determining the vent size is the rate of the temperature rise at the relief set pressure.

Gassy Systems

Gaseous decomposition reaction occurs without tempering. The total pressure in the reactor is equal to the gas pressure. The principal parameter determining the vent size is the maximum rate of pressure rise.

Hybrid Systems

Gaseous decomposition reaction occurs before boiling. The reaction is still tempered by vapor stripping. The total pressure in the reactor is the summation of the gas partial pressure and the vapor pressure. The principal parameters determining the vent size are the rates of temperature and pressure rise corresponding to the tempering condition. A tempered reactor contains a volatile fluid that vaporizes or flashes during the relieving process. This vaporization removes energy via the heat of vaporization and tempers the rate of temperature rise due to the exothermic reaction.

Adiabatic Calorimetry

Two-phase flow calculations are complex when conditions change rapidly as in runaway reactions. Because of this complexity, several experimental and analytical techniques have been developed over the past decade to obtain the relevant data for the relief vent calculations. The data required for the runaway calculations are determined with laboratory tools such as the Differential Scanning Calorimetry (DSC), the accelerating rate calorimeter (ARC), the vent sizing package (VSP), and recently, the laboratory calorimetric Reactive System Screening Tool (RSST). The RSST determines the type of reaction and principal parameters required for sizing reactor vents for vapor, hybrid, and gassy systems. Figures 5-10A and 5-10B show the principal features of the RSST. The principal data for relief sizing calculations are shown in Figures 5-11A, 5-11B, 5-11C, and 5-11D, the temperature rate at the set

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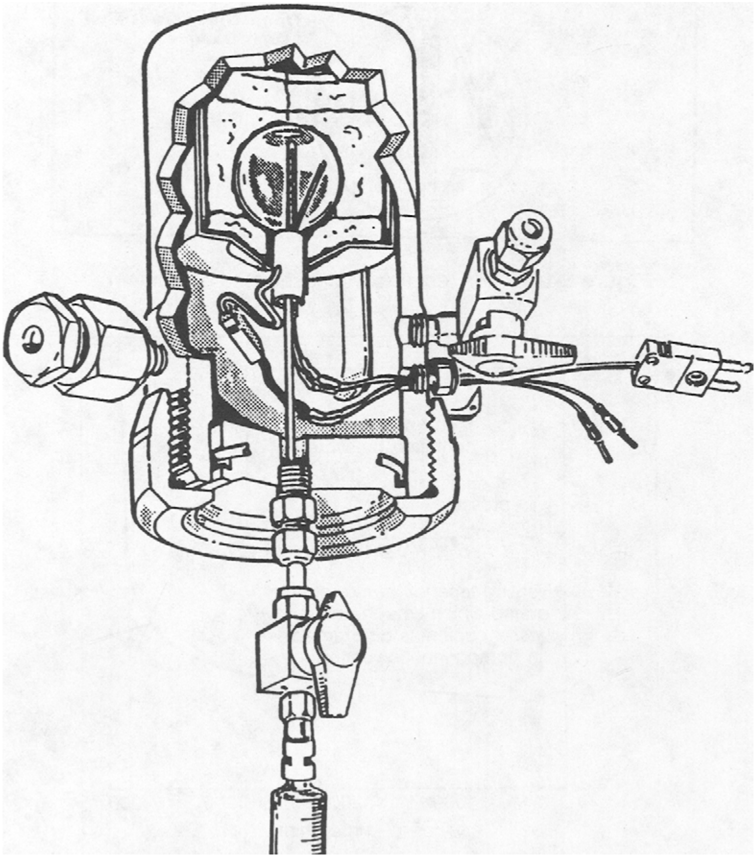

Figure 5-10A. The RSST vessel.

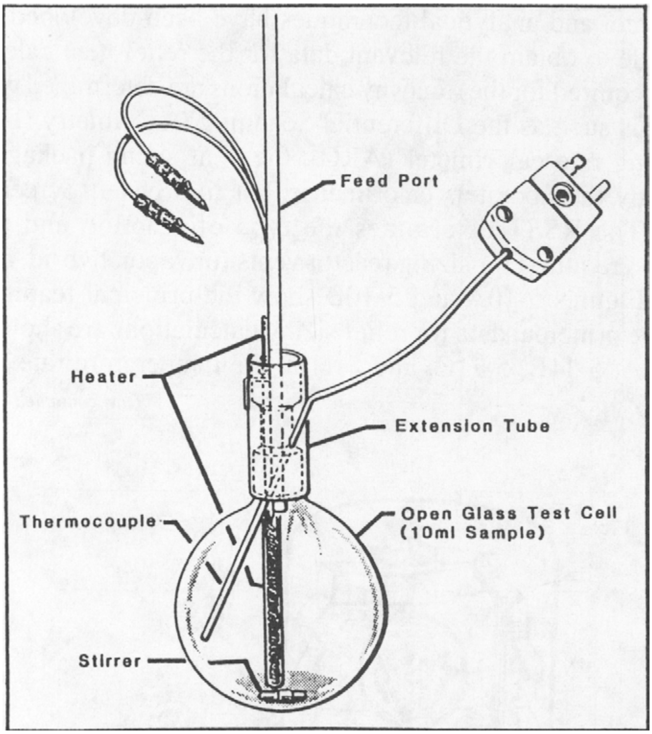

Figure 5-10B. The test cell and associated equipment.

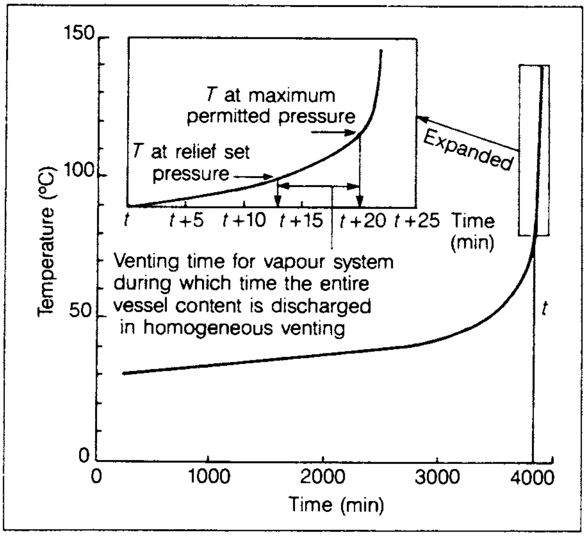

Figure 5-11A. Temperature against time for an abiabatic system.

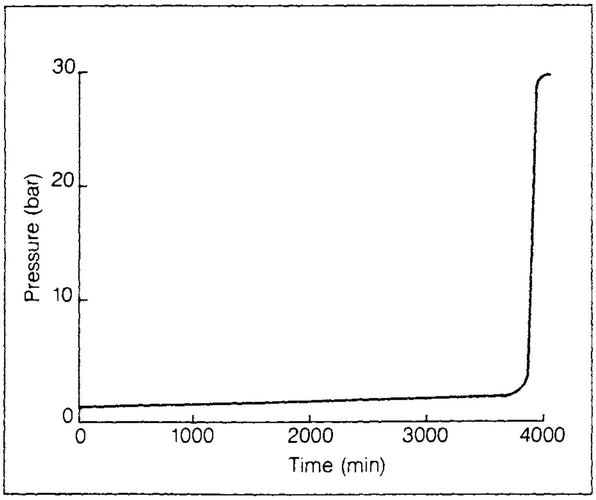

Figure 5-11B. Pressure against time for an abiabatic system.

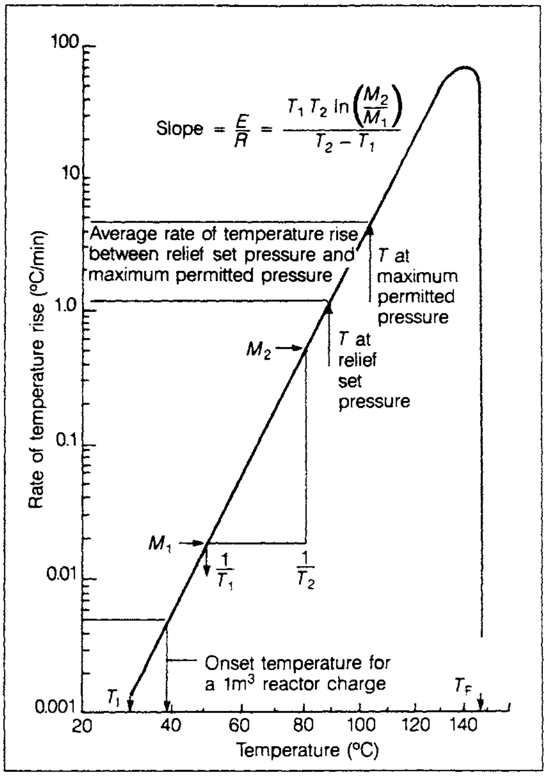

Figure 5-11C. Rate of temperature rise against temperature for an abiabatic system.

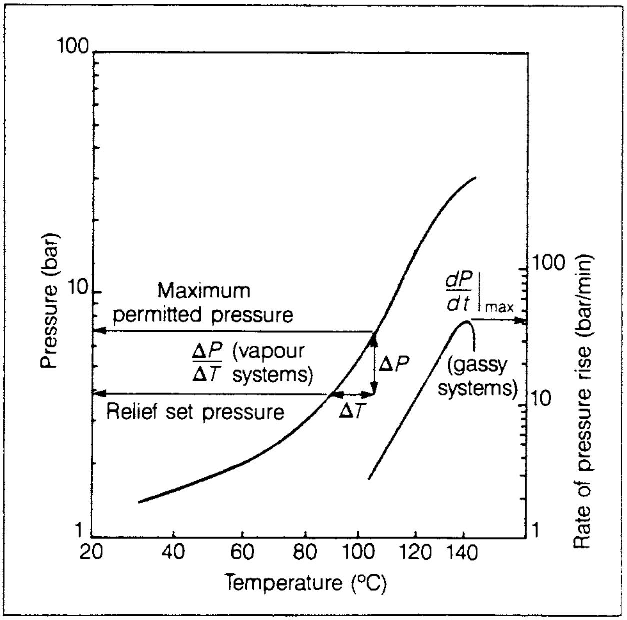

Figure 5-11D. Pressure and rate of pressure rise against temperature for an abiabatic system.

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pressure and the temperature increase, corresponding to the overpressure. In addition, the heat of reactions can be determined from the temperature vs. time data of the heat capacities if the monomers and products are available. Table 5-5 lists formulae for computing the area of the three systems.

Simplified Nomograph Method

Boyle [15] and Huff [16] first accounted for two-phase flow with relief system design for runaway chemical reactions. A computer simulation approach to vent sizing involves extensive thermokinetic and thermophysical characterization of the reaction system. Fisher [17] has provided an excellent review of emergency relief system design involving runaway reactions in reactors and vessels. Fauske [18] has developed a simplified chart to the two-phase calculation. He expressed the relief area as:

$$A_I = \frac{V\rho_r}{G\Delta t_v} \tag{5-57}$$

Table 5-5
Vent Areas and Diameters of the Three Systems

Vapor System		Gassy System		Hybrid System	
$A = 1.5\times10^{-5}\left(\dfrac{m_0\dfrac{dT}{dt}}{F.P_s}\right)$		$A = 3\times10^{-6}\left(\dfrac{1}{F}\right)\left(\dfrac{m_0}{m_t}\right)\left(\dfrac{\dfrac{dP}{dt}}{P^{1.5}_{MAP}}\right)$		$A = 5.6\times10^{-6}\left(\dfrac{1}{F}\right)\left(\dfrac{m_0}{m_t}\right)\left(\dfrac{\dfrac{dP}{dt}}{P^{1.5}_{s}}\right)$	
$d = \left(\dfrac{4A}{\pi}\right)^{0.5}$		$d = \left(\dfrac{4A}{\pi}\right)^{0.5}$		$d = \left(\dfrac{4A}{\pi}\right)^{0.5}$	
L/D=0,	F=1.00	L/D=0	F=1.00	L/D=0,	F=1.00
L/D=50,	F=0.85	L/D=50,	F=0.70	L/D=50,	F=0.70
L/D=100,	F=0.75	L/D=100,	F=0.60	L/D=100,	F=0.60
L/D=200,	F=0.65	L/D=200,	F=0.45	L/D=200,	F=0.45
L/D=400,	F=0.50	L/D=400,	F=0.33	L/D=400,	F=0.33

The mass flux can either be expressed as:

$$G \cong 0.9F_l \frac{\Delta P}{\Delta T}\left(\frac{g_c T_s}{C_p}\right)^{0.5} \tag{5-58}$$

or

$$G \cong 0.9F_l \frac{\Delta H_v}{v_{fg}}\left(\frac{g_c}{C_p T_s}\right)^{0.5} \tag{5-59}$$

The venting time is given by

$$\Delta t_v \cong \frac{(\Delta T)(C_p)}{q_s} \tag{5-60}$$

Combining Equations 5-58, 5-59, and 5-60, the area, A, is given by

$$A = \frac{V\rho q_s}{\Delta P}(g_c C_p T_s)^{-0.5} \tag{5-61}$$

Equation 5-61 gives a conservative estimate of the vent area and the simple design method represents overpressure (ΔP) between 10 and 30 percent. For a 20 percent absolute overpressure, a liquid heat capacity of 2510 J/kg.K for most organics, and considering that a saturated water relationship exists, the vent size area per 1,000 kg of reactants is:

$$A = \left(\frac{m^2}{1,000\,kg}\right) = \frac{0.00208\left(\frac{dT}{dt}\right)}{P_s}\,\frac{^\circ C/\min.}{bar} \tag{5-62}$$

Figure 5-12 shows a nomograph of determining the vent size. The vent area is calculated from the heating rate, the set pressure, and the mass of reactants. The nomograph is used for obtaining quick vent sizes and checking the results of the more rigorous computation. Crowl and Louvar [19] have expressed that the nomograph data of Figure 5-12 applies for a discharge coefficient of F = 0.5, representing a discharge L/D of 400.0. However, use of the nomograph at other discharge pipe lengths and different F requires a suitable conversion.

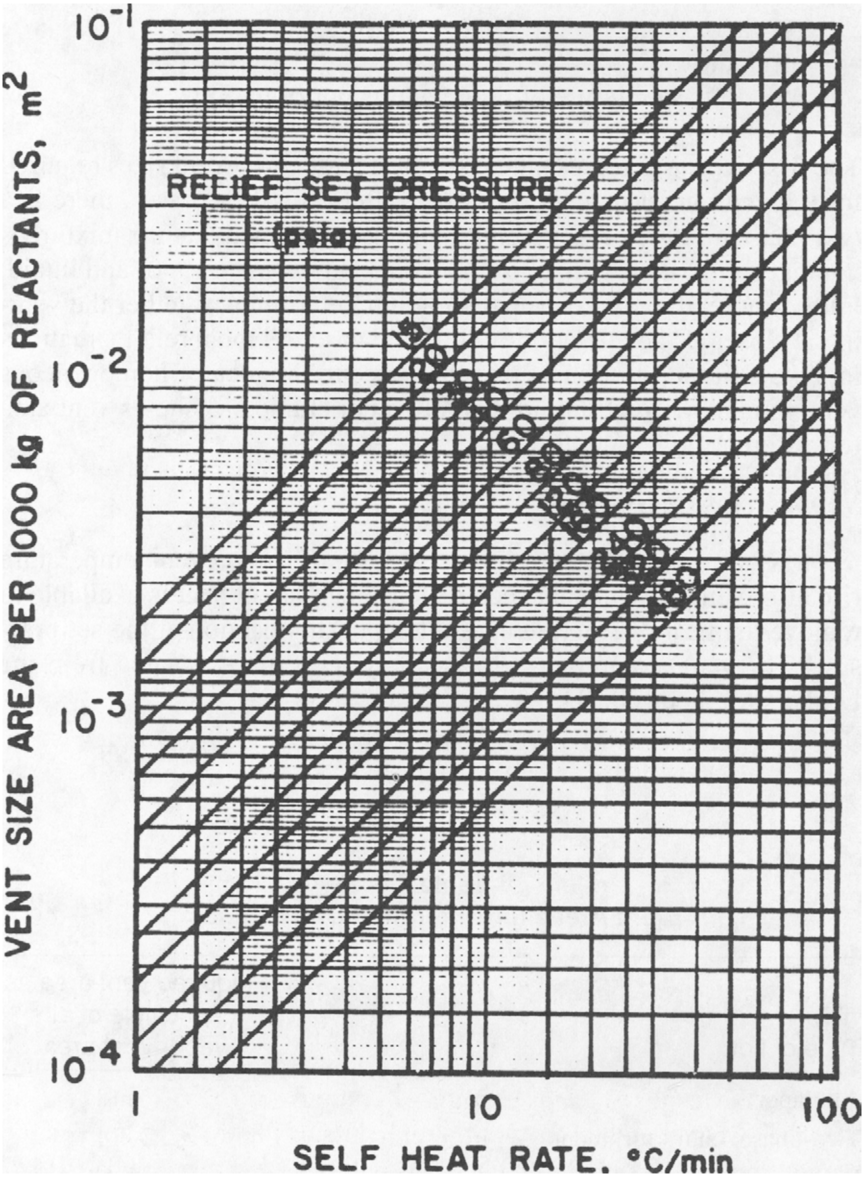

Figure 5-12. A vent sizing nomogram for tempered (high vapor pressure) runaway chemical reactions. (Courtesy of the American Institute of Chemical Engineers.)

Vent Sizing Methods

Vents are usually sized on the assumption that the vent flow is:

- all vapor or gas
- all liquid
- a two-phase mixture of liquid and vapor or gas

The first two cases represent the smallest and largest vent sizes required for a given rate at increased pressure. Between these cases, there is a two-phase mixture of vapor and liquid. It is assumed that the mixture is homogeneous, that is, that no slip occurs between the vapor and liquid. Furthermore, the ratio of vapor to liquid determines whether the venting is closer to the all vapor or all liquid case. As most relief situations involve a liquid fraction of over 80 percent, the idea of homogeneous venting is more to all liquid than all vapor. Table 5-6 shows vent area for different flow regimes.

Vapor Pressure Systems

These systems are called "tempering" (that is, to prevent temperature rise after venting) systems because sufficient latent heat is available to remove the heat of reaction and to temper the reaction at the set pressure. The vent requirements for such systems are estimated from the Leung's Method [20,21].

Table 5-6
Vent Areas for Different Flow Regimes

Type of flow	Required vent area as a multiple of all vapor vent area
All vapor	1
Two-phase: churn turbulent	2–5
Bubbly	7
Homogeneous	8
All liquid	10

$$A = \frac{M_0 q}{G\left[\left(\frac{V}{M_0} T_s \frac{dP}{dT}\right)^{0.5} + (C\Delta T)^{0.5}\right]^2} \tag{5-63}$$

Alternatively, the vent area can be expressed as:

$$A = \frac{M_0 q}{G\left[\left(\frac{V}{M_0} \frac{h_{fg}}{v_{fg}}\right)^{0.5} + (C\Delta T)^{0.5}\right]^2} \tag{5-64}$$

The vapor pressure systems obey the Antoine relationships:

$$\ln P = A + \frac{B}{T} \tag{5-65}$$

differentiating Equation 5-65 yields,

$$\frac{1}{P}\frac{dP}{dT} = -\frac{B}{T^2} \tag{5-66}$$

$$\frac{dP}{dT} = -\frac{B}{T^2} P \tag{5-67}$$

Fauske's Method

Fauske represented a nomograph for tempered reactions as shown in Figure 5-12. This accounts for turbulent flashing flow and requires information about the rate of temperature rise at the relief set pressure. This approach also accounts for vapor disengagement and frictional effects including laminar and turbulent flow conditions. For turbulent flow, the vent area is

$$A = \frac{1}{2} \frac{M_0 \left(\frac{dT}{dt}\right)_s (\alpha_D - \alpha_0)}{F_2 \left(\frac{T_s}{C_s}\right)^{0.5} \Delta P (1 - \alpha_0)} \tag{5-68}$$

Figure 5-13 shows a sketch of temperature profile for high vapor pressure systems.

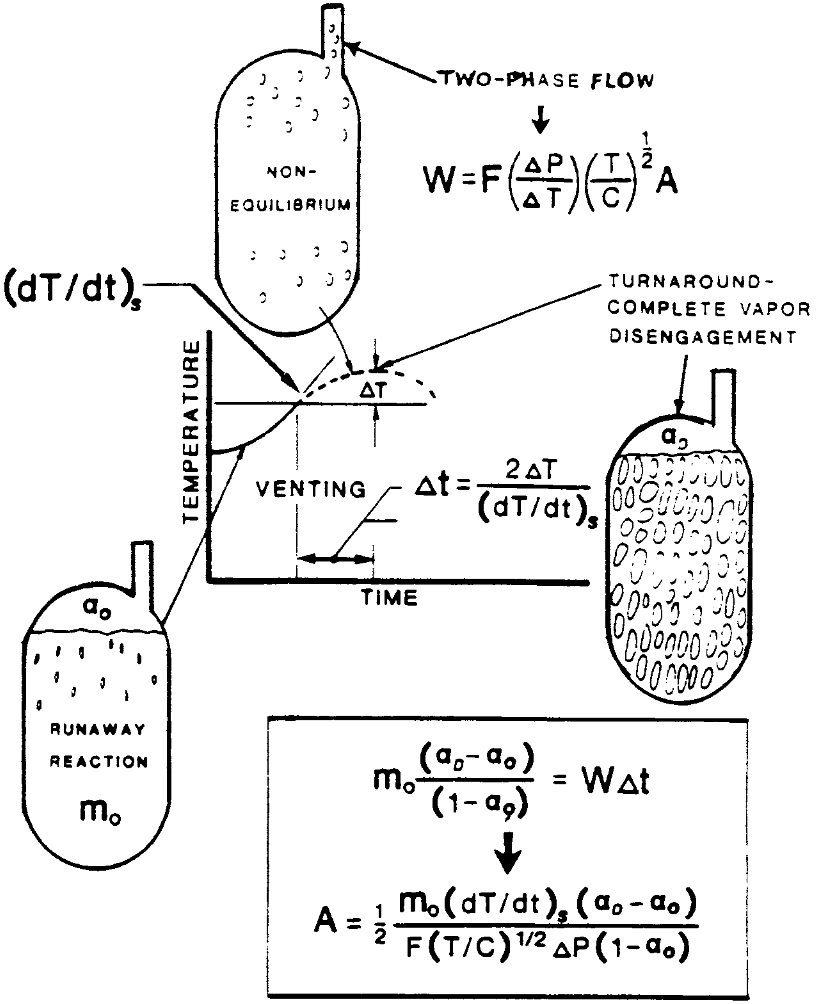

Figure 5-13. Vent sizing model for high vapor pressure systems. Due to non-equilibrium effects, turnaround in temperature is assumed to coincide with the onset of complete vapor disengagement.

Gassy Systems

The major method of vent sizing for gassy system is two-phase venting to keep the pressure constant. This method was employed before DIERS with an appropriate safety factor [22]. The vent area is expressed by:

$$A = \frac{Q_g(1 - \alpha)\rho_f}{G_l} = \frac{Q_g M}{GV} \tag{5-69}$$

Unlike systems with vapor present, gassy systems do not have appreciable latent heat to temper the reaction. The system pressure increases as the rate of gas generation with temperature increases, until it reaches the maximum value. The vent area could be underestimated if sizing is dependent on the rate of gas generated at the set pressure. Therefore, it is more plausible to size the vent area on the maximum rate of gas generation. Homogeneous two-phase venting is assumed even if the discharge of liquid during venting could reduce the rate of gas generation even further. The vent area is defined by

$$A = 3.6 \times 10^{-3} Q_g \left(\frac{M_0}{VP_m} \right)^{0.5} \tag{5-70}$$

The maximum rate of gas generation during a runaway reaction is proportional to the maximum value of dP/dt and can be calculated from

$$Q_{gl} = \frac{M_0}{M_t} \left(\frac{V_t}{P_m} \frac{dP}{dt} \right) \tag{5-71}$$

Homogeneous Two-Phase Venting Until Disengagement

Imperial Chemical Industry (ICI) [22] developed a method for sizing a relief system that accounts for vapor-liquid disengagement. They proposed that homogeneous two-phase venting occurs that increases to the point of disengagement. Furthermore, they based their derivations upon the following assumptions:

- vapor phase sensible heat terms may be neglected.
- vapor phase mass is negligible.
- heat evolution rate per unit mass of reactants is constant (or average value can be used).
- mass vent area per unit area is approximately constant.
- physical properties can be approximated by average values.

The vent area is given by the following equation.

$$A = \frac{q_1 V(\alpha - \alpha_0)}{G_1 v_f \left\{ \dfrac{h_{fg} v_f (\alpha - \alpha_0)}{v_{fg}(1 - \alpha_0)(1 - \alpha)} + C\Delta T_1 \right\}} \tag{5-72}$$

Equation 5-72 is valid if disengagement occurs before the pressure would have turned over during homogeneous venting; otherwise, Equation 5-72 gives an unsafe (too small) vent size. Therefore, it is necessary to verify that

$$q > \frac{G_l A h_{fg} v_f^2}{V v_{fg}(1-\alpha)^2} \tag{5-73}$$

is satisfied at the point of disengagement.

Two-Phase Flow Through An Orifice

Sizing formulae for flashing two-phase flow through relief devices were obtained through DIERS, which is based upon Fauske's equilibrium rate model (ERM) and assumes frozen flow (non flashing) from a stagnant vessel to the relief device throat. This is followed by flashing to equilibrium in the throat. The orifice area, A, is given by,

$$A = \frac{W}{C_D}\left\{\left(\frac{xV_G}{kP_l}\right) + \left[\frac{(V_G - V_L)^2 C_L T_l}{\lambda^2}\right]\right\}^{0.5} \tag{5-74}$$

The theoretical rate can be expressed as:

$$W = A_f(2\Delta P.\rho)^{0.5} \tag{5-75}$$

For a simple sharp-edged orifice, the value of C_D, the coefficient of discharge, is well established (about 0.6). For safety relief valves, its value depends upon the shape of the nozzle and other design features. In addition, the value C_D varies with the conditions at the orifice. For saturated liquid at the inlet, Equation 5-74 simplifies to the following expression.

$$A = \frac{W(V_G - V_L)(C_L T_l)^{0.5}}{C_D\lambda} = \frac{W}{C_D\left(\frac{dP}{dT}\right)\left(\frac{T_l}{C_L}\right)^{0.5}} \tag{5-76}$$

Equations 5-72 to 5-76 are based upon the following assumptions:

- vapor phase behaves as an ideal gas.
- liquid phase is an incompressible fluid.
- turbulent Newtonian flow is present.

- critical flow. This is usually the case because the critical pressure ratios of flashing liquid approach the value of 1.0.

Duxbury and Wilday [22] recommend that a safety factor of at least 2.0 be used. In certain cases, lower safety factors may be employed. However, the designer should consult the appropriate process safety section in the engineering department for advice.

Discharge System

Design of the Vent Pipe. The nature of the discharging fluid is necessary in determining the relief areas. DIERS and ICI techniques can analyze systems that exhibit "natural" surface active foaming and those that do not. DIERS further found that small quantities of impurities can affect the flow regime in the reactor. In addition, a variation in impurity level could arise by changing the supplier of a particular raw material. Therefore, care is needed in sizing emergency relief on homogeneous vessel behavior, that is, two-phase flow.

In certain instances, pressure relief during a runaway reaction can result in a three-phase discharge if solids are suspended in the reaction liquors. Solids can also be entrained by turbulence caused by boiling or gassing in the bulk of the liquid. Caution is required in sizing this type of relief system, especially where there is a significantly static head of fluid in the discharge pipe. Another aspect in the design of the relief system includes the possible blockage in the vent line. This could arise from the process material being solidified in cooler sections of the reactor. It is important to consider all discharge regimes when designing the discharge pipe work.

Safe Discharge

Reactors or storage vessels are fitted with overpressure protection vent directly to roof level. Such devices (e.g., relief valves) protect only against common process maloperations and not runaway reactions. The quantity of material ejected and the rate of discharge are low, resulting in good dispersion. The rise of bursting disc can result in large quantities of materials (95% of the reactor contents) being discharged for foaming systems.

The discharge of copious quantities of chemicals directly to atmosphere can give rise to secondary hazards, especially if the materials are toxic and can form flammable atmosphere in air (e.g., vapor or mist). In such cases, the provision of a knock-out device (scrubber, dump tank) of adequate size to contain the aerated/foaming fluid will be required.

Conditions of Use

- If Fauske's method yields a significantly different vent size, then the calculation should be reviewed.
- The answer obtained from the Leung's method should not be significantly smaller than that from Fauske's method.
- ICI recommends a safety factor of 1–2 on flow or area. The safety factor associated with the inaccuracies of the flow calculation will depend on the method used, the phase nature of the flow, and the pipe friction. For two-phase flow, use a safety factor of two to account for friction and static head.
- Choose the smaller of the vent size from the two methods.

A systematic evaluation of venting requires information on:

- the reaction—vapor, gassy, or hybrid.
- flow regime—foamy or nonfoamy.
- vent flow—laminar or turbulent.
- vent sizing parameters, such as dT/dt, $\Delta P/\Delta T$, ΔT.

It is important to ensure that all factors (e.g., long vent lines) are accounted for, independent of the methods used. Designers should ascertain that a valid method is chosen rather than the most convenient or the best one. For ease of use, the Leung's method for vapor pressure systems are rapid and easy. Different methods should give vent sizes with a factor of two. Nomographs give adequate vent sizes for long lines to L/D of 400, but sizes are divisible by two for nozzles. Table 5-6A lists the applicability of both Leung and Fauske's methods.

Nomenclature

A = vent area, m^2
A_1 = relief vent area
A_f = flow area, m^2
C = specific heat of the material, J/Kg.K
C_D = coefficient of discharge ($C_D = 0.6$)
C_L = average liquid specific heat capacity, J/Kg.K
C_p = specific heat at constant pressure, J/Kg.K
d = vent diameter, mm
F = flow reduction factor
F_l = correction factor, and for a length of pipe zero, F_l=1.0. As the pipe length increases, the value of F_l decreases.

Table 5-6A
Applicability of Recommended Vent Sizing Methods

Leung's Method	Fauske's Method
1. The overpressures are limited in the range 0–50% of absolute set pressure, i.e., $0 \le \Delta P \le 0.5P_s$	The overpressures are limited in the range of 10–30% of absolute set pressure, i.e., $0 \le \Delta P \le 0.3P_s$. It assumes that flow is turbulent and that the vapor behaves as an ideal gas.
2. The method includes the mass unit vent flow capacity per unit area, G. This allows the user to select any applicable vent capacity calculation method.	The method incorporates the equilibrium rate model for vent flow capacity when friction is negligible. In addition, a correction factor is used for longer vent lines of constant diameter and with negligible static head change.
3. The heat evolution rate per unit mass, the vent capacity per unit area, physical properties (e.g., latent heat of fluid, specific heat and vapor/liquid specific volumes) are constant.	It allows for total vapor-liquid disengagement of fluids that are not "natural" surface active foamers.
4. A hand calculation method that can be used to take account of two-phase relief when the materials in the vessel are "natural" surface active foamers.	To account for disengagement, the vessel void fraction at disengagement should be evaluated (i.e., the point at which the vent flow would cease to be two-phase and start to be vapor only).
5. The methods use drift-flux level-swell calculation models to take account of more vapor being in the inlet stream to relief device than the average for the vessel.	The method is potentially unsafe if early disengagement (before the pressure would otherwise have turned over during two-phase venting) occurs.
6. Methods are given for the bubbly and churn-turbulent flow regimes within the vessel.	The criterion for safe use to take account of disengagement is $q < \dfrac{G\,A\,h_{fg}\,v_f^2}{V\,v_{fg}(1-\alpha_D)^2}$. However, when disengagement is not accounted for, then $\alpha_D = 1.0$, and the above equation is not required.

F_2 = flow reduction factor for turbulent flow
G = mass flux through the relief
G_1 = mass vent capacity per unit area, kg/m^2s
g_c = dimensional gravitational constant, 1.0 $kg\ m/N\ s^2$
h_{fg} = latent heat, J/kg
ΔH_v = heat of vaporization of the fluid, J/kg
k = isentropic coefficient
M = mass of liquid in vessel, kg
M_o = initial mass of liquid in vessel, kg
m_t = mass of the sample in the RSST, kg
P_m = maximum allowable pressure during venting, bar
P_{MAP} = maximum allowable vessel pressure, psia
P_s = relief set pressure, psia
P_1 = pressure in the upstream vessel, N/m^2abs
ΔP = overpressure, bar
ΔP_1 = difference between the (reduced) set pressure and the maximum pressure allowable, N/m^2
ΔP_2 = pressure difference, N/m^2
dP/dt = maximum rate of pressure rise in the test vessel, bar/s
dP/dt = measured maximum rate of pressure rise in the RSTT, lb/in^2 min
Q_g = volumetric gas generation rate of temperature and pressure in reactor during relief, m^3/s
Q_{g1} = maximum rate of gas generation, m^3/s
q_1 = self-heat rate, W/kg
q = rate of heat production (W/kg) at the relief set pressure, or an average value between the relief set pressure and the maximum permitted pressure if this is more than 120% of the relief set pressure
T = temperature corresponding to relief actuation, K
T_s = absolute saturation temperature of the fluid at the set pressure, K
ΔT = temperature rise corresponding to the overpressure, K
ΔT_1 = temperature difference between that at the maximum pressure allowable, and that at the redefined set pressure, k.
Δt_v = venting time
$(dT/dt)_s$ = rate of temperature rise corresponding to the relief set pressure, K/s
V = reactor volume, m^3
= total vessel volume, m^3
v_{fg} = difference between vapor and liquid specific volume, m^3/kg

v_f = liquid specific volume, m^3/kg.
V_G = specific volume of gas, m^3/kg.
V_L = specific volume of liquid, m^3/kg.
W = required relief rate, kg/s
x = mass fraction of vapor at inlet
α = void fraction in vessel
α_D = vessel void fraction corresponding to complete vapor disengagement
α_o = initial free board volume
ρ = density, kg/m^3
ρ_f = liquid density, kg/m^3
ρ_r = density of the reactants, kg/m^3

PROBLEMS AND SOLUTIONS

Problem 5.1
Orifice Sizing for Liquid Flow

Calculate the size of an orifice for the bore of a flange-tapped orifice required to measure 12.84 ft^3/min of gasoline in a 2-inch schedule 80 pipe.

Design data:

Internal pipe diameter (I.D.)	= 1.939 inches
Normal differential pressure	= 64 in H2O
Flowing temperature	= 80.5°F
Density of gasoline	= 42.26 lb/ft^3
Viscosity of gasoline	= 0.6 cP
Assuming the coefficient of discharge C_D	= 0.62
F_a	= 1.0

Orifice Sizing for Gas Flow

Determine the size of an orifice to give a full-scale reading of 20 in. H_2O for 0.25 lb/s flow of gas through a 4-inch (I.D = 4.026) schedule 40 pipe. The upstream gas density is 0.075 lb/ft^3, viscosity of the gas is 0.0219 cP, the specific heat ratio, k, is 1.4, and the upstream pressure is 14.7 psi.

Solutions

The computer program **PROG51** calculates the orifice size for liquid and gas services. Tables 5-7 and 5-8 show the input data and results of the liquid and gas orifice calculations. For the liquid service of gasoline,

Table 5-7
Orifice Sizing for Liquid Flow: Program Inputs and Outputs

```
DATA51.DAT
------------------
LIQUID
INCH-H2O
1.939  64.0
42.26  12.84  0.6
                     ORIFICE SIZING FOR LIQUID FLOW
****************************************************************************
    TYPE OF FLOW:                                              LIQUID
    TYPE OF PRESSURE DROP:                                     INCH-H2O
    INTERNAL PIPE DIAMETER, inch:                                 1.939
    ORIFICE PRESSURE DROP, inch-H2O:                             64.000
    ORIFICE PRESSURE DROP, psi:                                   2.308
    LIQUID DENSITY, lb/ft^3:                                     42.260
    LIQUID VISCOSITY, cP:                                         .6000
    LIQUID VOLUMETRIC RATE, ft^3/min.:                           12.840
    LIQUID MASS RATE, lb/sec.:                                    9.044
    ORIFICE SIZE, inch:                                           1.501
    REYNOLDS NUMBER:                                                176582.
----------------------------------------------------------------------------
```

Table 5-8
Orifice Sizing for Gas Flow: Program Inputs and Outputs

```
DATA51.DAT
------------
GAS
INCH-H2O
4.026  14.7
1.4  0.075
0.0219
20.0  0.25
                          ORIFICE SIZING FOR GAS FLOWS
****************************************************************************
    TYPE OF FLOW:                                              GAS
    TYPE OF PRESSURE DROP:                                     INCH-H2O
    INSIDE PIPE DIAMETER, inch:                                   4.026
    UPSTREAM PRESSURE, psia.:                                    14.700
    ORIFICE PRESSURE DROP, INCH-H2O:                             20.000
    ORIFICE PRESSURE DROP, psi.:                                   .721
    SPECIFIC HEAT RATIO (k=Cp/Cv):                               1.4000
    UPSTREAM FLUID DENSITY, lb/ft^3:                               .075
    GAS VISCOSITY, cP:                                            .0219
    GAS FLOW RATE, ft^3/min.:                                   200.000
    GAS MASS RATE, lb/sec.:                                        .250
    EXPANSION FACTOR:                                             .0409
    ORIFICE DIAMETER, inch:                                       1.811
    FULL SCALE GAS FLOWRATE, lb/sec.:                              .250
    REYNOLDS NUMBER:                                                 64410.
----------------------------------------------------------------------------
```

the orifice diameter at the liquid flow rate of 12.84 ft^3/min and pipe diameter of 1.939 in. is 1.501 in. For the gas flow rate of 0.25 lb/s and pipe internal diameter of 4.026 in., the orifice size is 1.811 in.

Problem 5.2

(1) Determine the control valve capacity coefficient, C_v, for the following liquid flow conditions:

Flow = 400 gpm P_1 = 150 psia P_2 = 125 psia $SpGr_l$ = 1.0

(2) Calculate the control valve coefficient for gas flow under the following conditions:

Flow = 1200 ft^3/h P_1 = 550 psia P_2 = 150 psia $SpGr_g$ = 0.6 T = 100°F

(3) Calculate the steam flow through a valve with a capacity coefficient, C_v = 75, under the following conditions:

°F superheat = 0 P_1 = 70 psia P_2 = 60 psia

Solutions

The computer program PROG52 calculates the control valve capacity coefficient (C_v) or the maximum flow rate that will pass through the valve. Table 5-9 shows the input data and results of the control valve calculations for liquid, gas, and steam conditions. For the liquid service, at a flow rate of 400 gpm and the control valve pressure drop of 25 psi, the control valve capacity coefficient (C_v) is 80. The gas service with a flow rate of 1200 ft^3/h, and control valve pressure drop of 400 psi gives the control valve capacity coefficient (C_v) of 0.059. For the steam condition of capacity coefficient (C_v) = 75, and the control valve pressure drop of 10 psi, the maximum steam flow rate through the valve is 5511.4 lb/hr.

Problem 5.3

(1) In a biological plant, ammonia is used to control the pH during fermentation to obtain maximum yield of the product. For this purpose, liquid ammonia is vaporized by passing steam through a coil in a vaporizer. A relief valve from the vaporizer is set at a pressure of 290 psig. If the relieving rate of ammonia vapor is 620 lb/hr, determine the size of the relief valve required to relieve ammonia vapor during an emergency.

Design data are:

Ratio of specific heat capacities (C_p/C_v) = 1.33
Molecular weight of ammonia = 17.03
Critical Pressure, P_c = 111.3 atm
Critical Temperature, T_c = 405.6 K
Constants in Antoine's equation: A = 16.9481
B = 2132.5
C = –32.98

Table 5-9
Control Valve Sizing for Liquid, Gas and Steam Conditions: Program Inputs and Outputs

```
DATA52.DAT
--------------------------
LIQUID
400.0  0.0
150.0  125.0  1.0
GAS
1200.0  0.0
550.0   150.0  0.6  100.0
STEAM
75.0
70.0  60.0  0.0


                   CONTROL VALVE SIZING FOR LIQUID SERVICE
****************************************************************************
    FLUID SERVICE:                                        LIQUID
    LIQUID FLOWRATE, gpm:                                    400.00
    LIQUID SPECIFIC GRAVITY:                                  1.000
    INLET PRESSURE, psia:                                   150.000
    OUTLET PRESSURE, psia:                                  125.000
    CONTROL VALVE PRESSURE DROP, psi:                        25.000
    CONTROL VALVE CAPACITY COEFFICIENT:                      80.000
---------------------------------------------------------------------------


                   CONTROL VALVE SIZING FOR GAS SERVICE
***************************************************************************
    FLUID SERVICE:                                        GAS
    GAS FLOW RATE, ft^3/hr.:                               1200.000
    SPECIFIC GRAVITY:                                          .600
    INLET PRESSURE, psia:                                   550.000
    OULET PRESSURE, psia:                                   150.000
    CONTROL VALVE PRESSURE DROP, psi:                       400.000
    INLET TEMPERATURE, oF:                                  100.000
    CONTROL VALVE CAPACITY COEFFICIENT:                        .059
---------------------------------------------------------------------------


                   CONTROL VALVE SIZING FOR STEAM SERVICE
***************************************************************************
    FLUID SERVICE:                                        STEAM
    CALCULATED STEAM FLOW RATE, lb/hr.:                    5511.352
    DEGREE OF SUPERHEAT, oF:                                   .000
    INLET PRESSURE, psia:                                    70.000
    OUTLET PRESSURE, psia:                                   60.000
    CONTROL VALVE PRESSURE DROP, psi:                        10.000
    CONTROL VALVE CAPACITY COEFFICIENT:                      75.000
---------------------------------------------------------------------------
```

(2) A bellow style pressure relief valve is required to protect a vessel containing an organic liquid. The required relieving capacity is 310 gpm. Inlet temperature is 170°F. Set pressure is 100 psig. Allowable overpressure is 25%. Built-up back pressure is 25 psig. Specific gravity is 1.45 and viscosity is 3,200 cP. Determine the orifice size of the valve. The correction factors are:

$$K_v = 1.0 \quad K_w = 0.925 \quad K_d = 0.65$$

(3) Calculate the required area for the relief valve for a horizontal, non-insulated storage tank exposed to fire and containing liquid vinyl chloride monomer. The tank dimensions are shown in Figure 5-14, with the design pressure of 100 psig. Discharge from the relief valve will be vented to a gas holder operating at 0.5 psig. A 20% accumulation is assumed over the design pressure. Average inventory of the tank contents will equal 75% of the vessel's inside diameter.

Solutions

The computer program PROG53 sizes relief valves for vapor, steam, liquid, air, and fire conditions. Tables 5-10 and 5-11 show the input data and results of the vapor and liquid services. The results of the relief valve sizing of an ammonia vaporizer at the relieving rate of 620 lb/hr and a set pressure of 290 psig, indicate that the calculated orifice area is 0.030 in^2. The nearest standard orifice size is D with an orifice area of 0.110 in^2. The relief valve calculations for the organic liquid at the relieving rate of 310 gpm and a set pressure of 100 psig give the calculated orifice area of 2.233 in^2. The nearest standard orifice size is L, with an orifice area of 2.853 in^2.

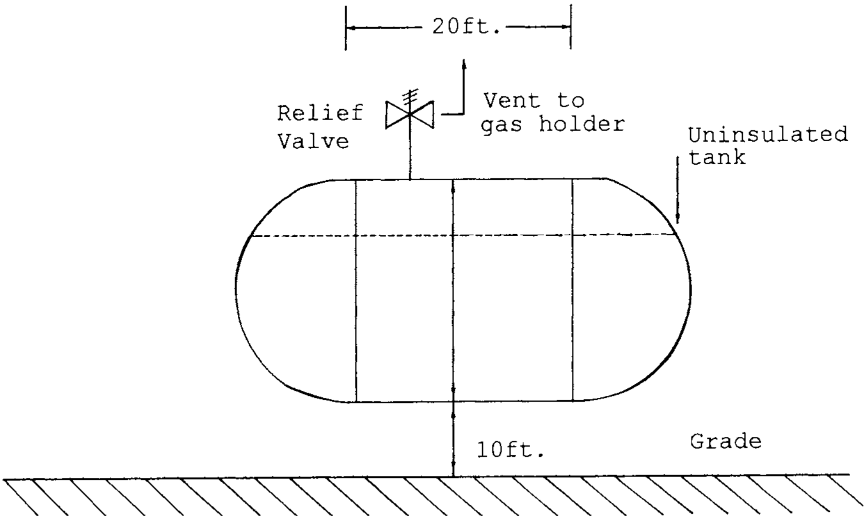

Figure 5-14. A horizontal, non-insulated storage tank.

Table 5-10
Relief Valve Sizing for Vapor Service: Program Inputs and Outputs

```
DATA53.DAT
------------
VAPOR
620.0  290.0
10.0  133.4
0.84  17.03
1.31
                   VAPOR RELIEF VALVE SIZING
****************************************************************************
  BASIS OF SELECTION:                                           VAPOR
  REQUIRED VAPOR RATE, lb/hr.:                                         620.
  VALVE SET PRESSURE, psig:                                       290.000
  PERCENTAGE IN OVERPRESSURE, (%):                                 10.000
  UPSTREAM FLUID TEMPERATURE, DEG. F:                             133.400
  COMPRESSIBILITY FACTOR:                                            .8400
  MOLECULAR WEIGHT OF VAPOR:                                       17.030
  RATIO OF SPECIFIC HEATS OF FLUID:                                 1.310
  GAS CONSTANT DETERMINED BY RATIO OF Cp/Cv:                      347.913
  CALCULATED VALVE ORIFICE AREA, in^2:                               .030
  NEAREST STANDARD ORIFICE AREA, in^2:                               .110
  NEAREST STANDARD ORIFICE SIZE:                                D
  PREFERRED VALVE BODY SIZE: (IN-OUT) inches:                     1-2
  MAXIMUM VAPOR FLOWRATE WITH STD. ORIFICE, lb/hr.:                   2302.
  REACTION FORCE, lb:                                                 28.
---------------------------------------------------------------------------
```

Table 5-11
Relief Valve Sizing for Liquid Service: Program Inputs and Outputs

```
DATA53.DAT
-------------
LIQUID
310.0  100.0
25.0  1.45
3200.0  1.0
0.925  0.65
                   RELIEF VALVE SIZING FOR LIQUID
****************************************************************************
  BASIS OF SELECTION:                                           LIQUID
  LIQUID FLOWRATE, US gpm:                                             310.
  VALVE SET PRESSURE, psig:                                       100.000
  BACK PRESSURE ON VALVE, psig:                                    25.000
  FLUID SPECIFIC GRAVITY:                                           1.450
  FLUID VISCOSITY, cP:                                          3200.0000
  VISCOSITY CORRECTION FACTOR, Kv:                                 1.0000
  BACKPRESSURE CORRECTION FACTOR, Kw:                               .9250
  EFFECTIVE COEFFICIENT OF DISCHARGE, Kd:                            .650
  CALCULATED VALVE ORIFICE AREA, in^2:                              1.772
  NEAREST STANDARD ORIFICE AREA, in^2:                              1.838
  NEAREST STANDARD ORIFICE SIZE:                                K
  PREFERRED VALVE BODY SIZE, (IN-OUT) inches:                     3-4
  MAXIMUM LIQUID FLOWRATE WITH STD. ORIFICE, gpm:                      322.
  VISCOSITY CORRECTION FACTOR:                                       .794
  REYNOLDS NUMBER:                                                     290.
  CALCULATED VALVE ORIFICE AREA, in^2:                              2.233
  NEAREST STANDARD ORIFICE AREA, in^2:                              2.853
  NEAREST STANDARD ORIFICE SIZE:                                L
  PREFERRED VALVE BODY SIZE, (IN-OUT) inches:                     3-4 or 4-6
  MAXIMUM LIQUID FLOWRATE WITH STD. ORIFICE, gpm:                      396.
---------------------------------------------------------------------------
```

Fire Relief Valve Sizing

The wetted surface for the vessel equals the wetted area of the two heads plus that of the cylindrical section. Thus:

$$A_w = \frac{2\pi(yD_1)^2}{4} + D_2 L\pi$$

where y = the fraction of the vessel's internal diameter (ID) that is equivalent to average liquid inventory.

D_1 = diameter of circular blank from which head is shaped (D_1 will depend on the type of head).

D_2 = y times the ID of the tank.

L = tangent-to-tangent length of the cylindrical section.

D_1 = 11 ft

Therefore, the wetted surface area is:

$$A_w = \frac{2\pi[(0.75)(11)]^2}{4} + \pi(0.75)(10)(20)$$

$$A_w = 578.15\ \text{ft}^2$$

The relieving temperature at the set pressure plus 20% accumulation plus 14.7 psia = 135°F. At this temperature, the latent heat of vaporization is 116 Btu/lb. Molecular weight of vinyl chloride, $M_w = 62.5$. Ratio of specific heat capacities, k = 1.17. The critical properties of vinyl chloride are:

$P_c = 809$ psia

$T_c = 313.7°F$

$P_r = P/P_c = 134.7/809 = 0.165$

$T_r = T/T_c = (135 + 460)/(313.7 + 460) = 0.77$

From a compressibility factor chart, Z = 0.86. The rate of heat input due to fire and flow rate of the vapor release can be determined by Equations 5-53 and 5-45. Table 5-12 gives the input data and results of vinyl chloride monomer. The results show that the calculated relief valve orifice area is 2.172 in^2. The nearest standard orifice size is L, with an orifice area of 2.853 in^2.

Table 5-12
Relief Valve Sizing for Fire Service: Program Inputs and Outputs

```
DATA53.DAT
-------------
FIRE
1.0  578.15
116.0  100.0
20.0  135.0
0.86  62.5
1.17
                   FIRE RELIEF VALVE SIZING
****************************************************************************
  BASIS OF SELECTION:                                          FIRE
  ENVIRONMENTAL FACTOR:                                            1.000
  WETTED SURFACE AREA OF VESSEL, ft^2:                           578.150
  LATENT HEAT OF VAPORIZATION, Btu/lb:                           116.000
  VALVE SET PRESSURE, psig:                                      100.000
  PERCENTAGE OF OVERPRESSURE, (%):                                20.000
  FLUID TEMPERATURE, DEG. F:                                     135.000
  FLUID COMPRESSIBILITY FACTOR:                                     .860
  FLUID MOLECULAR WEIGHT:                                         62.500
  RATIO OF SPECIFIC HEATS OF FLUID:                                1.170
  GAS CONSTANT DETERMINED BY RATIO OF Cp/Cv:                     334.173
  VAPOR RELIEF FLOW RATE, lb/h.:                                     33315.
  CALCULATED VALVE ORIFICE AREA, in^2:                             2.172
  NEAREST STANDARD ORIFICE AREA, in^2:                             2.853
  NEAREST STANDARD ORIFICE SIZE:                               L
  PREFERRED VALVE BODY SIZE, (IN-OUT) inches:                    3-4 or 4-6
  MAXIMUM VAPOR FLOWRATE WITH STD. ORIFICE lb/hr.:                   43760.
  REACTION FORCE, lb:                                                  271.
---------------------------------------------------------------------------
```

Problem 5.4

Determine the vent size for a vapor pressure system using the following data and physical properties.

Reactor Parameters

Volume, V = 10 m^3
Mass, M = 8,000 kg
Vent opening pressure = 15 bara
= 217.5 psia
Temperature at set pressure T_s = 170°C
= 443.15K
Overpressure allowed above operating pressure = 10%
= 1bar (10^5 Pa)

Material Properties

Specific heat, C_p = 3000 J/kg.K
Slope of vapor pressure and temperature curve dP/dT = 20,000 Pa/K

Rate of Reaction

$\Delta T = dP/20{,}000 = 10^5/20{,}000 = 5K$
Rate at set pressure, $(dT/dt)_s = 6.0$ K/min
Rate at maximum pressure = 6.6 K/min
Average rate = 6.3 K/min
= 0.105 K/s

Solution

Using Fauske's nomograph of Figure 5-12 at a self heat rate of 6.3 K/min. and a set pressure of 217.5 psia, the corresponding vent area per 1,000 kg of reactants = $0.0008m^2$.

The vent area of 8,000 kg reactants = $0.0064m^2$

The vent size

$$d = \left(\frac{4\,\text{Area}}{\pi}\right)^{0.5} = 90.27\,\text{mm}\,(3.6\,\text{in.})$$

If Figure 5-12 is applicable for F=0.5, then for F=1.0, the area is

$$A = (0.0064\,m^2)\left(\frac{0.5}{1.0}\right) = 0.0032\,m^2$$

The area assumes a 20% absolute overpressure.
The result can be adjusted for other overpressures by multiplying the area by a ratio of 20/(new absolute percent overpressure).

Using the Leung's method:

Assuming L/D = 0, F = 1.0
Two-phase mass flux from Equation 5-58

$$G = (0.9)(1.0)(20{,}000)\left(\frac{1.0 \times 443.15}{3{,}000}\right)^{0.5}$$

$$= 6918.1\,\frac{kg}{m.s^2}$$

Rate of heat generation: q

$$q = C_p\,\frac{dT}{dt}\left(\frac{J.K}{kg.K.s}\right) = (3{,}000)(0.105)\,\frac{W}{kg} = 315\,\frac{W}{kg}$$

From Equation 5-63, the vent area, A, is:

$$A = \frac{8,000 \times 315}{6918.1\left\{\left(\frac{10}{8,000} \times 443.15 \times 20,000\right)^{0.5} + (3,000 \times 5.0)^{0.5}\right\}^2}$$

$$A = 7.024 \times 10^{-3}\,\mathrm{m}^2$$

$$d = 94.56\,\mathrm{mm}\,(3.72\text{ in.})$$

The vent size is about 4.0 in.

Using the Fauske's method:

Assuming $\alpha = 1.0$, $\alpha_0 = 0.0$, $F = 1.0$

$\Delta P = 1\text{ bar} = 10^5 \mathrm{N/m^2}$

From Equation 5-68, the vent area, A, is

$$A = \frac{1}{2} \bullet \frac{(8,000)(0.105)(1-0)}{(1.0)\left(\frac{443.15}{3,000}\right)^{0.5}(10^5)(1-0)}$$

$$A = 10.927 \times 10^{-3}\,\mathrm{m}^2$$

$$d = 117.95\,\mathrm{mm}\,(4.64\text{ in.})$$

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```
      PROGRAM PROG51

C     ORIFICE SIZING FOR FLUID FLOWS.
C     THIS PROGRAM CALCULATES AN ORIFICE DIAMETER FOR BOTH LIQUID AND GAS
C     FLOWS USING FULL-SCALE FLOWRATES IN EITHER lb/s. OR ft^3/min. AND THE
C     FULL-SCALE PRESSURE DROPS IN EITHER  PSI. OR INCH-H2O.
C     THE PROGRAM APPLIES TO CORNER, FLANGE, VENA-CONTRACTA, AND
C     1/2 DIAMETER TAPS.
C     ************************************************************************
C
C     ACFM    =   FULL-SCALE FLOWRATE AT UPSTREAM CONDITIONS, ft^3/min.
C     CD      =   COEFFICIENT OF DISCHARGE.
C     D       =   INSIDE PIPE DIAMETER, inch.
C     OD      =   ORIFICE DIAMETER FOR FULL-SCALE PRESSURE DROP, inch.
C     FA      =   AREA THERMAL-EXPANSION FACTOR.  ACCOUNTS FOR THE
C                 EXPANSION OF THE ORIFICE WITH TEMPERATURE CHANGES.
C     Hw      =   FULL-SCALE ORIFICE PRESSURE-DIFFERENTIAL.  INCH-H2O AT
C                 68oF.
C     K       =   SPECIFIC HEAT RATIO (CONSTANT PRESSURE TO CONSTANT VOLUME).
C     G       =   FULL-SCALE FLOWRATE, lb/s.
C     UP      =   UPSTREAM PRESSURE, psia.
C     DELP    =   FULL-SCALE ORIFICE PRESSURE-DIFFERENTIAL, psi.
C     Y       =   EXPANSION FACTOR.
C     BETA    =   RATIO OF ORIFICE DIAMETER TO PIPE INTERNAL DIAMETER.
C     DEN     =   UPSTREAM FLUID DENSITY, lb/ft^3.
C     CHOICE  =   DETERMINES WHETHER THE ORIFICE PRESSURE DROP IS PSI
C                 OR INCH-H2O.
C     FLOW    =   CHECKS WHETHER THE FLOW CONDITION IS LIQUID OR GAS.
C     ************************************************************************

      CHARACTER*10 CHOICE, FLOW

      REAL K, ID, OD, N, L, FMASS
      COMMON/DATA1/FLOW, CHOICE

      OPEN (UNIT=3, FILE ='DATA51.DAT', STATUS ='OLD', ERR=18)
      OPEN (UNIT=1, FILE ='PRN')

C     CHECK WHETHER THE DATA FOR THE ORIFICE PRESSURE DROP IS PSI. OR
C     INCH-H2O.

C     CHOOSE TYPE OF FLOW FOR SIZING (LIQUID/GAS)

      READ (3, 5, ERR=19) FLOW
 5    FORMAT (A)

      IF (FLOW .EQ. 'LIQUID' .OR. FLOW .EQ. 'liquid') THEN

      GO TO 20

      ELSEIF (FLOW .EQ. 'GAS' .OR. FLOW .EQ. 'gas') THEN
      ENDIF

C     CHOOSE TYPE OF PRESSURE DROP.

      READ (3, 10, ERR=19) CHOICE
 10   FORMAT (A)
```

```
C       D        =   PIPE INTERNAL DIAMETER, inch.
C       UP       =   THE UPSTREAM PRESSURE, psia.
C       K        =   THE RATIO OF SPECIFIC HEAT CAPACITIES, Cp/Cv.
C       DEN      =   THE GAS DENSITY, lb/ft^3.
C       VISG     =   THE GAS VISCOSITY, cP.


        READ (3, *, ERR=19) D, UP
        READ (3, *, ERR=19) K, DEN
        READ (3, *, ERR=19) VISG


        IF (CHOICE .EQ. 'INCH-H2O' .OR. CHOICE .EQ. 'inch-H2O') THEN

C       READ THE ORIFICE PRESSURE DROP IN INCH-H2O AND THE FLUID FLOW
C       RATE IN lb/s.


        READ (3, *, ERR=19) DELP2, G2


C       CALCULATE THE ORIFICE PRESSURE DROP IN PSI.
C       CALCULATE THE GAS FLOW RATE IN ft^3/min.

        DELP1=0.036063*DELP2
        G1 = (G2*60.0)/DEN

        GO TO 25

        ELSEIF (CHOICE .EQ. 'PSI' .OR. CHOICE  .EQ. 'psi') THEN


C       READ THE ORIFICE PRESSURE DROP IN PSI. AND THE GAS
C       FLOW RATE IN ft^3/min.


        READ (3, *, ERR=19) DELP1, G1


C       GAS FLOWRATE, (G2) IN lb/sec.
C       ORIFICE PRESSURE DROP (DELP2) IN INCH-H2O

        G2 = (G1*DEN)/60.0
        DELP2 = 27.72925*DELP1
        ENDIF

        GO TO 25


 20     READ (3, 30, ERR=19) CHOICE
 30     FORMAT (A)

        IF (CHOICE .EQ. 'INCH-H2O' .OR. CHOICE .EQ. 'inch-H2O') THEN

C       ID       =   PIPE INTERNAL DIAMETER, inch.
C       DELP     =   ORIFICE PRESSURE DROP, INCH-H2O
C       DEN      =   LIQUID DENSITY, lb/ft^3.
C       Q        =   LIQUID FLOWRATE, ft^3/min.
C       VISL     =   LIQUID VISCOSITY, cP.
```

```
        READ (3, *, ERR=19) ID, DELP
        READ (3, *, ERR=19) DEN, Q, VISL


C       CALCULATE THE ORIFICE PRESSURE DROP IN PSI.
C       CALCULATE THE LIQUID FLOW RATE IN lb/sec.

         DELP1 = 0.036063*DELP
         FMASS = (Q*DEN)/60.0

        CALL LIQUIDF (ID, DELP, DELP1, DEN, Q, FMASS, VISL)

        GO TO 999

        ELSEIF (CHOICE .EQ. 'PSI' .OR. CHOICE .EQ. 'psi') THEN

C       ID      =   PIPE INTERNAL DIAMETER, inch.
C       DELP1   =   ORIFICE DIFFERENTIAL PRESSURE, PSI.
C       DEN     =   LIQUID DENSITY, lb/ft.^3.
C       FMASS   =   LIQUID FLOW RATE, lb/sec.
C       VISL    =   LIQUID VISCOSITY, cP.


        READ (3, *, ERR=19) ID, DELP1
        READ (3, *, ERR=19) DEN, FMASS, VISL

C       CALCULATE THE ORIFICE PRESSURE DROP IN INCH-H2O
C       CALCULATE THE LIQUID FLOW RATE IN ft^3/min.

        DELP = 27.72925*DELP1
        Q = (FMASS*60.0)/DEN


        CALL LIQUIDF (ID, DELP, DELP1, DEN, Q, FMASS, VISL)

        ENDIF

        GO TO 999

 18     WRITE (*, 100)
 100    FORMAT (3X,'DATA FILE DOES NOT EXIST')

        GO TO 999
 19     WRITE (*, 110)
 110    FORMAT (3X,'ERROR MESSAGE IN THE DATA VALUE')

        GO TO 999


 25     N = 1.0-(0.41*DELP1)/(UP*K)
        T = (0.35*DELP1)/(UP*K)


        SRT = (DEN *DELP1)**0.5
        L = G2/(0.3255*(D**2)*SRT)
        P = (2.0*N)/T

        Q = (N**2+L**2)/(T*T)
```

```
      R=-(L**2)/(T*T)

      A = (3.0*Q-(P*P))/3.0
      B = ((2.0*(P**3))-(9.0*P*Q)+(27.0*R))/27.0

      SUM1 = (((B**2)/4.0)+((A**3)/27.0))**0.5

      VAL1 = (-B/2.0+SUM1)**(1.0/3.0)

      Y = VAL1 + ((-B/2-SUM1)**(1.0/3.0))


      Y = ABS(Y-(2.0*N)/(3.0*T))

      OD = D*(Y**0.25)

C     USING THE ORIFICE DIAMETER, CHECK WHETHER THE CALCULATED GAS
C     RATE IS THE SAME AS THE INITIAL GAS RATE.

C     CALCULATE THE EXPANSION FACTOR, Y1

      BETA = OD/D
      Y1 = 1.0-(0.41+0.35*(BETA**4))*(DELP1/(UP*K))
      FA = 1.0
      CD = 0.62

      VAL1 = (1.0-(BETA**4))**0.5
      G = 0.52502*CD*Y1*(OD**2)*FA*SRT
      GR = G/VAL1


C     CALCULATE THE REYNOLDS NUMBER

      REG = (6.31*3600.0*G2)/(D*VISG)


      WRITE (1, 120)
 120  FORMAT (25X,'ORIFICE SIZING FOR GAS FLOWS', /1H ,76(1H*))

      WRITE (1, 130)FLOW
 130  FORMAT (5X,'TYPE OF FLOW:', T65, A)

      WRITE (1, 140) CHOICE
 140  FORMAT (5X,'TYPE OF PRESSURE DROP:', T65, A)

      WRITE (1, 150) D, UP, DELP2, DELP1, K, DEN, VISG, G1, G2
 150  FORMAT (5X,'INSIDE PIPE DIAMETER, inch:', T65, F8.3,/,
     *        5X,'UPSTREAM PRESSURE, psia.:', T65, F8.3,/,
     *        5X,'ORIFICE PRESSURE DROP, INCH-H2O:', T65, F8.3,/,
     *        5X,'ORIFICE PRESSURE DROP, psi.:', T65, F8.3,/,
     *        5X,'SPECIFIC HEAT RATIO (k=Cp/Cv):', T65, F8.4,/,
     *        5X,'UPSTREAM FLUID DENSITY, lb/ft^3:', T65, F8.3,/,
     *        5X,'GAS VISCOSITY, cP:', T65, F8.4,/,
     *        5X,'GAS FLOW RATE, ft^3/min.:', T65, F8.3,/,
     *        5X,'GAS MASS RATE, lb/sec.:', T65, F8.3)

      WRITE (1, 160)Y, OD, GR, REG
 160  FORMAT (5X,'EXPANSION FACTOR:', T65, F8.4,/,
     *        5X,'ORIFICE DIAMETER, inch:', T65, F8.3,/,
     *        5X,'FULL SCALE GAS FLOWRATE, lb/sec.:', T65, F8.3,/,
```

```
     *           5X,'REYNOLDS NUMBER:', T65, F12.0)

        WRITE (1, 170)
 170    FORMAT (1H ,76(1H-))


C       FORM FEED THE PRINTING PAPER TO THE TOP OF NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE (UNIT=3, STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END
C
C       ************************************************************
C       THE FORMULA FOR CALCULATING THE ORIFICE PLATE FOR LIQUID
C       FLOW IS:
C
C       M = 0.52502((Cd.Y.d^2.Fa)(SQRT(DEN.DELP)/(SQRT(1-(DO/D)^4)
C       WHERE FOR LIQUID FLOW, Cd=0.62, Fa=1.0 AND Y=1.0
C       DO   = ORIFICE DIAMETER
C       D    = PIPE INTERNAL DIAMETER
C       DEN  = DENSITY OF LIQUID, lb/ft^3.
C       DELP = PRESSURE DROP ACROSS THE ORIFICE, inch-H2O OR psi.
C       M    = MASS FLOW RATE, lb/s.
C       ************************************************************
        SUBROUTINE LIQUIDF (ID, DELP, DELP1, DEN, Q, FMASS, VISL)


        CHARACTER*10 FLOW, CHOICE
        COMMON/DATA1/FLOW, CHOICE
        REAL ID, OD


C       CALCULATE THE ORIFICE DIAMETER, inch.

C       PRESSURE DROP ACROSS THE ORIFICE (DELP1), PSI.
C       LIQUID FLOW RATE (FMASS), lb/sec.


        Z = (0.52502*0.62*(DEN*DELP1)**0.5)/FMASS
        RATIO = (ID**4)/(1+((ID**4)*(Z**2)))
        OD = RATIO**0.25

C       CALCULATE THE REYNOLDS NUMBER, REL

        REL = (6.31*3600.0*FMASS)/(ID*VISL)

C       PRINT THE RESULTS OF ORIFICE SIZING FOR LIQUID FLOW.

        WRITE (1, 180)
 180    FORMAT (20X, 'ORIFICE SIZING FOR LIQUID FLOW', /1H ,76(1H*))

        WRITE (1, 190) FLOW
 190    FORMAT (5X,'TYPE OF FLOW:', T65, A)

        WRITE (1, 200)CHOICE
 200    FORMAT (5X,'TYPE OF PRESSURE DROP:',T65, A)
```

```
        WRITE (1, 210) ID, DELP, DELP1, DEN, VISL, Q, FMASS, OD, REL
 210    FORMAT (5X,'INTERNAL PIPE DIAMETER, inch:', T65, F8.3,/,
    *           5X,'ORIFICE PRESSURE DROP, inch-H2O:',T65,F8.3,/,
    *           5X,'ORIFICE PRESSURE DROP, psi:', T65, F8.3,/,
    *           5X,'LIQUID DENSITY, lb/ft^3:', T65, F8.3,/,
    *           5X,'LIQUID VISCOSITY, cP:', T65, F8.4,/,
    *           5X,'LIQUID VOLUMETRIC RATE, ft^3/min.:',T65,F8.3,/,
    *           5X,'LIQUID MASS RATE, lb/sec.:', T65, F8.3,/,
    *           5X,'ORIFICE SIZE, inch:',T65, F8.3,/,
    *           5X,'REYNOLDS NUMBER:', T65, F12.0)


         WRITE (1, 220)
 220     FORMAT (1H ,76(1H-))

C        FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

         WRITE (1, *) CHAR(12)

         RETURN
         END
```

```
      PROGRAM PROG52

C     THIS PROGRAM CALCULATES THE CONTROL VALVE CAPACITY COEFFICIENT (Cv)
C     OR MAXIMUM FLUID RATE FOR LIQUID, VAPOR AND STEAM IN PROCESS
C     OPERATIONS. IF THE CONTROL-VALVE COEFFICIENT(Cv) IS ALREADY KNOWN,
C     THE PROGRAM WILL CALCULATE THE MAXIMUM FLUID FLOW RATE (LIQUID,
C     VAPOR OR STEAM) THAT CAN PASS THROUGH THE VALVE FOR A GIVEN SET
C     OF PROCESS CONDITIONS.
C
C     TO COMPUTE THE FLUID FLOW FOR LIQUID, GAS AND STEAM CONDITIONS,
C     VALUES OF THE VALVE CAPACITY COEFFICIENT MUST BE KNOWN (i.e. Cv>0)
C     ******************************************************************
C     Cv      =   CAPACITY COEFFICIENT FOR FULLY OPEN VALVE
C     DELP    =   CONTROL VALVE PRESSURE DROP, psi.
C     V       =   LIQUID FLOW, GPM
C     SPL     =   SPECIFIC GRAVITY OF LIQUID
C     Q       =   GAS FLOW, ft^3/h @ 14.7 psia and 60 oF
C     SPG     =   SPECIFIC GRAVITY OF GAS = (M.W. gas/M.W. air)
C     P1      =   INLET PRESSURE, psia
C     P2      =   OUTLET PRESSURE, psia
C     T       =   FLOWING TEMPERATURE, oF
C     W       =   STEAM FLOW, lb/h
C     K       =   SUPERHEAT CORRECTION FACTOR
C     ****************************************************************
C
C
      CHARACTER*10 CHOICE

      COMMON/DATA1/ V, P1, P2, DELPL, SPL, CVL
      COMMON/DATA2/ Q, P21, P22, DELPG, SPG, T, CVG
      COMMON/DATA3/ W, P31, P32, DELPS, F, CVS


      OPEN (UNIT=3, FILE='DATA52.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT=1, FILE='PRN')


 5    READ (3, 6)CHOICE
 6    FORMAT (A)

      IF (CHOICE .EQ. 'LIQUID' .OR. CHOICE .EQ. 'liquid') THEN
      GO TO 11
      ELSEIF (CHOICE .EQ. 'GAS' .OR. CHOICE .EQ. 'gas') THEN
      GO TO 22
      ELSEIF (CHOICE .EQ. 'STEAM' .OR. CHOICE .EQ. 'steam') THEN
      GO TO 33
      ENDIF

 11   READ(3,*,ERR=10) V, CVL
      READ(3,*,ERR=10) P1, P2, SPL

      GO TO 44

 22   READ(3,*,ERR=10) Q, CVG
      READ(3,*,ERR=10) P21, P22, SPG, T

      GO TO 55

 33   READ(3,*,ERR=10) CVS
```

```
      READ(3,*,ERR=10) P31, P32, F

      GO TO 66

 18   WRITE(1,12)
 12   FORMAT(3X,'FILE DOES NOT EXIST')
 10   WRITE(1,13)
      GO TO 999
 13   FORMAT(3X,'ERROR MESSAGE IN THE DATA VALUE')
      GO TO 999

 44   WRITE (1, 100)
 100  FORMAT (//,20X,'CONTROL VALVE SIZING FOR LIQUID SERVICE',/,
     *        1H ,76(1H*))


C     CALCULATE THE CONTROL VALVE FOR LIQUID SERVICE

      CALL LIQUID


      WRITE (1, 110) CHOICE
 110  FORMAT (5X,'FLUID SERVICE:', T60, A)

      IF (CVL .GT. 0.0) THEN

      WRITE (1, 120) V, SPL, P1, P2, DELPL, CVL
 120  FORMAT (5X,'LIQUID FLOWRATE, gpm:', T60, F9.2,/,
     *        5X,'LIQUID SPECIFIC GRAVITY:', T60, F9.3,/,
     *        5X,'INLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'OUTLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'CONTROL VALVE PRESSURE DROP, psi:', T60, F9.3,/,
     *        5X,'CONTROL VALVE CAPACITY COEFFICIENT:', T60, F9.3)

      WRITE (1, 130)
 130  FORMAT (76(1H-))


      ELSE

      WRITE (1, 140) V, SPL, P1, P2, DELPL, CVL
 140  FORMAT (5X,'LIQUID FLOWRATE, gpm:', T60, F9.2,/,
     *        5X,'LIQUID SPECIFIC GRAVITY:', T60, F9.3,/,
     *        5X,'INLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'OUTLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'CONTROL VALVE PRESSURE DROP, psi:', T60, F9.3,/,
     *        5X,'CONTROL VALVE CAPACITY COEFFICIENT:', T60, F9.3)

      WRITE (1, 150)
 150  FORMAT (76(1H-))

      ENDIF

      GO TO 5

 55   WRITE (1, 160)
 160  FORMAT (//,20X,'CONTROL VALVE SIZING FOR GAS SERVICE',/,76(1H*))


C     CALCULATE THE CONTROL VALVE FOR GAS SERVICE.
```

```
      CALL GAS

      WRITE (1, 170) CHOICE
 170  FORMAT (5X,'FLUID SERVICE:', T60, A)

      IF (CVG .GT. 0.0) THEN

      WRITE (1, 180) Q, SPG, P21, P22, DELPG, T, CVG
 180  FORMAT (5X,'GAS FLOW RATE, ft^3/hr.:', T60, F9.3,/,
     *        5X,'SPECIFIC GRAVITY:', T60, F9.3,/,
     *        5X,'INLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'OULET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'CONTROL VALVE PRESSURE DROP, psi:', T60, F9.3,/,
     *        5X,'INLET TEMPERATURE, oF:', T60, F9.3,/,
     *        5X,'CONTROL VALVE CAPACITY COEFFICIENT:', T60, F9.3)

      ELSE

      WRITE (1, 190) Q, SPG, P21, P22, DELPG, T, CVG
 190  FORMAT (5X,'GAS FLOW RATE, ft^3/hr.:', T60, F9.3,/,
     *        5X,'SPECIFIC GRAVITY:', T60, F9.3,/,
     *        5X,'INLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'OUTLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'CONTROL VALVE PRESSURE DROP, psi:', T60, F9.3,/,
     *        5X,'INLET TEMPERATURE, oF:', T60, F9.3,/,
     *        5X,'CONTROL VALVE CAPACITY COEFFICIENT:', T60, F9.3)

      ENDIF

      WRITE (1, 200)
 200  FORMAT (76(1H-))

      GO TO 5

 66   WRITE (1, 210)
 210  FORMAT (//,20X, 'CONTROL VALVE SIZING FOR STEAM SERVICE',
     *       /,76(1H*))


C     CALCULATE THE CONTROL VALVE FOR STEAM SERVICE.

      CALL STEAM

      WRITE (1, 220) CHOICE
 220  FORMAT (5X,'FLUID SERVICE:', T60, A)

      IF (CVS .GT. 0.0 ) THEN

      WRITE (1, 230) W, F, P31, P32, DELPS, CVS
 230  FORMAT (5X,'CALCULATED STEAM FLOW RATE, lb/hr.:', T60, F9.3,/,
     *        5X,'DEGREE OF SUPERHEAT, oF:', T60, F9.3,/,
     *        5X,'INLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'OUTLET PRESSURE, psia:', T60, F9.3,/,
     *        5X,'CONTROL VALVE PRESSURE DROP, psi:', T60, F9.3,/,
     *        5X,'CONTROL VALVE CAPACITY COEFFICIENT:', T60, F9.3)

      WRITE (1, 240)

 240  FORMAT (76(1H-))
```

```
C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        ELSE

        WRITE (1, 250) W, F, P31, P32, DELPS, CVS
 250    FORMAT (5X,'STEAM FLOW RATE, lb/hr.:', T60, F9.3,/,
     *          5X,'DEGREE OF SUPERHEAT, oF:', T60, F9.3,/,
     *          5X,'INLET PRESSURE, psia:', T60, F9.3,/,
     *          5X,'OUTLET PRESSURE, psia:', T60, F9.3,/,
     *          5X,'CONTROL VALVE PRESSURE DROP, psi:', T60, F9.3,/,
     *          5X,'CONTROL VALVE CAPACITY COEFFICIENT:', T60, F9.3)


        WRITE (1, 260)
 260    FORMAT (76(1H-))

        ENDIF

C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *)CHAR(12)

        CLOSE(3,STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END


C       ***************************************************************
C       THIS PROGRAM CALCULATES THE CONTROL VALVE CAPACITY COEFFICIENT
C       OR THE MAXIMUM FLOWRATE FOR FULLY OPEN CONTROL VALVE AND LIQUID
C       FLOW CONDITIONS.
C       ***************************************************************
        SUBROUTINE LIQUID

        COMMON/DATA1/ V, P1, P2, DELPL, SPL, CVL

C       CHECK WHETHER COMPUTATION REQUIRES CAPACITY COEFFICIENT OR
C       MAXIMUM LIQUID FLOW RATE.

C       CALCULATE THE PRESSURE DROP ACROSS THE CONTROL VALVE, psi.

        DELPL = P1 - P2

        IF (CVL .GT. 0.0) THEN
        GO TO 10
        ELSE

C       CALCULATE THE VALVE CAPACITY COEFFICIENT (Cv)

        CVL = V*SQRT(SPL)/SQRT(DELPL)
        ENDIF

        GO TO 30
```

```
C       CALCULATE THE MAXIMUM LIQUID FLOW RATE, gpm.

 10     V = CVL*SQRT(DELPL)/SQRT(SPL)

 30     RETURN
        END

C       ******************************************************************
C       THIS PROGRAM CALCULATES THE CONTROL VALVE CAPACITY COEFFICIENT OR
C       THE MAXIMUM GAS FLOW RATE FOR GAS FLOW CONDITIONS
C       *******************************************************************
C
        SUBROUTINE GAS

        COMMON/DATA2/ Q, P21, P22, DELPG, SPG, T, CVG

        T = T+460.0

C       CALCULATE THE CONTROL VALVE PRESSURE DROP, psi.

        DELPG = P21 - P22

        VALG = P22*DELPG

C       CHECK WHETHER COMPUTATION REQUIRES CAPACITY COEFFICIENT OR
C       MAXIMUM GAS FLOW RATE.

        IF (CVG .GT. 0.0) THEN
        GO TO 10
        ELSE
        ENDIF

C       CHECK WHETHER FLOW IS CRITICAL OR SUBCRITICAL

        IF ((P21/2.) .GE. P22) THEN
        GO TO 15
        ELSE

C       CALCULATE THE VALVE CAPACITY COEFFICIENT FOR SUBCRITICAL FLOW

        CVG = Q*SQRT(SPG*T)/(1360.0*SQRT(VALG))
        ENDIF

        GO TO 20
C
C       CALCULATE THE VALVE CAPACITY COEFFICIENT FOR CRITICAL FLOW.

 15     WRITE (*, 25)
 25     FORMAT (3X,'CRITICAL GAS FLOW')

        pause

        CVG = Q*SQRT(SPG*T)/(1360.0*0.5*P21)

        GO TO 20

C       CALCULATE THE MAXIMUM GAS FLOW RATE, ft^3/hr. FOR SUBCRITICAL
C       FLOW.

 10     IF ((P21/2.0) .GE. P22) THEN
```

```
        GO TO 35
        ELSE
        Q = (CVG*1360.0*SQRT(VALG))/SQRT(SPG*T)
        ENDIF

        GO TO 20

C       CALCULATE THE MAXIMUM GAS FLOW RATE, ft^/hr. FOR CRITICAL FLOW

 35     WRITE (*, 45)
 45     FORMAT(3X,'CRITICAL GAS FLOW')

        pause

        Q = (CVG*1360.0*0.5*P21)/SQRT(SPG*T)

 20     T = T- 460.0

        RETURN
        END
C
C       *****************************************************************
C       THIS PROGRAM CALCULATES THE CONTROL VALVE CAPACITY COEFFICIENT
C       OR THE MAXIMUM STEAM FLOW RATE FOR FULLY OPEN CONTROL VALVE AND
C       FLOW CONDITIONS.
C       ******************************************************************

        SUBROUTINE STEAM

        REAL K
        COMMON/DATA3/ W, P31, P32, DELPS, F, CVS

        K = 1.0+.0007*F

C       CALCULATE THE CONTROL VALVE PRESSURE DROP, psi.

        DELPS = P31 - P32

        VALS = P32*DELPS

C       CHECK WHETHER COMPUTATION REQUIRES CAPACITY COEFFICIENT OR
C       MAXIMUM FLOW RATE.


        IF (CVS .GT. 0.0) THEN
        GO TO 10
        ELSE
        ENDIF

C       CHECK WHETHER FLOW IS CRITICAL OR SUBCRITICAL

        IF ((P31/2.) .GE. P32) THEN
        GO TO 15
        ELSE
        ENDIF

C       CALCULATE THE CAPACITY COEFFICIENT FOR SUBCRITICAL FLOW

        CVS = (W*K)/3.*SQRT(VALS)
```

```
        GO TO 20

 15     WRITE(*,25)
 25     FORMAT(3X,'CRITICAL STEAM FLOW')

        pause

C       CALCULATE THE CAPACITY COEFFICIENT FOR CRITICAL FLOW.

        CVS = (W*K)/(1.5*P31)


        GO TO 20

C       CHECK WHETHER FLOW IS CRITICAL OR SUBCRITICAL FLOW AND
C       CALCULATE THE FLOW.

 10     IF ((P31/2.) .GE. P32) THEN
        GO TO 35

        ELSE

C       CALCULATE THE MAXIMUM FLOW RATE FOR CRITICAL FLOW.

        W = 3.0*CVS*SQRT(VALS)/K
        ENDIF


        GO TO 20

 35     WRITE(*, 45)
 45     FORMAT(3X,'CRITICAL STEAM FLOW')

        pause

C       CALCULATE THE MAXIMUM FLOW RATE FOR CRITICAL FLOW.

        W=(1.5*P31*CVS)/K

 20     RETURN
        END
```

```
      PROGRAM PROG53
C     RELIEF-VALVE SIZING FOR VAPOR, STEAM, LIQUID, AIR AND FIRE.
C     THE PROGRAM USES THE EQUATIONS AND CORRELATIONS PRESENTED IN
C     AMERICAN PETROLEUM INSTITUTE (API) 520 RECOMMENDED PRACTICES
C     FOR THE DESIGN AND INSTALLATION OF PRESSURE-RELIEVING SYSTEMS
C     IN REFERINERIES FOR THE SIZING OF RELIEF VALVES IN VAPOR,
C     STEAM, LIQUID, AIR AND FIRE SERVICES.
C     ************************************************************

      CHARACTER COUNT(14),REGIME(14),REG(14),REG1(14)
      CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14),ACONT(14)
      CHARACTER*10 CHOICE

      REAL OP1, MW1, N1
      REAL OP2, KSH, MW2, N2
      REAL KV, KV1, KW, KD
      REAL OP4
      REAL LAT, OP5, MW5, N5

      DIMENSION Y(14)
      COMMON/NAME/I,Y,IJK
      COMMON/DATA/REG1,ACONT
      COMMON/DATA1/WGMAX,ADES1,ACAL1,C1
      COMMON/DATA2/WSMAX,ADES2,ACAL2,C2
      COMMON/DATA3/GP1MAX,GP2MAX,ADES3,ACAL3,ACAL31,ADES31,RE
      COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL,REG, ACOUNT
      COMMON/DATA5/FORCE
      COMMON/DATA6/ADES4,VAMAX,ACAL4,C4
      COMMON/DATA7/Q,WF
      COMMON/DATA8/KV1
      COMMON CHOICE

      DATA COUNT/'D','E','F','G','H','J','K','L','M','N',
     *           'P','Q','R','T'/

      DATA COUNT1/'   1-2          ','   1-2         ',
     *             '  1.5-2       ','   1.5-2      ',
     *             ' 1.5-3 or 2-3 ','  2-3 or 2.5-4',
     *             '  3-4         ','  3-4 or 4-6  ',
     *             '  4-6         ','   4-6        ',
     *             '  4-6         ','   6-8        ',
     *             ' 6-8 or 6-10  ','   8-10       '/


      OPEN (UNIT=3, FILE='DATA53.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT =1, FILE ='PRN')

      READ(3, 5, ERR=19) CHOICE
 5    FORMAT (A)

      IF (CHOICE .EQ. 'VAPOR' .OR. CHOICE .EQ. 'vapor') THEN
          GO TO 10
      ELSEIF (CHOICE .EQ. 'STEAM' .OR. CHOICE .EQ. 'steam') THEN
          GO TO 20
      ELSEIF (CHOICE .EQ. 'LIQUID' .OR. CHOICE .EQ. 'liquid') THEN
          GO TO 30
      ELSEIF (CHOICE .EQ. 'AIR' .OR. CHOICE .EQ. 'air') THEN
          GO TO 40
      ELSEIF (CHOICE .EQ. 'FIRE' .OR. CHOICE .EQ. 'fire') THEN
```

```
            GO TO 50

        ENDIF

C       CALCULATE RELIEF VALVE FOR VAPOR CONDITION
C       INPUT DATA FOR VAPOR CONDITION

C       WG       =   VAPOR FLOW RATE, lb/hr.
C       SP1      =   RELIEF VALVE SET PRESSURE, psig.
C       OP1      =   ALLOWABLE OVERPRESSURE, (%).
C       T1       =   RELIEVING TEMPERATURE OF THE INLET VAPOR (oF).
C       Z1       =   COMPRESSIBILITY FACTOR.
C       MW1      =   MOLECULAR WEIGHT OF VAPOR.
C       N1       =   RATIO OF THE SPECIFIC HEATS.

 10     READ (3, *, ERR=19) WG, SP1
        READ (3, *, ERR=19) OP1, T1
        READ (3, *, ERR=19) Z1, MW1
        READ (3, *, ERR=19) N1

C       DETERMINE THE RELIEF VALVE ORIFICE AREA FOR VAPOR CONDITION

        CALL VAPOR (WG, SP1, OP1, T1, Z1, MW1, N1)

C       PRINT RESULTS

        CALL OUT1 (WG, SP1, OP1, T1, Z1, MW1, N1)

        GO TO 60

C       INPUT DATA FOR STEAM RELIEF CONDITION.

C       WS       =   STEAM FLOW RATE, lb/hr.
C       SP2      =   RELIEF VALVE SET PRESSURE, psig.
C       OP2      =   ALLOWABLE OVERPRESSURE (%).
C       KSH      =   SUPERHEAT STEAM CORRECTION FACTOR.
C       T2       =   RELIEF TEMPERATURE, oF.
C       MW2      =   MOLECULAR WEIGHT OF STEAM.
C       N2       =   RATIO OF THE SPECIFIC HEATS.

 20     READ (3, *, ERR=19) WS, SP2
        READ (3, *, ERR=19) OP2, KSH
        READ (3, *, ERR=19) T2, MW2
        READ (3, *, ERR=19) N2

C       DETERMINE THE RELIEF VALVE ORIFICE AREA FOR STEAM CONDITION

        CALL STEAM (WS, SP2, OP2, KSH, T2, MW2, N2)

C       PRINT RESULTS

        CALL OUT2 (WS, SP2, OP2, KSH, T2, MW2, N2)

         GO TO 60

C       INPUT DATA FOR LIQUID RELIEF

C       GPM      =   LIQUID FLOW RATE, U.S. gpm.
C       SP3      =   UPSTREAM RELIEVING SET PRESSURE, psig.
C       PB       =   TOTAL BACK PRESSURE, psig.
```

```
C        SPL      =   SPECIFIC GRAVITY OF THE LIQUID.
C        VISL     =   VISCOSITY OF LIQUID, cP.
C        KV       =   CORRECTION FACTOR DUE TO VISCOSITY.
C        KW       =   CORRECTION FACTOR DUE TO BACK PRESSURE.
C        KD       =   EFFECTIVE COEFFICIENT OF DISCHARGE.

 30      READ (3, *, ERR =19) GPM, SP3
         READ (3, *, ERR = 19) PB, SPL
         READ (3, *, ERR=19) VISL, KV
         READ (3, *, ERR=19) KW, KD

C        DETERMINE THE RELIEF VALVE ORIFICE AREA FOR LIQUID CONDITION

         CALL LIQUID (GPM, SP3, PB, SPL, VISL, KV, KW, KD)

C        PRINT RESULTS

         IF (VISL .LT. 10.0) THEN

         CALL OUT3 (GPM, SP3, PB, SPL, VISL, KV, KW, KD)

         GO TO 60
         ELSE

         CALL OUT32 (VISL)

         GO TO 60

         ENDIF

C        INPUT DATA FOR AIR RELIEF

C        VA       =   REQUIRED AIR CAPACITY, ft^3/min.
C        T        =   INLET TEMPERATURE, oF.
C        P        =   RELIEVING PRESSURE, psia.
C        SP4      =   RELIEF VALVE SET PRESSURE, psig.

 40      READ (3, *, ERR=19) VA, T
         READ (3, *, ERR=19) P, SP4

C        DETERMINE THE RELIEF VALVE ORIFICE AREA FOR AIR CONDITION

         CALL AIR (VA, T, P, SP4)

C        PRINT RESULTS

         CALL OUT4 (VA, T, P, SP4)

         GO TO 60

C        DETERMINE THE RELIEF VALVE ORIFICE AREA FOR FIRE CONDITION.

C        F        =   ENVIRONMENTAL FACTOR.
C        A        =   TOTAL WETTED SURFACE AREA, ft^2.
C        LAT      =   LATENT HEAT OF VAPORIZATION, Btu/lb.
C        SP5      =   RELIEF VALVE SET PRESSURE, psig.
C        OP5      =   ALLOWABLE OVERPRESSURE, (%).
C        T        =   RELIEVING TEMPERATURE, oF.
C        Z        =   COMPRESSIBILITY FACTOR.
C        MW5      =   FLUID MOLECULAR WEIGHT.
```

```
C       N5      =   RATIO OF THE SPECIFIC HEATS.

C       INPUT DATA FOR FIRE RELIEF CONDITION.

 50     READ (3, *, ERR=19) F, A
        READ (3, *, ERR=19) LAT, SP5
        READ (3, *, ERR=19) OP5, T
        READ (3, *, ERR=19) Z, MW5
        READ (3, *, ERR=19) N5

C       DETERMINE THE RELIEF VALVE ORIFICE AREA FOR FIRE CONDITION

        CALL FIRE (F, A, LAT, SP5, OP5, T, Z, MW5, N5)

C       PRINT RESULTS

        CALL OUT5 (F, A, LAT, SP5, OP5, T, Z, MW5, N5)

        GO TO 60

 18     WRITE (*, 750)
 750    FORMAT (3X, 'DATA FILE DOES NOT EXIST')

        GO TO 60

 19     WRITE (*, 800)
 800    FORMAT (3X, 'ERROR MESSAGE IN THE DATA VALUE')

        GO TO 60

        CLOSE (3, STATUS = 'KEEP')
        CLOSE (1)

 60     STOP
        END

C       ****************************************************************
C       THIS PROGRAM SIZES THE RELIEF VALVE FOR VAPOR CONDITIONS
C       ****************************************************************

        SUBROUTINE VAPOR (WG, SP1, OP1, T1, Z1, MW1, N1)

        CHARACTER COUNT(14),REGIME(14), REG(14)
        CHARACTER*14 COUNT1(14), COUNLL(14), ACOUNT(14)
        REAL K,KB,MW1,N1,OP1
        COMMON/NAME/I,Y,IJK
        COMMON/DATA1/WGMAX,ADES1,ACAL1,C1
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL,REG, ACOUNT
        COMMON/DATA5/FORCE
        DIMENSION Y(14)

C       CALCULATE THE GAS COEFFICIENT (C1) AND THE ORIFICE AREA.

        K=0.975
        KB=1.0
        T1=T1+460.0
        P1=SP1+(SP1*OP1/100.0)+14.7
        VAL1=N1*(2.0/(N1+1.0))**((N1+1.0)/(N1-1.0))
        C1=520.0*SQRT(VAL1)
        VAL2=C1*K*P1*KB*SQRT(MW1)
```

```
        ACAL1=WG*SQRT(T1*Z1)/VAL2

        DO 22 I=1, 14
            IF (Y(I) .GT. ACAL1) THEN
            GO TO 25
        ELSE
        ENDIF
 22     CONTINUE

 25     ADES1=Y(I)

C       CALCULATE THE MAXIMUM FLOWRATE FROM THE MANUFACTURER'S
C       ORIFICE AREA

        CALL MANUF(ADES1)
        WGMAX=ADES1*VAL2/SQRT(T1*Z1)

C       CALCULATE THE REACTIVE FORCE

        CALL REACTF(WGMAX,N1,T1,MW1)

        T1 = T1-460.0
        RETURN
        END

C       ***************************************************************
C       THIS PROGRAM SIZES THE RELIEF-VALVE FOR STEAM CONDITION
C       ***************************************************************

        SUBROUTINE STEAM (WS, SP2, OP2, KSH, T2, MW2, N2)
        CHARACTER COUNT(14),REGIME(14), REG (14)
        CHARACTER*14 COUNT1(14),COUNLL(14), ACOUNT(14)
        COMMON/NAME/I,Y,IJK
        COMMON/DATA2/WSMAX,ADES2,ACAL2,C2
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL,REG, ACOUNT
        DIMENSION Y(14)
        REAL KSH,OP2,MW2,N2,KN,KD

C       KD = THE EFFECTIVE COEFFICIENT OF DISCHARGE (KD=0.975)
C       KN = CORRECTION FACTOR FOR NAPIER EQUATION (KN=1)

C       CALCULATE THE GAS COEFFICIENT (C2) AND THE ORIFICE AREA

        KN = 1.0
        KD = 0.975
        T2 =T2+460.0
        P2=SP2+(SP2*OP2/100.0)+14.7
        VAL3=N2*(2.0/(N2+1.0))**((N2+1.0)/(N2-1.0))
        C2=520.0*SQRT(VAL3)
        ACAL2=WS/(51.5*P2*KSH*KD*KN)

        DO 33 I=1,14
                IF (Y(I) .GT. ACAL2) THEN
                GO TO 25
        ELSE
        ENDIF
 33     CONTINUE

C       CALCULATE THE MAXIMUM FLOWRATE FROM THE MANUFACTURER'S ORIFICE
C       AREA.
```

```
 25     ADES2=Y(I)
        CALL MANUF(ADES2)
        WSMAX=51.5*P2*KSH*KN*KD*ADES2

C       CALCULATE THE REACTIVE FORCE.

        CALL REACTF(WSMAX,N2,T2,MW2)
        T2 = T2-460.0
        RETURN
        END

C       ****************************************************************
C       THIS PROGRAM SIZES THE RELIEF VALVE FOR LIQUID CONDITION.
C       SIZING FOR LIQUID RELIEF VALVES REQUIRING LIQUID CAPACITY
C       CERTIFICATION.
C       ****************************************************************

        SUBROUTINE LIQUID (GPM, SP3, PB, SPL, VISL, KV, KW, KD)

        DIMENSION Y(14)

        CHARACTER COUNT(14),REGIME(14),REG(14),REG1(14)
        CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14),ACONT(14)

        REAL KD, KW, KV, KV1

        COMMON/DATA3/GP1MAX,GP2MAX,ADES3,ACAL3,ACAL31,ADES31,RE
        COMMON/NAME/I,Y, IJK
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
        COMMON/DATA8/KV1
        COMMON/DATA/REG1,ACONT

C       CALCULATE THE ORIFICE AREA FOR LIQUID CAPACITY CERTIFICATION.

        SP3 = SP3+(0.1*SP3)
        VAL3 = (SP3-PB)
        VAL4=38.0*KD*KW*KV*SQRT(VAL3)
        ACAL3=GPM*SQRT(SPL)/VAL4

        DO 44 I =1, 14
        IF (Y(I) .GT. ACAL3) THEN
            GO TO 25
            ELSE
        ENDIF
 44     CONTINUE

 25     ADES3=Y(I)

        IJK = I
C

C       CALCULATE THE MANUFACTURER'S ORIFICE AREA AND THE MAXIMUM
C       LIQUID FLOWRATE.

        CALL MANUF(ADES3)
        GP1MAX=(ADES3*VAL4)/SQRT(SPL)

        CALL OUT3 (GPM, SP3, PB, SPL, VISL, KV, KW, KD)
```

```
C       CHECK WHETHER THE VISCOSITY IS EQUAL TO OR GREATER THAN 10.0cP

        IF (VISL .GE. 10.) THEN
            GO TO 30
            ELSE
        ENDIF
        GO TO 90

 30     CALL AMANU(ADES3)

        REG1(I)=REG(I)
        ACONT(I)=ACOUNT(I)
        GP1MAX=(ADES3*VAL4)/SQRT(SPL)

C       CALL OUT31(GPM,SP3,PB,SPL,VISL,KV,KW,KP)

        RE=(GPM*2800.0*SPL)/(VISL*SQRT(ADES3))
        VAL6=(1.2502*ALOG(RE))-(0.17510*(ALOG(RE))**2)
        VAL7=(0.01087*(ALOG(RE))**3)-(0.00025*(ALOG(RE))**4)
        KV1=-2.38878+VAL6+VAL7
        VAL8=38.0*KD*KW*KV1*SQRT(VAL3)
        ACAL31=GPM*SQRT(SPL)/VAL8
C
        DO 66 I=1,14
            IF (Y(I) .GT. ACAL31) THEN
            GO TO 77
            ELSE
        ENDIF
 66     CONTINUE

 77     ADES31=Y(I)
        CALL MANUFL(ADES3,ADES31)
        GP2MAX=(ADES31*VAL8)/SQRT(SPL)
 90     RETURN
        END


C       ******************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF VAPOR RELIEF SIZING ONTO A
C       PRINTER
C       ******************************************************************

        SUBROUTINE OUT1 (WG, SP1, OP1, T1, Z1, MW1, N1)
        CHARACTER COUNT(14),REGIME(14),REG(14),REG1(14)
        CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14),ACONT(14)
        CHARACTER*10 CHOICE

        COMMON/NAME/I,Y,IJK
        COMMON/DATA1/WGMAX,ADES1,ACAL1,C1
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
        COMMON/DATA5/FORCE
        COMMON CHOICE
        REAL OP1,MW1,N1
        DIMENSION Y(14)


        WRITE(1, 100)
 100    FORMAT(20X,'VAPOR RELIEF VALVE SIZING')
        WRITE(1, 110)
```

```
      WRITE (1, 105)CHOICE
 105  FORMAT (3X,'BASIS OF SELECTION:', T65, A)
 110  FORMAT(1H ,76(1H*))
      WRITE(1, 120)WG
 120  FORMAT(3X,'REQUIRED VAPOR RATE, lb/hr.:',T65, F12.0)

      WRITE(1, 130) SP1
 130  FORMAT(3X,'VALVE SET PRESSURE, psig:',T65, F9.3)
      WRITE(1, 140) OP1
 140  FORMAT(3X,'PERCENTAGE IN OVERPRESSURE, (%):',T65, F9.3)

      WRITE(1, 150)T1
 150  FORMAT(3X,'UPSTREAM FLUID TEMPERATURE, DEG. F:',T65, F9.3)
      WRITE(1, 160)Z1
 160  FORMAT(3X,'COMPRESSIBILITY FACTOR:',T65, F9.4)


      WRITE(1, 170) MW1
 170  FORMAT(3X,'MOLECULAR WEIGHT OF VAPOR:', T65, F9.3)

      WRITE(1, 180)N1
 180  FORMAT(3X,'RATIO OF SPECIFIC HEATS OF FLUID:', T65, F9.3)

      WRITE(1, 190) C1
 190  FORMAT(3X,'GAS CONSTANT DETERMINED BY RATIO OF Cp/Cv:',T65,F9.3)

      WRITE(1, 200) ACAL1
 200  FORMAT(3X,'CALCULATED VALVE ORIFICE AREA, in^2:',T65, F9.3)

      WRITE(1, 210) ADES1
 210  FORMAT(3X,'NEAREST STANDARD ORIFICE AREA, in^2:',T65, F9.3)

      WRITE(1, 220) REGIME(I)
 220  FORMAT(3X,'NEAREST STANDARD ORIFICE SIZE:', T65, A)

      WRITE(1, 230) COUNT1 (I)
 230  FORMAT(3X,'PREFERRED VALVE BODY SIZE: (IN-OUT) inches:',T65,A14)

      WRITE(1, 240) WGMAX
 240  FORMAT(3X,'MAXIMUM VAPOR FLOWRATE WITH STD. ORIFICE, lb/hr.:',
     *       T65,F12.0)

      WRITE(1, 250) FORCE
 250  FORMAT(3X,'REACTION FORCE, lb:',T65, F9.0)

      WRITE (1, 260)
 260  FORMAT (76(1H-))

C     FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

      WRITE (1, *)CHAR(12)


      RETURN
 20   STOP
      END

C     ***************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF LIQUID RELIEF CONDITION
```

```
C        ONTO A PRINTER
C        ***************************************************************

         SUBROUTINE OUT3 (GPM, SP3, PB, SPL, VISL, KV, KW, KD)
         DIMENSION Y(14)
         CHARACTER COUNT(14),REGIME(14),REG(14),REG1(14)
         CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14),ACONT(14)
         CHARACTER*10 CHOICE
         COMMON/NAME/I,Y,IJK
         COMMON/DATA/REG1,ACONT
         COMMON/DATA3/GP1MAX,GP2MAX,ADES3,ACAL3,ACAL31,ADES31,RE
         COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
         COMMON/DATA8/KV1
         COMMON CHOICE
         REAL KV,KW,KD,KV1

         WRITE(1, 270)
 270     FORMAT(20X,'RELIEF VALVE SIZING FOR LIQUID')
         WRITE(1, 280)
 280     FORMAT(1H ,76(1H*))

         WRITE (1, 285)CHOICE
 285     FORMAT (3X,'BASIS OF SELECTION:', T65, A)
         WRITE(1, 290) GPM
 290     FORMAT(3X,'LIQUID FLOWRATE, US gpm:',T65, F12.0)
         WRITE(1, 300) SP3
 300     FORMAT(3X,'VALVE SET PRESSURE, psig:',T65, F9.3)
         WRITE(1,310) PB
 310     FORMAT(3X,'BACK PRESSURE ON VALVE, psig:',T65, F9.3)
         WRITE(1, 320) SPL
 320     FORMAT(3X,'FLUID SPECIFIC GRAVITY:', T65, F9.3)

         WRITE(1,330) VISL
 330     FORMAT(3X,'FLUID VISCOSITY, cP:', T65, F9.4)

         WRITE(1, 340) KV
 340     FORMAT(3X,'VISCOSITY CORRECTION FACTOR, Kv:',T65, F9.4)

         WRITE(1, 350) KW
 350     FORMAT(3X,'BACKPRESSURE CORRECTION FACTOR, Kw:',T65, F9.4)

         WRITE(1, 360) KD
 360     FORMAT(3X,'EFFECTIVE COEFFICIENT OF DISCHARGE, Kd:', T65, F9.3)
         WRITE(1, 370) ACAL3
 370     FORMAT(3X,'CALCULATED VALVE ORIFICE AREA, in^2:',T65,F9.3)

         WRITE(1, 380) ADES3
 380     FORMAT(3X,'NEAREST STANDARD ORIFICE AREA, in^2:', T65,F9.3)

         WRITE(1, 390) REGIME (I)
 390     FORMAT(3X,'NEAREST STANDARD ORIFICE SIZE:', T65, A)

         WRITE(1, 400) COUNLL(I)
 400     FORMAT(3X,'PREFERRED VALVE BODY SIZE, (IN-OUT) inches:',T65,A14)

         WRITE(1, 410) GP1MAX
 410     FORMAT(3X,'MAXIMUM LIQUID FLOWRATE WITH STD. ORIFICE, gpm:',
     *          T65,F12.0)
```

```
C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        RETURN
        END

C       **********************************************************

        SUBROUTINE OUT31 (GPM, SP3, PB, SPL, VISL, KV, KW, KD)
        CHARACTER COUNT(14),REGIME(14),REG(14),REG1(14)
        CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14),ACONT(14)
        CHARACTER*10 CHOICE
        DIMENSION Y(14)
        COMMON/NAME/I,Y,IJK
        COMMON/DATA/REG1,ACONT
        COMMON/DATA3/GP1MAX,GP2MAX,ADES3,ACAL3,ACAL31,ADES31,RE
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
        COMMON/DATA8/KV1
        COMMON CHOICE
        REAL KV,KW,KD,KV1

        WRITE(1, 420)
 420    FORMAT(20X,'RELIEF VALVE SIZING FOR LIQUID')
        WRITE(1, 430)
 430    FORMAT(1H ,76(1H*))
        WRITE (1, 440)CHOICE
 440    FORMAT (3X,'BASIS OF SELECTION:', T65, A)
        WRITE(1, 450) GPM
 450    FORMAT(3X,'LIQUID FLOW RATE, U.S gpm:',T65,F12.0)

        WRITE(1, 460) SP3
 460    FORMAT(3X,'VALVE SET PRESSURE, psig:',T65,F9.3)

        WRITE(1,470) SPL
 470    FORMAT(3X,'FLUID SPECIFIC GRAVITY:',T65, F9.3)
        WRITE(1, 480) KV
 480    FORMAT(3X,'VISCOSITY CORRECTION FACTOR Kv=1.0:',T65,F9.3)
        WRITE(1, 490) KW
 490    FORMAT(3X,'BACK PRESSURE CORRECTION FACTOR Kw=1.0:',T65,F9.3)

        WRITE(1, 500)KD
 500    FORMAT(3X,.'COEFFICIENT OF DISCHARGE Kd=0.65:',T65, F9.3)

        WRITE(1, 510) ACAL3
 510    FORMAT(3X,'CALCULATED VALVE ORIFICE AREA, in^2:',T65,F9.3)

        WRITE(1, 520) ADES3
 520    FORMAT(3X,'NEAREST STANDARD ORIFICE AREA, in^2:', T65,F9.3)

        WRITE(1, 530) REG1(I)
 530    FORMAT(3X,'NEAREST STANDARD ORIFICE SIZE:',T65, A)

        WRITE(1, 540) ACONT(I)
 540    FORMAT(3X,'PREFERRED VALVE BODY SIZE, (IN-OUT) inches:',
     *         T65,A14)

        WRITE(1, 550) GP1MAX
 550    FORMAT(3X,'MAXIMUM LIQUID FLOWRATE WITH STD. ORIFICE, gpm:',
     *         T65,F12.0)

        WRITE(1, 560)
```

```
 560    FORMAT (76(1H-))

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

        WRITE (1, *)CHAR(12)


        RETURN
        END

C       *****************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF LIQUID RELIEF VALVE
C       SIZING WITH VISCOSITY GREATER THAN 10cP.
C       *****************************************************

        SUBROUTINE OUT32 (VISL)
        DIMENSION Y(14)
        CHARACTER COUNT(14),REGIME(14),REG(14),REG1(14)
        CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14),ACONT(14)
        COMMON/NAME/I,Y, IJK
        COMMON/DATA3/GP1MAX,GP2MAX,ADES3,ACAL3,ACAL31,ADES31,RE
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
        COMMON/DATA8/KV1
        REAL KV1

        WRITE(1, 570) KV1
 570    FORMAT(3X,'VISCOSITY CORRECTION FACTOR:', T65, F9.3)


        WRITE(1, 580) RE
 580    FORMAT(3X,'REYNOLDS NUMBER:', T65, F12.0)

        WRITE(1, 590) ACAL31
 590    FORMAT(3X,'CALCULATED VALVE ORIFICE AREA, in^2:',T65,F9.3)


        WRITE(1, 600) ADES31
 600    FORMAT(3X,'NEAREST STANDARD ORIFICE AREA, in^2:', T65,F9.3)

        WRITE(1, 610) REGIME (I)
 610    FORMAT(3X,'NEAREST STANDARD ORIFICE SIZE:', T65, A)

        WRITE(1, 620) COUNLL (I)
 620    FORMAT(3X,'PREFERRED VALVE BODY SIZE, (IN-OUT) inches:',T65,A14)

        WRITE(1, 630) GP2MAX
 630    FORMAT(3X,'MAXIMUM LIQUID FLOWRATE WITH STD. ORIFICE, gpm:',
     *         T65,F12.0)

        WRITE (1, 640)
 640    FORMAT (76(1H-))

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

        WRITE (1, *)CHAR(12)


        RETURN
        END
```

```
C     ****************************************************************
C     THIS PROGRAM PRINTS THE RESULTS OF STEAM RELIEF SIZING
C     ONTO A PRINTER
C     ****************************************************************
      SUBROUTINE OUT2 (WS, SP2, OP2, KSH, T2, MW2, N2)
      CHARACTER COUNT(14),REGIME(14), REG(14)
      CHARACTER*14 COUNT1(14), COUNLL(14), ACOUNT(14)
      CHARACTER*10 CHOICE
      COMMON/NAME/I,Y,IJK
      COMMON/DATA2/WSMAX,ADES2,ACAL2,C2
      COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL,REG, ACOUNT
      COMMON/DATA5/FORCE
      COMMON CHOICE
      DIMENSION Y(14)
      REAL KSH,MW2,N2

      WRITE(1, 650)
 650  FORMAT(20X,'RELIEF VALVE SIZING FOR STEAM CONDITION')
      WRITE(1, 660)
 660  FORMAT(1H ,76(1H*))
      WRITE (1, 665)CHOICE
 665  FORMAT (3X, 'BASIS OF SELECTION:', T65, A)
      WRITE(1, 670) WS
 670  FORMAT(3X,'REQUIRED STEAM RATE, lb/hr.:',T65,F12.0)
      WRITE(1, 680)SP2
 680  FORMAT(3X,'VALVE SET PRESSURE, psig:',T65,F9.3)
      WRITE(1, 690) OP2
 690  FORMAT(3X,'PERCENTAGE OF OVERPRESSURE, (%):',T65,F9.3)
      WRITE(1, 700) KSH
 700  FORMAT(3X,'FACTOR FOR SUPERHEATED KSH=0.88/SATURATED KSH=1:',
     *       T65,F9.3)
      WRITE(1, 710) T2
 710  FORMAT(3X,'STEAM TEMPERATURE, DEG. F:',T65,F9.3)
      WRITE(1, 720) MW2
 720  FORMAT(3X,'MOLECULAR WEIGHT:', T65, F9.3)
      WRITE(1, 730) N2
 730  FORMAT(3X,'RATIO OF SPECIFIC HEATS OF STEAM:', T65, F9.3)
      WRITE(1, 740) C2
 740  FORMAT(3X,'GAS CONSTANT DETERMINED BY RATIO OF Cp/Cv:',T65,F9.3)
      WRITE(1, 750) ACAL2
 750  FORMAT(3X,'CALCULATED VALVE ORIFICE AREA, in^2:', T65, F9.3)
      WRITE(1, 760) ADES2
 760  FORMAT(3X,'NEAREST STANDARD AREA, in^2:', T65, F9.3)
      WRITE(1, 770) REGIME (I)
 770  FORMAT(3X,'NEAREST STANDARD ORIFICE SIZE:', T65, A)
      WRITE(1, 780) COUNT1(I)
 780  FORMAT(3X,'PREFERRED VALVE BODY SIZE, (IN-OUT) inches:',T65,A14)
      WRITE(1, 790) WSMAX
 790  FORMAT(3X,'MAXIMUM STEAM FLOWRATE WITH STD. ORIFICE, lb/hr.:',
     *       T65,F12.0)
      WRITE(1, 800)FORCE
 800  FORMAT(3X,'REACTION FORCE, lb:',T65,F12.0)
      WRITE (1, 810)
 810  FORMAT (76(1H-))

C     FORM  FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

      WRITE (1, *)CHAR(12)
      RETURN
      END
```

```
C       ****************************************************************
C       THIS PROGRAM SIZES THE RELIEF VALVE FOR AIR-CONDITION
C       ****************************************************************
        SUBROUTINE AIR (VA, T4, SP4, OP4)
        REAL OP4,N,MW,KB,KD
        CHARACTER COUNT(14),REGIME(14), REG(14)
        CHARACTER*14 COUNT1(14), COUNLL(14),ACOUNT(14)
        COMMON/NAME/I,Y,IJK
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
        COMMON/DATA5/FORCE
        COMMON/DATA6/ADES4,VAMAX,ACAL4,C4
        DIMENSION Y(14)

C       CALCULATE THE ORIFICE AREA AND THE GAS COEFFICIENT.

        KB =1.0
        KD=0.953
        T = T4+460.0
        MW=28.97
        N=1.40
        P4=SP4+(SP4*OP4/100.0)+14.7
        RHO=(MW*P4)/(10.72*T)
        ACAL4=(VA*SQRT(T))/(418.0*KB*KD*P4)
        VAL4=N*(2.0/(N+1.0))**((N+1.0)/(N-1.0))
        C4=520.0*SQRT(VAL4)

        DO 44 I=1,14
        IF (Y (I) .GT. ACAL4) THEN
            GO TO 30
            ELSE
        ENDIF
 44     CONTINUE

C       CALCULATE THE MANUFACTURER'S AREA AND MAXIMUM AIR RATE.

 30     ADES4=Y(I)
        CALL MANUF(ADES4)
        VAMAX=(418.0*ADES4*P4*KB*KD)/SQRT(T)
        WAMAX=(60.0*VAMAX*RHO)

C       CALCULATE THE REACTIVE FORCE.

        FORCE = WAMAX/15.9
        RETURN
        END

C       ****************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF AIR RELIEF VALVE SIZING ONTO
C       A PRINTER
C       ****************************************************************
        SUBROUTINE OUT4 (VA, T4, SP4, OP4)
        CHARACTER*14 COUNT1(14), COUNLL(14), ACOUNT(14)
        CHARACTER*10 CHOICE
        CHARACTER COUNT(14),REGIME(14), REG (14)
        COMMON/NAME/I,Y,IJK
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
        COMMON/DATA5/FORCE
        COMMON/DATA6/ADES4,VAMAX,ACAL4,C4
        COMMON CHOICE
```

```
      DIMENSION Y(14)
      REAL OP4

      WRITE(1, 820)
 820  FORMAT(20X,'RELIEF VALVE SIZE FOR AIR CONDITION')
      WRITE(1, 830)
 830  FORMAT(1H ,76(1H*))
      WRITE (1, 835)CHOICE
 835  FORMAT (3X,'BASIS OF SELECTION:', T65, A)
      WRITE(1, 840)VA
 840  FORMAT(3X,'REQUIRED AIR FLOWRATE, S.ft^3/min:',T65,F12.0)
      WRITE(1, 850) T4
 850  FORMAT(3X,'AIR TEMPERATURE, DEG. F:',T65,F9.3)
      WRITE(1, 860) SP4
 860  FORMAT(3X,'VALVE SET PRESSURE, psig:',T65,F9.3)
      WRITE(1, 870) OP4
 870  FORMAT(3X,'PERCENTAGE OF OVERPRESSURE, (%):',T65,F9.3)
      WRITE(1, 880) C4
 880  FORMAT(3X,'GAS CONSTANT DETERMINED BY RATIO OF Cp/Cv:',T65,F9.3)
      WRITE(1, 890) ACAL4
 890  FORMAT(3X,'CALCULATED VALVE ORIFICE AREA, in^2:',T65,F9.3)
      WRITE(1, 900) ADES4
 900  FORMAT(3X,'NEAREST STANDARD AREA, in^2:', T65, F9.3)
      WRITE(1, 1000) REGIME (I)
 1000 FORMAT(3X,'NEAREST STANDARD ORIFICE SIZE:',T65,A)
      WRITE(1, 1100) ACOUNT(I)
 1100 FORMAT(3X,'PREFERRED VALVE BODY SIZE, (IN-OUT) inches:',T65,A14)
      WRITE(1, 1200) VAMAX
 1200 FORMAT(3X,'MAXIMUM AIR FLOWRATE WITH STD. ORIFICE, ft^3/min:',
     *       T65,F12.0)
      WRITE(1, 1300) FORCE
 1300 FORMAT(3X,'REACTION FORCE, lb:',T65,F12.0)

      WRITE (1, 1400)
 1400 FORMAT (76(1H-))

C     FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

      WRITE (1, *)CHAR(12)

      RETURN
      END

C     ****************************************************************
C     THIS PROGRAM SIZES THE RELIEF VALVE FOR FIRE CONDITION
C     ****************************************************************
      SUBROUTINE FIRE (F, AREA, LAT, SP5, OP5, T5, Z5, MW5, N5)
      REAL LAT,OP5,MW5,N5
      CHARACTER COUNT(14),REGIME(14), REG (14)
      CHARACTER*14 COUNT1(14),COUNLL(14), ACOUNT(14)
      COMMON/NAME/I,Y,IJK
      COMMON/DATA1/WGMAX,ADES1,ACAL1,C1
      COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL,REG, ACOUNT
      COMMON/DATA5/FORCE
      COMMON/DATA7/Q,WF
      DIMENSION Y(14)

C     CALCULATE THE TOTAL HEAT ABSORBED

      Q=21000.0*F*(AREA)**0.82
```

```
C       CALCULATE THE VAPOR RATE

        WF=Q/LAT

C       CALCULATE THE ORIFICE AREA FOR FIRE CONDITION.

        CALL VAPOR (WF, SP5, OP5, T5, Z5, MW5, N5)
        RETURN
        END

C       **************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF FIRE RELIEF SIZING ONTO A
C       PRINTER
C       **************************************************************
        SUBROUTINE OUT5 (F, AREA, LAT, SP5, OP5, T5, Z5, MW5, N5)
        CHARACTER COUNT(14),REGIME(14), REG(14)
        CHARACTER*14 COUNT1(14),COUNLL(14), ACOUNT(14)
        CHARACTER*10 CHOICE
        COMMON/NAME/I,Y,IJK
        COMMON/DATA1/WGMAX,ADES1,ACAL1,C1
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL,REG,ACOUNT
        COMMON/DATA5/FORCE
        COMMON/DATA7/Q,WF
        COMMON CHOICE
        DIMENSION Y(14)
        REAL LAT,OP5,MW5,N5
C
        WRITE(1, 1500)
 1500   FORMAT(20X,'FIRE RELIEF VALVE SIZING')
        WRITE(1, 1600)
 1600   FORMAT(1H ,76(1H*))
        WRITE (1, 1650)CHOICE
 1650   FORMAT (3X,'BASIS OF SELECTION:', T65, A)
        WRITE(1, 1700) F
 1700   FORMAT(3X,'ENVIRONMENTAL FACTOR:',T65,F9.3)
        WRITE(1, 1800) AREA
 1800   FORMAT(3X,'WETTED SURFACE AREA OF VESSEL, ft^2:',T65,F9.3)
        WRITE(1, 1900) LAT
 1900   FORMAT(3X,'LATENT HEAT OF VAPORIZATION, Btu/lb:',T65,F9.3)
        WRITE(1, 2000) SP5
 2000   FORMAT(3X,'VALVE SET PRESSURE, psig:',T65,F9.3)
        WRITE(1, 2100) OP5
 2100   FORMAT(3X,'PERCENTAGE OF OVERPRESSURE, (%):',T65,F9.3)
        WRITE(1, 2200) T5
 2200   FORMAT(3X,'FLUID TEMPERATURE, DEG. F:',T65,F9.3)
        WRITE(1, 2300) Z5
 2300   FORMAT(3X,'FLUID COMPRESSIBILITY FACTOR:',T65,F9.3)
        WRITE(1, 2400) MW5
 2400   FORMAT(3X,'FLUID MOLECULAR WEIGHT:',T65,F9.3)
        WRITE(1, 2500) N5
 2500   FORMAT(3X,'RATIO OF SPECIFIC HEATS OF FLUID:',T65,F9.3)
        WRITE(1, 2600) C1
 2600   FORMAT(3X,'GAS CONSTANT DETERMINED BY RATIO OF Cp/Cv:',T65,F9.3)
        WRITE(1, 2700) WF
 2700   FORMAT(3X,'VAPOR RELIEF FLOW RATE, lb/h.:',T65,F12.0)
        WRITE(1, 2800) ACAL1
 2800   FORMAT(3X,'CALCULATED VALVE ORIFICE AREA, in^2:', T65,F9.3)
        WRITE(1, 2900) ADES1
 2900   FORMAT(3X,'NEAREST STANDARD ORIFICE AREA, in^2:', T65,F9.3)
```

```
        WRITE(1, 3000) REGIME(I)
 3000   FORMAT(3X,'NEAREST STANDARD ORIFICE SIZE:',T65,A)
        WRITE(1, 3100) COUNT1(I)
 3100   FORMAT(3X,'PREFERRED VALVE BODY SIZE, (IN-OUT) inches:',T65,A14)

        WRITE(1, 3200) WGMAX
 3200   FORMAT(3X,'MAXIMUM VAPOR FLOWRATE WITH STD. ORIFICE lb/hr.:',
     *         T65,F12.0)
        WRITE(1, 3300) FORCE
 3300   FORMAT(3X,'REACTION FORCE, lb:',T65,F12.0)

        WRITE (1, 3400)
 3400   FORMAT (76(1H-))

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

        WRITE (1, *)CHAR(12)

        RETURN
        STOP
        END

C       ***************************************************************
C       THIS PROGRAM STORES THE MANUFACTURERS' ORIFICE SIZES
C       ***************************************************************
        SUBROUTINE MANUF (ADES)
        CHARACTER COUNT(14),REGIME(14),REG(14)
        CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14)
        COMMON/NAME/I,Y, IJK
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL,REG, ACOUNT
        DIMENSION Y(14)
        DO 10 I=1,14
        IF (ADES .EQ. Y(I)) THEN
                REGIME(I)=COUNT(I)
                COUNLL(I)=COUNT1(I)
                GO TO 20
        ELSE
        ENDIF
 10     CONTINUE

 20     RETURN
        END
C
C       *************************************************************
C       THIS PROGRAM STORES THE MANUFACTURERS' ORIFICE SIZES
C       *************************************************************
        SUBROUTINE AMANU (ADES3)
        CHARACTER COUNT(14),REGIME(14),REG(14),REG1(14)
        CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14),ACONT(14)
        COMMON/NAME/I,Y,IJK
        COMMON/DATA/REG1,ACONT
        COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
        DIMENSION Y(14)
        DO 10 I=1,14
            IF (ADES3 .EQ. Y(I)) THEN
            REG(I)=COUNT(I)
            ACOUNT(I)=COUNT1(I)
            ELSE
        ENDIF
 10     CONTINUE
```

```
      RETURN
      END
C     ***************************************************************
C     THIS PROGRAM STORES THE MANUFACTURERS' ORIFICE SIZES
C     ***************************************************************
      SUBROUTINE MANUFL (ADES3, ADES31)
      CHARACTER COUNT(14),REGIME(14),REG(14)
      CHARACTER*14 COUNT1(14),ACOUNT(14),COUNLL(14)
      COMMON/NAME/I,Y,IJK
      COMMON/DATA4/COUNT,REGIME,COUNT1,COUNLL, REG, ACOUNT
      DIMENSION Y(14)
      DO 10 I=1, 14
          IF (ADES3 .EQ. Y(I)) THEN
          REG(I)=COUNT(I)
          ACOUNT(I)=COUNT1(I)
          ELSE
      ENDIF
 10   CONTINUE

      DO 20 I=1,14
          IF (ADES31 .EQ. Y(I)) THEN
          REGIME(I)=COUNT(I)
          COUNLL(I)=COUNT1(I)
          GO TO 30
          ELSE
      ENDIF
 20   CONTINUE
 30   RETURN
      END

C     ***************************************************************
C     THIS PROGRAM DETERMINES THE REACTION FORCES IN AN
C     OPEN DISCHARGE SYSTEM
C     ***************************************************************
      SUBROUTINE REACTF (WG, N, T, MW)
      REAL N,MW
      COMMON/DATA5/FORCE
      VAL1=(N*T)/((N+1.0)*MW)
      FORCE=(WG*SQRT(VAL1))/366.0
      RETURN
      END
C     ***************************************************************
      BLOCK DATA
      REAL Y(14)
      COMMON/NAME/I,Y,IJK
      DATA Y(1)/0.11/,Y(2)/0.196/,Y(3)/0.307/,Y(4)/0.503/
      DATA Y(5)/0.785/,Y(6)/1.287/,Y(7)/1.838/,Y(8)/2.853/
      DATA Y(9)/3.60/,Y(10)/4.34/,Y(11)/6.38/,Y(12)/11.05/
      DATA Y(13)/16.00/,Y(14)/26.00/
      END
```

CHAPTER 6

Compressors

INTRODUCTION

Compressors are gas movers and devices where mechanical work is done on the gas resulting in an increased pressure. Centrifugal compressors are used in a variety of chemical process industries (CPI). Their performance often varies with changes in process conditions. Sometimes the performance curves supplied by the manufacturer as discharge pressure and power requirement against an inlet volumetric flow may not be valid for variations in process conditions. Lapina [1] has provided a technique of obtaining a usable performance curve that is valid for the actual process conditions. Gas compressor applications are employed in the following duties:

- refrigeration
- gas injection
- gas transmission
- gas lift
- wellhead separator boosting

There is no single type of compressor that can be adapted to a particular application. The operating conditions, space, and weight restrictions must be reviewed before the appropriate compressor is selected. In addition, the type of driver requires selection because its selection and process conditions are interrelated.

Compressors can be classified into two basic types: reciprocating and centrifugal. The reciprocating compressor is well suited for high pressures and low volume flow rates, while the centrifugal is preferred for lower pressures and high volume flow rates. A centrifugal compressor uses the relationship between the velocity and pressure to increase the gas pressure. The gas enters a rotating impeller at the eye. The vanes force the gas to the outside rim, and subsequently throw it away from the rim at a high velocity. The gas is flung into the surrounding diffuser and volute passageways with a large volume, resulting in a reduced velocity. The velocity energy is thus changed into pressure energy and subsequently increases the gas pressure.

CENTRIFUGAL COMPRESSORS

In a centrifugal compressor, at least half the driver power (e.g., an electric gas or a steam turbine or a gas engine) is changed into gas velocity energy. The increased velocity can be carried forward to the next impeller for further increase in the velocity. A centrifugal compressor uses the impeller to furnish rotational pressure, which squeezes the gas outward and closer together, resulting in some pressure increase. As the impeller is rotated faster, more energy is expended from the driver. Figure 6-1 shows the flow of gas in a centrifugal compressor. The amount of pressure a compressor impeller can develop depends on its speed and diameter. Increased velocity and pressure are required for high speed, large diameter impellers. The impeller metal will have the same centrifugal force as the gas flowing through it. Also the impeller metal can tear apart if the diameter is too large or the impeller turns too rapidly. Therefore, the pressure that is developed with a single impeller is

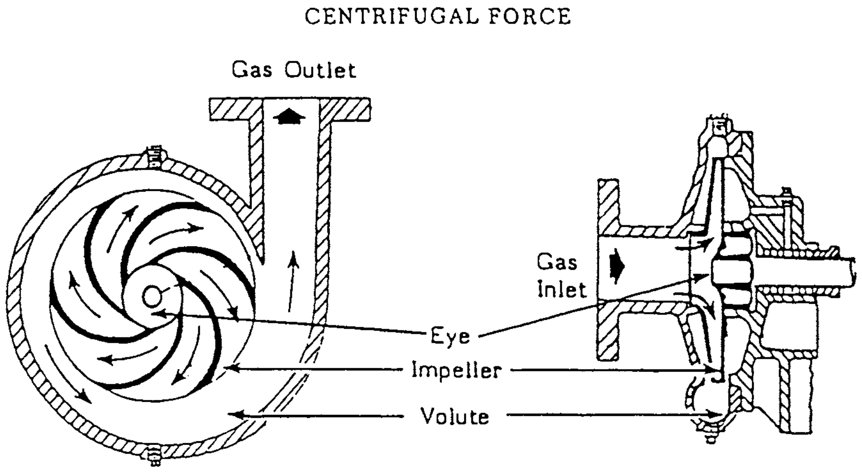

Figure 6-1. Gas flow in centrifugal compressor.

limited by the strength of the impeller metal. An additional impeller is used where one impeller is incapable of providing the required pressure. The gas leaving one rim enters the next stage eye of the impeller, consequently boosting its pressure.

RECIPROCATING COMPRESSORS

Reciprocating compressors are furnished as single stage or multistage with ratings from fractional to more than 20,000 horsepower per unit. The pressures range from a low vacuum at suction to 30,000 psi and higher at discharge. The number of stages depends on the overall compression ratio. The compression ratio per stage is limited by the discharge temperature and does not exceed four [2].

Multistage compressors are provided with intercoolers between stages and with an aftercooler at the compressor discharge. These are heat exchangers that remove the heat of compression from the gas and reduce its temperature to approximately the temperature existing at the compressor intake. In certain cases, aftercooling and interstage cooling are not always beneficial. If the gas must be heated before entering a reactor, downstream heaters can be designed for a lower duty if the heat of compression is not removed. Multistage compressors are intercooled when the inlet temperature of the gas and the required compression ratio are such that the discharge temperature of the gas exceeds 300°F. The coolers reduce the actual volume of gas flowing to the high pressure cylinders, the horsepower requirement, and keep the temperature within safe operating limits. In instances where a compressor with intercoolers is used to compress gases with condensable vapors, the combined effect of compression and cooling can condense out the liquid. Therefore, the liquid condensate must be removed by installing a knock-out pot after the intercooler. This will prevent damage to the downstream of the compressor.

THE EQUATIONS

Compressors are rated in feet of compression head developed. This is the energy conveyed to a gas stream by a compressor. It is observed by the increase in gas pressure as the gas passes through the compressor. Centrifugal compressors more nearly follow polytropic operation and are widely used to handle large volumes of gas at pressure ranges of 0.5 to several hundred psi.

There are two ways to carry out the thermodynamic calculations for compression, namely by assuming:

1. An adiabatic (isentropic) reversible path: A process during which there is no heat added or removed from the system. The entropy is constant.

That is

$$pV^k = \text{Constant} \tag{6-1}$$

2. A polytropic reversible path: A process in which changes in gas characteristics during compression are reviewed.

That is

$$pV^n = \text{Constant} \tag{6-2}$$

The constant temperature process is a case when n=1, which is equivalent to isothermal compression, the constant pressure process n = 0; and the constant volume process n = ∞. Generally, it is impractical to build sufficient heat transfer equipment into the design of most compressors to convey the bulk of the heat of compression. Therefore most machines tend to operate along a polytropic path that approaches the adiabatic. Most compressor calculations are based on the adiabatic curve [3].

Relationships may be developed between the temperature, pressure, and volume for a polytropic process between state 1 and state 2. The ideal gas law states that:

$$pV = RT \tag{6-3}$$

That is

$$p_1 V_1^n = p_2 V_2^n \tag{6-4}$$

$$p_1 = \frac{RT_1}{V_1}, \quad p_2 = \frac{RT_2}{V_2} \tag{6-5}$$

Rearranging p_1 and p_2 in Equation 6-5

$$\frac{p_1}{p_2} = \left(\frac{T_1}{T_2}\right)\left(\frac{V_2}{V_1}\right) \tag{6-6}$$

For a polytropic process between states 1 and 2,

$$\frac{p_1}{p_2} = \left(\frac{V_2}{V_1}\right)^n \tag{6-7}$$

Substituting Equation 6-6 into Equation 6-7

$$\left(\frac{T_1}{T_2}\right)\left(\frac{V_2}{V_1}\right) = \left(\frac{V_2}{V_1}\right)^n \tag{6-8}$$

Therefore

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1} \tag{6-9}$$

or

$$\frac{V_2}{V_1} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{n-1}} \tag{6-10}$$

Substituting Equation 6-10 into Equation 6-7

$$\frac{p_1}{p_2} = \left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}} \tag{6-11}$$

The compression work can be calculated from the pressure-volume relationship as follows:

$$W = \int_1^2 p dV \tag{6-12}$$

and

$pV^n = C$ for a polytropic process

$$W = \int_1^2 C \frac{dV}{V^n} \tag{6-13}$$

Integrating Equation 6-13

$$W = C\int_1^2 V^{-n} dv = \left[\frac{CV_2^{1-n} - CV_1^{1-n}}{1-n}\right] \tag{6-14}$$

$$C = p_2V_2^n = p_1V_1^n$$

Therefore Equation 6-14 can be expressed as

$$W = \left[\frac{p_2V_2 - p_1V_1}{1 - n}\right] \tag{6-15}$$

Using the ideal gas laws,

$$p_2V_2 = mRT_2$$

and

$$p_1V_1 = mRT_1$$

Equation 6-15 is given by

$$W = \frac{mR(T_2 - T_1)}{1 - n} \tag{6-16}$$

For the polytropic compression, work done is defined by

$$W = \frac{nR(T_2 - T_1)}{1 - n} \tag{6-17}$$

The polytropic compression work can be expressed as:

$$W = \frac{n}{n - 1}[p_1V_1 - p_2V_2] \tag{6-18}$$

Since the process from 1 to 2 is polytropic, then

$$p_1V_1^n = p_2V_2^n \tag{6-19}$$

and

$$\frac{V_2}{V_1} = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}} \tag{6-20}$$

From Equation 6-18

$$W = \frac{n}{n - 1}p_1V_1\left[1 - \frac{p_2V_2}{p_1V_1}\right] \tag{6-21}$$

and

$$\frac{p_2V_2}{p_1V_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \tag{6-22}$$

Substituting Equation 6-22 into Equation 6-21

$$W = \frac{n}{n-1} p_1V_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right] \tag{6-23}$$

where $R_c = p_2/p_1$ = compression ratio

Equation 6-23 is given by

$$W = \frac{n}{n-1} p_1V_1 \left[1 - R_c^{\frac{n-1}{n}}\right] \tag{6-24}$$

Polytropic Compressor

Real compression processes operate between adiabatic and isothermal compression. Actual compression processes are polytropic processes. This is because the gas being compressed is not at constant entropy as in the adiabatic process, or at constant temperature as in the isothermal processes. Generally, compressors have performance characteristics that are analogous to those of pumps. Their performance curves relate flow capacity to head. The head developed by a fluid between states 1 and 2 can be derived from the general thermodynamic equation.

$$H = \int_{p_1}^{p_2} \overline{V} dP \tag{6-25}$$

where H = head, ft of fluid
p = pressure, psi
$\overline{V}$ = specific volume of the fluid, ft^3/lb

For polytropic compression, the pressure-volume relationship is

$$pV^n = \text{constant}$$

or

$$V = \frac{C_1}{p^{\frac{1}{n}}} \tag{6-26}$$

where V = mole volume, ft^3/(lb mol)

For the polytropic head, H_p, V can be substituted in Equation 6-25. The polytropic head is defined by

$$H_p = \int_{p_1}^{p_2} \frac{C_1}{p^{\frac{1}{n}}} dP \tag{6-27}$$

Integrating Equation 6-27, H_p becomes

$$H_p = C_1\left(\frac{n}{n-1}\right)\left[p_2^{\frac{n-1}{n}} - p_1^{\frac{n-1}{n}}\right] \tag{6-28}$$

$$= C_1\left(\frac{n}{n-1}\right)p_1^{\left(\frac{n-1}{n}\right)}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] \tag{6-29}$$

where

$$p_1^{\frac{1}{n}}V_1 = p_2^{\frac{1}{n}}V_2 = C_1 \quad \text{and} \quad R_c = \frac{p_2}{p_1} \tag{6-30}$$

Substituting these into Equation 6-29, to eliminate C_1 gives

$$H_p = \left(\frac{n}{n-1}\right)p_1V_1\left[R_c^{\frac{n-1}{n}} - 1\right] \tag{6-31}$$

Using the gas law relationship

$$p_1V_1 = \frac{Z_1RT_1}{M_w} \tag{6-32}$$

where Z_1 = compressibility factor at suction
T_1 = absolute temperature at suction, °R
M_w = molecular weight, (lb/lb mol)
R = gas constant

Substituting Equation 6-32 into Equation 6-31, the polytropic head, H_p, becomes:

$$H_p = \frac{Z_1 R T_1}{M_w}\left(\frac{n}{n-1}\right)\left[R_c^{\frac{n-1}{n}} - 1\right] \tag{6-33}$$

If the compressibility factor, Z_2, for the gas at discharge conditions is significantly different from that of the suction, then the average compressibility factor, Z_{avg}, is used to calculate the polytropic head.

$$Z_{avg} = \frac{Z_1 + Z_2}{2} \tag{6-34}$$

The polytropic head is defined by

$$H_p = \frac{Z_{avg} R T_1}{M_w}\left(\frac{n}{n-1}\right)\left[R_c^{\frac{n-1}{n}} - 1\right] \tag{6-35}$$

This can also be expressed as:

$$H_p = \left(\frac{1545.Z_{avg}.T_1}{M_w}\right)\left(\frac{n}{n-1}\right)\left[R_c^{\frac{n-1}{n}} - 1\right] \tag{6-36}$$

The discharge temperature, °F, is given by

$$t_2 = \frac{(H_p)(M_w)}{(Z_{avg}.R)}\left(\frac{n-1}{n}\right) + t_1 \tag{6-37}$$

There is a limit on the temperature as in the olefin or butadiene plants to prevent polymerization. At temperatures greater than 450 – 500°F, the approximate mechanical limit, problems of sealing and casing growth could occur. High temperature requires a special, high machine cost. Therefore, multistage compressors are designed within the temperature range of 250°F – 300°F. In addition, a single-stage polytropic compressor can handle 7,000 to 11,000 feet of liquid, depending on the gas properties and inlet temperature [4].

The gas horsepower is expressed as

$$Gh_p = \frac{w.H_p}{1.98 \times 10^6.E_p} \tag{6-38}$$

The polytropic efficiency is used to compare adiabatic with polytropic performance. This is defined by

$$\frac{n}{n-1} = \left(\frac{k}{k-1}\right). E_p \tag{6-39}$$

Figure 6-2 shows the relationship between the polytropic efficiency and adiabatic (isentropic) efficiency of a perfect gas.

Adiabatic Compressor

The performance of reciprocating (piston) compressors with large valve area, or where valve losses are evaluated, is considered as close to

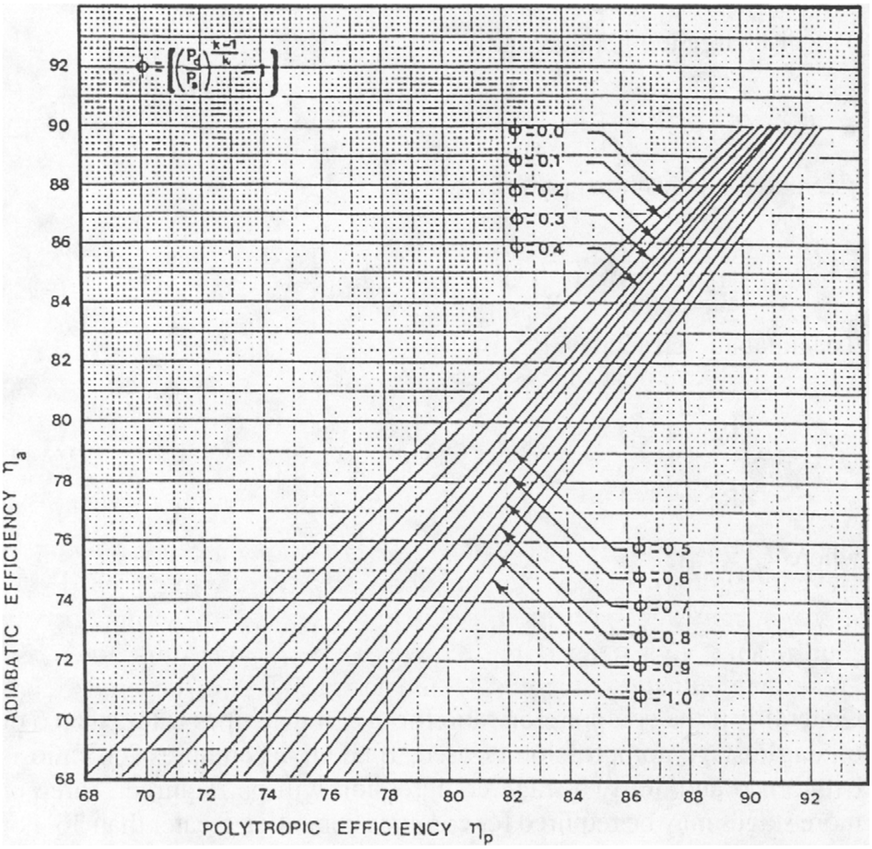

Figure 6-2. The relationship between the polytropic efficiency and the adiabatic efficiency for a perfect gas (Z = 1). (Source: A. K. Escoe, *Mechanical Design of Process Systems*, Volume 2, Gulf Publishing Company.)

adiabatic behavior as can be measured. The thermodynamic definition of an adiabatic process requires that no heat be added or removed from a system in which a change of state occurs. The adiabatic head produces the following equation, which is similar to the polytropic head of Equation 6-33. This is expressed as:

$$H_{ad} = \left(\frac{Z_{avg}.R.T}{M_w}\right)\left(\frac{k}{k-1}\right)\left[R_c^{\frac{k-1}{k}} - 1\right] \quad (6\text{-}40)$$

This can also be given by

$$H_{ad} = \left(\frac{1545.Z_{avg}.T_1}{M_w}\right)\left(\frac{k}{k-1}\right)\left[R_c^{\frac{k-1}{k}} - 1\right] \quad (6\text{-}41)$$

The discharge temperature is:

$$T_2 = T_1.R_c^{\left(\frac{k-1}{k}\right)} \quad (6\text{-}42)$$

The adiabatic gas horsepower is:

$$Gh_p = \frac{w.H_{ad}}{1.98 \times 10^6.E_{ad}} \quad (6\text{-}43)$$

The adiabatic efficiency, E_{ad}, is:

$$E_{ad} = \frac{R_c^{\left(\frac{k-1}{k}\right)} - 1}{R_c^{\left(\frac{n-1}{n}\right)} - 1} \quad (6\text{-}44)$$

where

$$k = \frac{M_w C_p}{M_w C_p - 1.986} \quad (6\text{-}45)$$

Generally, if the compression ratio for piston machines is less than 5 or 6, single-stage compression is used. If the total compression ratio is between 6 and 36, two-stage compression will be required. Three or more stages may be required for compression ratios greater than 36. For two-stage compression, calculate the square root of the total compression ratio. Then assume that the compression ratio per stage will be equal to the square root of the total compression [2].

Mechanical Losses

After the gas horsepower is calculated by either the polytropic or adiabatic compression method, horsepower losses due to friction in bearings, seal, and speed increasing gears should be added. Although, there is no accurate method in estimating mechanical losses from gas power requirements, Table 6-1 gives approximate mechanical losses as a percentage of the gas power requirement [5].

The mechanical losses can be calculated by

$$\text{Mechanical losses} = (\text{Gh}_p)(\%\ \text{mechanical losses}) \tag{6-46}$$

The brake horsepower is:

$$\text{Bh}_p = \text{Gh}_p + \text{mechanical losses} \tag{6-47}$$

The volumetric flow rate at suction or inlet condition can be expressed as:

$$Q_s = (\text{ICFM}) = \left[\frac{(\text{MMSCFD}) \times 10^6}{60 \times 24}\right]\left[\frac{14.7}{P_s}\right]\left[\frac{T_s}{520}\right] \times \left[\frac{Z_s}{1.0}\right] \quad \text{ft}^3/\text{min} \tag{6-48}$$

The actual mass flow rate is

$$G = Q_s\left[\frac{P_s \,.\, M_w}{1545 Z_s T_s}\right] \quad \text{lb/min} \tag{6-49}$$

Table 6-1
Approximate Mechanical Losses as a Percentage of a Gas Power Requirement

Gas Power Requirement English (hp)	Metric (kW)	Mechanical Losses %
0–3,000	0–2,500	3
3,000–6,000	2,500–5,000	2.5
6,000–10,000	5,000–7,500	2
10,000+	7,500+	1.5

The accuracy of the developed polytropic head and efficiency curve may be reduced due to volume ratio effects. These effects are the influences that the performance of one impeller has on those of the impellers downstream. Lapina [1] stated these effects are greater as the number of impellers within a compression section increases. He proposed some guidelines to assess the volume-ratio effects for differences in the inlet conditions. An equation to calculate the value of θ for both the old or reference inlet conditions and the proposed new inlet conditions is given by

$$\theta = \left[\frac{(26.1)(M_w)}{K.Z.T}\right]^{0.5} \tag{6-50}$$

MULTICOMPONENT GAS STREAMS

The design of a gas compressor for a gas mixture involves estimating the thermodynamic properties. The procedure for calculating the properties of a gas mixture is to use the weighted molal average of the property. These thermodynamic properties are estimated as follows:

Molecular weight $$M_{w,mixture} = \sum_{i=1}^{n} y_i M_i \tag{6-51}$$

Reduced temperature $$T_{r,mixture} = \sum_{i=1}^{n} y_i T_{r,i} \tag{6-52}$$

Reduced pressure $$P_{r,mixture} = \sum_{i=1}^{n} y_i P_{r,i} \tag{6-53}$$

Molal heat capacity $$MC_{p,mixture} = \sum_{i=1}^{n} y_i MC_{p,i} \tag{6-54}$$

Ratio of molal heat capacities $$k_{mixture} = \frac{MC_{p,mixture}}{MC_{v,mixture}} = \frac{MC_{p,mixture}}{(MC_{p,mixture} - 1.986)} \tag{6-55}$$

Compressibility factor $Z_{mixture} = f(T_r, P_r)$ for the mixture (6-56)

where y_i = mole fraction of component i.

Table 6-2 summarizes the differences between reciprocating and centrifugal compressors.

Surge Control of Compressors

All dynamic compressors have a limited range of capacity for a given selection of impellers at a fixed speed. Below the minimum value of 50 to 70% of the rated flow, the compressor will surge, that is, it will become unstable in operation. Excessive vibration and possibly sudden failure or shutdown may arise.

It is essential that all compressor systems be designed to avoid possible surge operation. This is done by incorporating some type of antisurge control system. This is to ensure that the flow into the compressor is sufficient to maintain stability at the required pressure drop across the compressor. The surge control system should be used only for surge control and must not be linked with other functions of the process control system; otherwise, this could result in the damage of the compressor.

Table 6-2
Comparison of Reciprocating and Centrifugal Compressors

Centrifugal Compressors	Reciprocating Compressors
1. Lower installed first cost where pressure and volume conditions are favorable.	1. Greater flexibility in capacity and pressure range.
2. Lower maintenance cost.	2. High compressor efficiency and lower power cost.
3. Greater continuity of service and dependability.	3. Capability of delivering higher pressure.
4. Less operating attention.	4. Capability of handling smaller volumes.
5. Greater volume capacity per unit of plot area.	5. Less sensitive to changes in gas composition and density.
6. Adaptability to high speed low maintenance cost drivers.	

Another surge control may be a blow off valve. This is automatically controlled to open or blow off excess capacity to the atmosphere if the process flow requirement is too low. In some cases, suction control valves are used. For gases that cannot be designed to atmosphere, a bypass control is the common antisurge control. This action bypasses unwanted flow back to the suction source. However, because the gas has already been compressed, its temperature is increased, and must therefore be cooled before entering the compressor a second time. In this case, a bypass cooler may be installed. The cooler may be avoided where the suction source is large or far away and the heat is dissipated by mixing or radiation. Figure 6-2A shows generalized flow characteristics of a compressor. In this figure, as the system resistance decreases, the compressor-system operating point moves to the right with a corresponding increase in the volumetric gas flow. However, the gas flow through the compressor cannot increase without a limit. This limit is known as "stonewall," and is caused by the choking of the gas as it exits from the compressor. These two operating limits are shown in Figure 6-2A. The designer should ensure that the system compressor curve-intersection point is well away from the surge or stonewall for efficient operation.

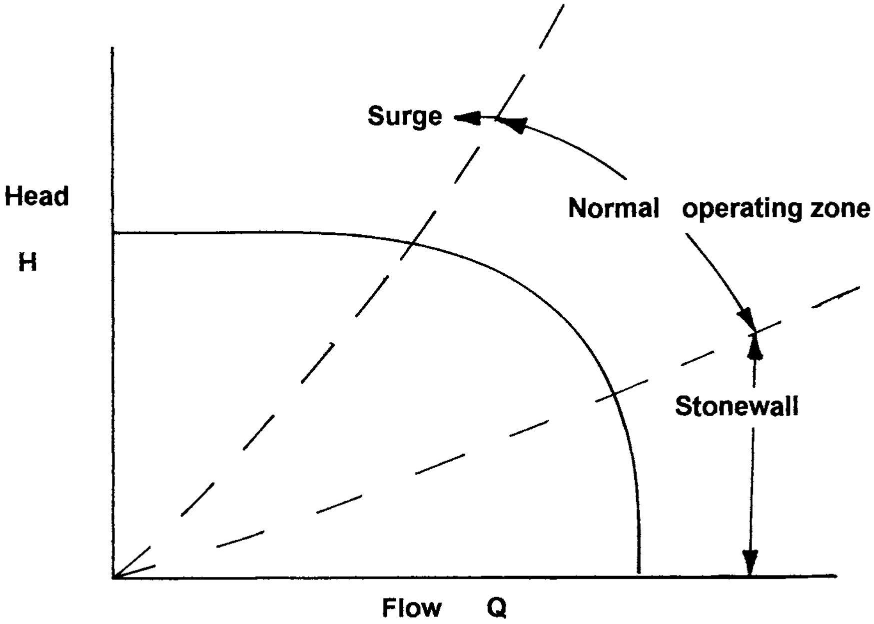

Figure 6-2A. Generalized flow characteristics of a compressor.

Treatment of Compressor Fluids

The discharge from any compressor is a dirty corrosive liquid. Removing the sludge from a compressor air system can effect the following:

- reduce installation costs incurred or drain traps, pipe and fittings, filters and regulators.
- reduce the maintenance of drain trap and the failure rate of pneumatic equipment, which is caused by dirt and moisture in the supply line.
- increase the life of pneumatic equipment.

Cases of high performance equipment require high quality of clean and dry compressed air. Compressed air contains water, oil, and dirty particles, which affects the performance of pneumatic equipment. Compressed air dryers are used to remove water vapor and to dry the air. Two main types of dryers are used in the CPI: refrigerant and desiccant dryers. Desiccant dryers use an adsorbent material, such as activated alumina, or molecular sieves to remove moisture from the compressed air. Also, desiccant dryers can be either heat regenerated or heatless. The main advantage of desiccant dryers is their ability to cool the air to a very low temperature. They are more expensive in terms of both capital and running costs. They are important when higher quality air is required. These dryers are widely used in offshore oil industry, where extreme ambient conditions are required. The design of desiccant dryers for removing water vapor from a natural gas is explained in Chapter Four.

Nomenclature

Bh_p = brake or shaft horsepower, bhp
C = constant
C_p = specific heat at constant pressure, Btu/lb°F
C_v = specific heat at constant volume, Btu/lb°F
D = impeller diameter or rotor, ft
D_s = specific diameter, ft
E_{ad} = adiabatic efficiency
E_p = polytropic efficiency (try 0.75 for preliminary work)
G = gas flowrate, lb/min
Gh_p = gas horsepower, actual compression horsepower, excluding mechanical losses, hp
H = head, $(ft. lb_f)/lb_m$

H_{ad} = adiabatic head, (ft lb_f)/lb_m
H_p = polytropic head, (ft lb_f)/lb_m
ICFM = volume flow referred to inlet condition, ft^3/min
k = adiabatic (isentropic) exponent, C_p/C_v
MC_p = molar specific heat at constant pressure, Btu/(lb mol°F)
MC_v = molar specific heat at constant volume, Btu/(lb mol°F)
M_w = molecular weight
MMSCFD = million standard cubic feet per 24-hour day
N = speed, rpm
N_s = specific speed, rpm
n = polytropic exponent
P = absolute pressure, psia
P_1 = suction pressure, psia
P_2 = discharge pressure, psia
P_s = suction pressure, psia
Q = volume flow, ft^3/s
Q_s= volume flow, ft^3/min
R = universal gas constant
= 10.73(psia ft^3/lb mole °R)
= 1545[(lb ft^2) ft^3/lb mole °R] or ft lb/lb mole °R
= 1.986(Btu/lb mole °R
R_c = compression ratio, P_2/P_1
T_1 = suction temperature, °R
T_2 = discharge temperature, °R
T_s = suction temperature, °R
t_1 = inlet temperature, °F
t_2 = discharge temperature, °F
W = workdone, Btu/lb–mole
w = gas flow, lb/h
Z_{avg} = average compressibility factor for gas from suction to discharge conditions. A value of 1.0 will give conservative results.

CENTRIFUGAL PUMP HYDRAULICS

Introduction

Selecting the correct pump requires a knowledge of the system in which the pump must operate. In the chemical process industries (CPI), the engineer should start from the process flow sheets and schematics such as piping and instrument diagrams. The engineer must determine the optimum height and co-ordinate pump requirements, where pumps take suction from vessels or drums with the height above the pump. Where friction loss through piping forms a significant part of the total head, the designer should influence the selection of the allowable pressure drop (ΔP). In addition, volatile liquids, hot liquids, viscous liquids, and slurries will require a special approach and selection methods. If the pump is installed in a sump or a pit, essential factors require the correct sizing of the pit. These involve the flow requirements as the liquid flows toward the pump, and the positioning of the pump in the pit with sufficient baffles and spacing. Pump selection and troubleshooting are illustrated by Garay [6], McGuire [7], McNaughton [8], and have appeared in the literature [9,10,11].

This chapter considers the design of centrifugal pumps for given flow rates and physical properties.

Hydraulics of the System

The required factors in pump hydraulics are:

Density. The weight per unit volume of a substance, sometimes called specific weight. The density of water is 62.3 pounds per cubic foot.

Specific Gravity (SpGr). The ratio of the density or specific weight of a substance to that of some standard substance. For liquids, the standard is water usually at 60°F. In the petrochemical industry, API gravity use is 10° API. This corresponds to a specific gravity of 1.0.

$$\text{SpGr(relative to water at } 60^\circ\text{ F)} = \frac{141.5}{131.5 + ^\circ\text{ API}} \tag{6-57}$$

In the chemical industry, degrees Baume´ are commonly used. For liquids lighter than water,

$$\text{SpGr} = \frac{141.5}{130 + \text{ degrees Baume}'} \tag{6-58}$$

For liquids heavier than water,

$$\text{SpGr} = \frac{145}{145 - \text{ degrees Baume}'} \tag{6-59}$$

Pressure. The force exerted per unit area of a fluid, often designated as pounds per square inch (psi).

Barometric Pressure. The atmospheric pressure at the pump location. It changes with the weather conditions.

Gauge Pressure (psig). The gauge pressure is the pressure above atmospheric (or below in a vacuum).

Atmospheric Pressure (psi). The force exerted on a unit area by the weight of the atmosphere. The pressure at sea level due to the atmosphere is 14.7 psi.

Absolute Pressure (psia). The sum of atmospheric and gauge pressures. Absolute pressure in a perfect vacuum is 0, and at the atmosphere at sea level is 14.7 psi (0 psig).

1 atmosphere (bar) = 14.7 psi = 34 ft of water
conversion factor = 34/14.7 = 2.31

$$\text{psi} = \frac{\text{head in feet} \times \text{SpGr}}{2.31} \tag{6-60}$$

Vapor Pressure. The pressure at which a liquid at a specified temperature is in equilibrium with the atmosphere or with its vapor in a closed system. At pressures below the vapor pressure at a given temperature, the liquid will start to vaporize. This is due to a reduced pressure at the surface of the liquid.

Head. The height of a fluid column, measured in feet, to ascertain the gauge pressure at the bottom of the column.

$$\text{Head, ft} = \frac{2.31(\text{pressure, psi})}{(\text{SpGr})} \tag{6-61}$$

Friction Head. The pressure to overcome the resistance to the flow in the pipe and fittings. It is expressed as lbs/sq. in. or feet of liquid.

Static Head. Fluid elevation above or below the datum line. For horizontal centrifugal pumps, static head is calculated from the pump center line; with vertical pumps, it is taken from the eye of the first-stage impeller.

Velocity Head. The kinetic energy of a flowing fluid. It is defined by

$$k = \frac{V^2}{2g} \tag{6-62}$$

Suction Lift. The manometer reading in feet of liquid at the pump suction (corrected to a datum), minus the velocity head. This term expresses the suction head when it is below atmospheric pressure.

Static Suction Lift. The vertical distance from the center line of the pump down to the free level of the liquid source.

Net or Dynamic Suction Lift. Static suction lift, friction head, and velocity head.

Suction Head. Occurs when the source of supply is above the center line of the liquid.

Static Discharge Head. The vertical elevation from the center line of the pump to the point of free discharge.

Dynamic Discharge Head. The static discharge head plus dynamic suction lift or minus dynamic suction head.

Total Discharge Head. The pressure reading at the pump discharge in feet of liquid, corrected to a datum, plus the velocity head.

Total Head. The algebraic difference between the discharge and suction heads. A suction lift is added to the total discharge head; a positive suction head is subtracted from the discharge head.

Head Losses. The frictional head losses caused by fluid flow through pipes, fittings, valves, and nozzles.

NPSH. The net positive suction head is the most critical factor in a pumping system. A sufficient NPSH is essential, whether working with centrifugal, rotary, or reciprocating pumps. Marginal or inadequate NPSH will cause cavitation, which is the formation and rapid collapse of vapor bubbles in a fluid system. Collapsing bubbles place an extra load on pump parts and can remove a considerable amount of metal from impeller vanes. Cavitation often takes place before the symptoms become evident. Factors that indicate cavitation are increased noise, loss of discharge head, and reduced fluid flow.

Pump Hydraulics Calculations

Pump sizing computation requires the following information on the process flow diagram or a pump calculation sheet: service, size and type, fluid, pump temperature, density at pump temperature, design capacity in gpm at pump temperature, suction head, discharge head, design differential, NPSH (net positive suction head) and power requirements.

Calculating the suction condition of a pump comprises the following:

1. vessel pressure (original pressure).
2. add the suction head or minus for a suction lift, S.Hd.
3. minus the line pressure drop, L loss.

That is

$$\text{Suction pressure} = \text{orig. pres.} + \text{S.Hd.} - \text{L. loss} \tag{6-63}$$

The discharge condition of a pump considers the following:

1. delivery pressure
2. static head
3. control valve pressure drop
4. exchanger pressure drop
5. orifice pressure drop
6. furnace pressure drop
7. line pressure drop
8. other pressure drop

$$\text{The NPSH} = (\text{orig. pres.} - \text{vapor pres.}) + \text{S.Hd} - \text{L. loss, ft} \tag{6-64}$$

The net head at the suction of the pump impeller must not exceed a certain value to prevent formation of vapor and cause cavitation of the metal. This minimum head is called the available $NPSH_a$, and must be greater than the required $NPSH_r$ for a stable pump operation.

$$\begin{aligned}\text{Pump discharge pres.} = {} & \text{del. pres.} + \text{Shd.}\\ & + \Delta P\ \text{Cont. v.} + \Delta P\ \text{exch.}\\ & + \Delta P\ \text{orif.} + \Delta P\ \text{furn.}\\ & + \Delta P\ \text{line} + \Delta P\ \text{Other.}\end{aligned} \tag{6-65}$$

$$\text{Total pump } \Delta P = \text{pump discharge pres.} - \text{pump suction pres.} \tag{6-66}$$

$$\text{Bhp (brake horsepower)} = \frac{(\text{flow rate, gpm})(\text{pump } \Delta P\text{, psi})}{(1715)(\text{EFF})} \tag{6-67}$$

$$\text{Bhp} = \frac{(\text{gpm})(\text{H})(\text{SpGr})}{(3960)(\text{EFF})} \tag{6-68}$$

where H = total discharge head

Table 6-3 shows a pump hydraulic design calculation data sheet.

Centrifugal Pump Efficiency

The design engineer must use the expected pump efficiency provided in the pump performance curve to evaluate the required brake horsepower for a centrifugal pump. In the early stages of the design, it is customary to estimate a value for the efficiency. Final values depend on the specified pump and the operating conditions that are encountered. Branan [4] has developed an equation to calculate the centrifugal pump efficiency and pump horsepower. The equation was based on pump efficiency curves of the NGPSA Engineering Data Book. These efficiency

Table 6-3
Pump Hydraulic Design Calculation Sheet

Fluid		Gas Oil	
Viscosity at Pumping temperature (P.T), cP		0.6	
Vapor Pressure at pumping temperature (P.T), psia		0.01	
Specific gravity, (SpGr) at P.T.		1.04	
Density at P.T., lb/ft^3		64.87	
Operating flow at P.T., gpm		250.0	
Design Flow at P.T., gpm		250.0	
Suction		**Discharge**	
Vessel pressure, Orig. Pres., psia	27.7	Delivery pressure, psia.	28.2
Static head S.Hd., psi	5.4	Static head S.Hd., psi	14.86
– Line loss ΔPf, psi.	0.23	ΔP Control valve, psi	10.0
Suction pres. = Orig. pres. + S.Hd. – L. line	32.78	ΔP Exchanger, psi	5.0
NPSH = (orig. pres. – vapor pres.) + S.Hd. – L.loss, psia.	32.77	ΔP Orifice, psi	2.0
		ΔP Furnace , psi	
		Line loss ΔP psi	4.38
		Other ΔP, contigency, psi	

curves give good results with the vendor data (the range of developed heads, 50ft to 300ft, and the flow rates, 100 to 1000 gpm). The equation for calculating the pump efficiency is expressed as:

$$\begin{aligned} \mathrm{EFF} = (&80 - 0.2855H + 3.78 \times 10^{-4} HQ \\ &- 2.38 \times 10^{-7} HQ^2 + 5.39 \times 10^{-4} H^2 \\ &- 6.39 \times 10^{-7} H^2Q + 4 \times 10^{-10} H^2Q^2)(1/100) \end{aligned} \qquad (6\text{-}69)$$

The actual brake horsepower required for pump operation Bhp is:

$$\mathrm{Bhp} = \frac{\mathrm{HBhp}}{\mathrm{EFF}} \qquad (6\text{-}70)$$

where EFF = pump efficiency (decimal fraction)
H = developed pump head, ft
Q = flow rate through pump, gpm
HBhp = hydraulic brake horsepower, hp
Bhp = actual brake horsepower required for pump operation, hp

Using Equation 6-69, Figure 6-3 shows typical characteristic curves for a 6-inch centrifugal pump operating at 1750 rpm. Equation 6-69 gives

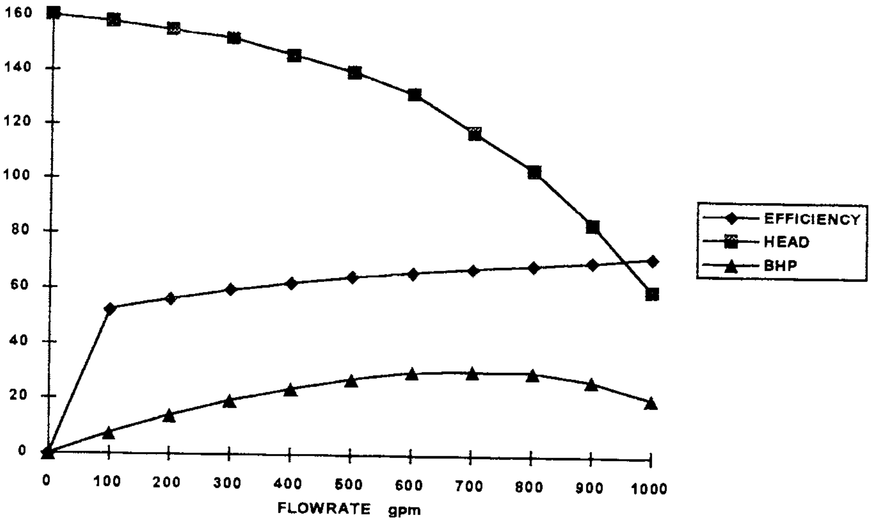

Figure 6-3. Typical characteristic curves for a 6-inch centrifugal pump operating at 1750 rpm.

results within 7% of the actual pump curves for the range of applicability (H = 50 to 300 ft, Q = 100 to 1000 gpm). For flows in the range of 25 to 99 gpm, an approximate efficiency can be obtained by solving Equation 6-69 for 100 gpm and then subtracting 0.35% gpm times the difference between 100 gpm and the low flow rate in gpm. For low flow rates, near 25–30 gpm, this will give results within about 15% for the middle of the head range (pump ΔP) and 25% at the extremes. The horsepower at the 25–30 gpm level is normally below 10 [4].

AFFINITY LAWS

The affinity laws express the mathematical relationship between the variables involved in a pump's performance. By applying the principles of dimensional analysis on the physical properties affecting pump operation, the relationship is:

$$f\left\{\frac{Q}{(g_cH)^{0.5}D^2}, \frac{NQ^{0.5}}{(g_cH)^{0.75}}, \frac{\rho QD}{\mu D^2}\right\} = 0 \qquad (6\text{-}71)$$

where the dimensionless expressions are:

$$\pi_1 = \frac{Q}{(g_cH^{0.5})D^2} \qquad (6\text{-}72)$$

$$\pi_2 = \frac{NQ^{0.5}}{(g_cH)^{0.75}} \qquad (6\text{-}73)$$

$$\pi_3 = \frac{\rho QD}{\mu D^2} \qquad (6\text{-}74)$$

For true dynamic similarity, π_1, π_2, and π_3 must be constant for similar pumps or for the same pump at different speeds. π_3, which is the Reynolds number, cannot be maintained constant with changes in pump speed or size if the same liquid is pumped. Therefore, for practical application, the Reynolds number can be neglected when considering the conditions for dynamic similarity.

The conditions for dynamic similarity are constant values of π_1 and π_2. Equation 6-71 can be altered by appropriate mathematical operation to yield

$$f\left\{\frac{Q}{(g_cH)^{0.5}D^2}, \frac{ND}{(g_cH)^{0.5}}\right\} = 0 \qquad (6\text{-}75)$$

where

$$\pi_2' = \frac{ND}{(g_cH)^{0.5}} \qquad (6\text{-}76)$$

Therefore, for conditions of similarity of flow π_1, π_2, and π_2' are constant. Stepanoff [12] has shown that the velocity diagrams at the impeller are geometrically similar when the pumps are operating at the same efficiency for similar pumps or for the same pump at different speeds.

Applications of Affinity Laws

For the same pumps or geometrically similar pumps, $Q/(g_cH)^{0.5}D^2$, $NQ^{0.5}/(g_cH)^{0.75}$ and $ND/(g_cH)^{0.5}$ have unique values corresponding to each efficiency. In addition, these values remain constant despite the impeller diameter or pump speed. For the same pump operating at different speeds the impeller diameter, D, is constant.

That is

$$D = \text{constant}$$

Therefore at any given efficiency

Capacity:

$$\frac{Q}{(g_cH)^{0.5}D^2} \text{ and } \frac{ND}{(g_cH)^{0.5}} \text{ are constant}$$

or

$$\frac{Q}{(g_cH)^{0.5}D^2} \bigg/ \frac{ND}{(g_cH)^{0.5}} = \text{Constant} \qquad (6\text{-}77)$$

Therefore

$$\frac{Q}{ND^3} = \text{Constant} = K \qquad (6\text{-}78)$$

But D is constant

Therefore

$$Q = K'N \qquad (6\text{-}79)$$

where K′ and K are constants

Therefore

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \tag{6-80}$$

Head:

$$\frac{ND}{(g_c H)^{0.5}} = \text{Constant} = J \tag{6-81}$$

or

$$\frac{N^2 D^2}{H} = J' \tag{6-82}$$

where J and J′ are constants.

Therefore at a constant diameter

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2 \tag{6-83}$$

Break horsepower (Bhp)

Bhp α QH α N^3 at constant D

Therefore

$$\frac{Bhp_2}{Bhp_1} = \left(\frac{N_2}{N_1}\right)^3 \tag{6-84}$$

These laws apply only for efficiencies of the same value.

For geometrically similar pumps with different impeller diameters but same speeds:

From Equation 6-78

$$Q = KND^3 \tag{6-85}$$

At constant speed

$Q = K''D^3$ where K and K" are constants.

or

$$\frac{Q_2}{Q_1} = \left(\frac{D_2}{D_1}\right)^3 \tag{6-86}$$

Head:

At constant speed from Equation 6-82

$$\frac{H_2}{H_1} = \left(\frac{D_2}{D_1}\right)^2 \tag{6-87}$$

Brake horsepower (Bhp)

$$\frac{Bhp_2}{Bhp_1} = \left(\frac{D_2}{D_1}\right)^5 \tag{6-88}$$

Specific Speed

One dimensionless expression in the affinity laws is:

$$\frac{NQ^{0.5}}{(g_cH)^{0.75}} = \text{constant at a given efficiency}$$

It is often used by designers in sizing and selecting the type of pump or compressor. The performance of centrifugal pumps is related to a parameter called specific speed. It is a correlation of capacity, head, and speed at optimum efficiency that classifies pump impellers with respect to their geometric similarity. Specific speed is a number expressed algebraically as:

$$N_s = \frac{NQ^{0.5}}{H^{0.75}} \tag{6-89}$$

where N_s = specific speed of the pump
N = pump speed, rpm
Q = flow at optimum efficiency, gpm
H = head per impeller, ft

The specific speed of an impeller is the rotation in rpm. This is a geometrically similar impeller that would run if it were of such size as to discharge 1 gpm against a total head of 1 ft. Specific speed is used to determine the NPSH required by a given impeller. Those that produced high total dynamic head (TDH) have low specific speeds, and conversely, low TDH impellers have high specific speeds. At a particular head and capacity, a pump of low specific speed will operate safely at lower NPSH than one with a high specific speed. Designers should ensure that the capacity or TDH is increased when recommending speeding up an existing pump. This will enable that the new NPSH does not exceed what is available.

$$D_s = \frac{DH^{0.25}}{Q^{0.5}} \tag{6-90}$$

Figure 6-4 shows the dimensionless parameters as presented by Balje. The figure is the graphical combination of Equations 6-89 and 6-90.

Nomenclature

Bhp = brake or shaft horsepower, bhp
C = constant
D = impeller diameter or rotor, ft
del. pres. = pump delivery pressure, psia
D_s = specific diameter, ft
EFF = pump efficiency
gpm = fluid flow rate through pump
H = head, (ft lb)/lb
HBhp = hydraulic brake horsepower required by pump (pump efficiency = 1.0 for HBHP calculation)
L. loss = pressure drop due to piping, psi or ft
orig. pres. = vessel pressure on pump suction, psia
pump dish. pres. = pump discharge pressure, psia
Q = Volumetric flowrate, gpm
vap. pres. = vapor pressure of pumped fluid at pumping temperature, psia
suc. pres. = pump suction pressure, psia
S.Hd. = static head of liquid on pump suction or discharge, ft
total pump ΔP = pressure rise across pump, psi or ft

PROBLEMS AND SOLUTIONS

Problem 6.1

A centrifugal compressor is to be specified for a gas plant. The unit is to compress 18,000 lb_m/hr of gas mixture at 50 psia and 150°F to 200 psia. The gas mixture consists of 30% hydrogen (H_2), 45% methane (CH_4),

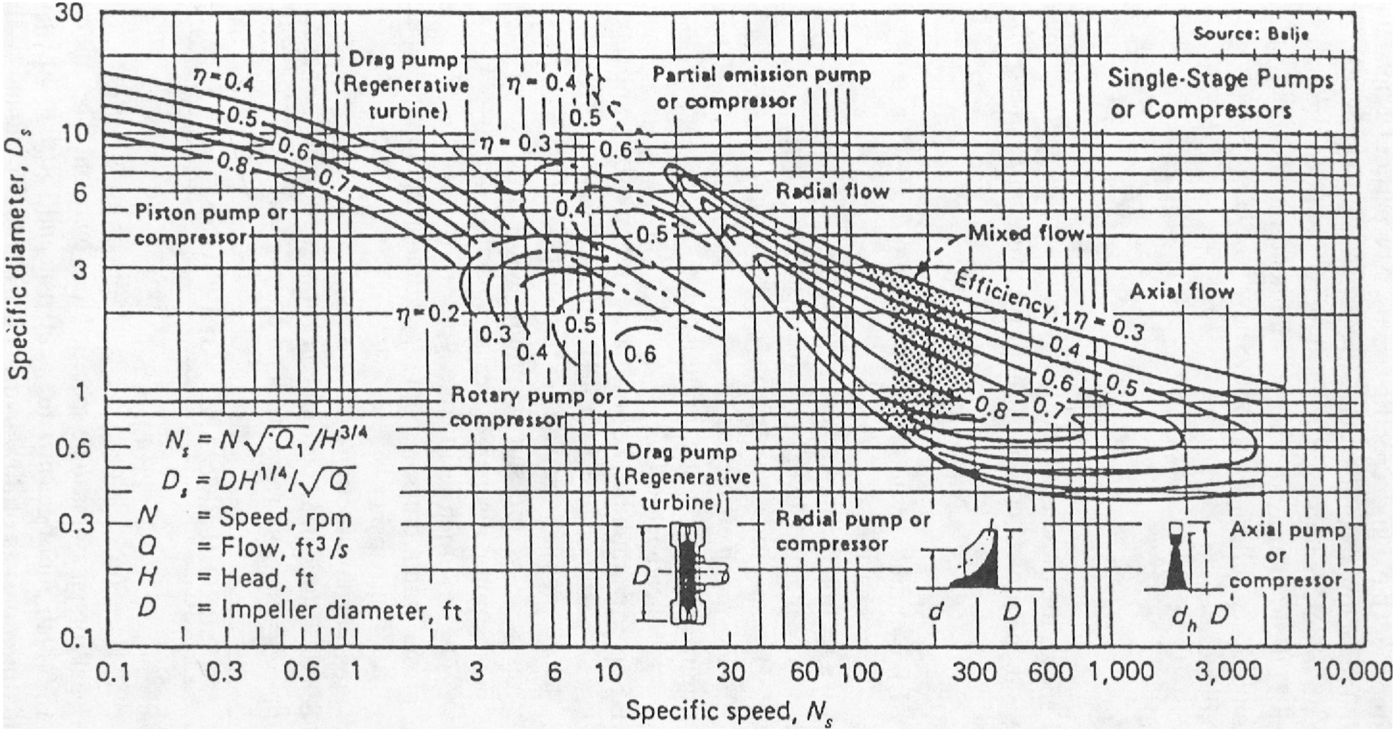

Figure 6-4. Specific speed and specific diameter enable the initial selection of a definite type of single-stage compressor. (O. E. Balje, "A Study on Design Criteria and Matching of Turbomachines: Part B", Transaction of the American Society of Mechanical Engineers, *Journal of Engineering Power*, Vol. 84, January 1962.)

15% ethane (C_2H_6), 7% propane (C_3H_8), and 3% n-butane ($n - C_4H_{10}$). Assuming a polytropic efficiency of 75%, and the average compressibility factor, $Z_{avg} = 0.95$, calculate the polytropic head, total break horsepower, and the discharge temperature. Table 6-4 gives the properties of the gas mixture.

The mixture specific heat ratio, k, is defined by

$$k = \frac{MC_p}{MC_v} = \frac{MC_p}{MC_p - 1.986}$$

$$k = \frac{10.317}{8.331}$$

$$k = 1.238$$

The average molecular weight, $M_w = 17.162$

Solution

The computer program PROG61 calculates the polytropic and adiabatic heads of a compressor. Table 6-5 shows the input data and results of the gas mixture. The gas discharge temperature is 310.4°F and the compressor polytropic head is 76874 ft with a total break horsepower ≅ 960 hp.

Table 6-4
Properties of the Gas Mixture

Gas	Mole fraction y	Molecular weight M_w	yM_w	P_c psia	T_c (°R)	MC_p $\left(\frac{\text{Btu}}{\text{lb}_m \cdot \text{mol} \cdot {}^\circ\text{R}}\right)$ @ 150°F	yMC_p @ 150°F
H_2	0.30	2.01	0.603	188.1	60.2	6.94	2.082
CH_4	0.45	16.04	7.218	666.0	343	8.95	4.028
C_2H_6	0.15	30.07	4.511	707	550	13.78	2.067
C_3H_8	0.07	44.09	3.086	616	660	19.52	1.366
nC_4H_{10}	0.03	58.12	1.744	551	765	25.81	0.774
		M_w=	17.162			MC_p=	10.317

Table 6-5
Input Data and Computer Output of Polytropic Compressor Calculations

```
DATA61.DAT
--------------------------
POLYTROPIC
18000.0  50.0     200.0
80.0       1.238   17.162
0.95       0.75
```

```
                                     POLYTROPIC COMPRESSOR CALCULATION
*****************************************************************************
    TYPE OF SERVICE:                                                  POLYTROPIC
    GAS FLOWRATE, lb/hr.:                                              18000.000
    SUCTION PRESSURE, psia:                                               50.000
    DISCHARGE PRESSURE, psia:                                            200.000
    COMPRESSION RATIO:                                                     4.000
    INLET TEMPERATURE, oF:                                                80.000
    RATIO OF SPECIFIC HEAT CAPACITIES, k:                                  1.238
    MOLECULAR WEIGHT OF GAS, lb/lb-mole:                                  17.162
    AVERAGE COMPRESSIBILITY FACTOR, Z:                                 .9500
    POLYTROPIC EFFICIENCY:                                              .75
    POLYTROPIC HEAD, ft:                                               76873.770
    GAS DISCHARGE TEMPERATURE, oF:                                       310.404
    GAS HORSEPOWER, hp:                                                  931.803
    MECHANICAL LOSSES, hp:                                                27.954
    TOTAL BRAKE HORSEPOWER, hp:                                          959.757
    WORK DONE, lb-mole/hr.:                                              735.634
-----------------------------------------------------------------------------
```

Problem 6.2

Size a centrifugal pump with a 4-inch suction nozzle, and a 3-inch discharge nozzle that handles a gas oil at normal flow rate of 250 gpm through piping and component's system as shown in Figure 6-5, at the following conditions, temperature t = 555°F, specific gravity = 1.04, and viscosity of the gas oil $\mu = 0.6$ cP. Table 6-3 gives the details on a pump calculation sheet. Other piping details are shown in Table 6-6.

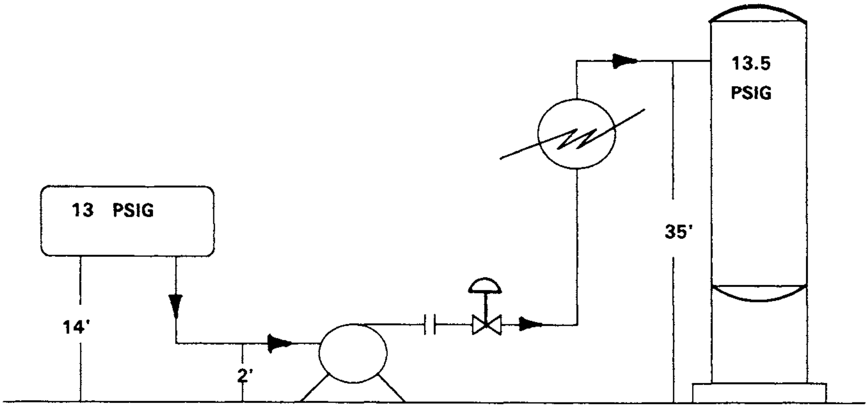

Figure 6-5. Gas oil transfer pump system.

Table 6-6
Piping Details and Fittings

Schedule 40	Suction Line	Discharge Line
Normal size, inch	6	4
Inside diameter, inch	6.065	4.026
Actual pipe length,ft	39	156
Fittings		
Long radius 90° elbows	5	20
Reducer, inch	4.026	3.068
Gate valve	1	4
Entrance	1	
exit		1

Solution

The line pressure drops for the suction and the discharge can be calculated by the method described in Chapter Three.

The total suction pressure drop is:

$$\text{Total suction } \Delta P_{\text{suct}} = 5.40 + 27.7 - 0.23$$

$$= 32.87 \text{ psi}$$

$$\text{Total discharge } \Delta P_{\text{disch}} = 28.2 + 14.86 + 10.0 + 5.0 + 2.0 + 4.38$$

$$= 64.44 \text{ psi}$$

$$\text{Differential pressure } \Delta P = \Delta P_{\text{disch}} - \Delta P_{\text{suct}}$$

$$= 64.44 - 32.87$$

$$= 31.57 \text{ psi}$$

$$\text{The brake horsepower Bhp} = \frac{(Q, \text{gpm})(\Delta P, \text{psi})}{(1715)(\text{EFF})}$$

$$= \frac{(250)(31.57)}{(1715)(0.7)}$$

$$= 6.57 \text{ hp}$$

$$\cong 7.0 \text{ hp}$$

The computer program PROG62 sizes the centrifugal pump for the given flow rate and fluid characteristics. The program calculates the hydraulic brake horsepower required by the pump and the actual brake horsepower. In addition, the program computes the available net positive suction head (NPSH) and the pump efficiency. Table 6-7 shows the input data and results of the pump hydraulic design calculation. The available NPSH is 64 ft, and the actual brake horsepower required for the pump operation is 7.0hp, with a pump efficiency of 68%.

Table 6-7
Centrigugal Pump Sizing: Program Inputs and Outputs

```
DATA62.DAT
------------------
GAS-OIL
555.0  0.6  1.04
4.0  250.0
27.7  0.22  12.0
28.2  33.0  10.0
5.0  2.0  0.0
4.38  0.0  0.0
                         CENTRIFUGAL PUMP SIZING
*******************************************************************************
    FLUID NAME:                                                  GAS-OIL
    FLUID OPERATING TEMPERATURE, oF:                              555.000
    FLUID VISCOSITY, cP:                                           .6000
    FLUID SPECIFIC GRAVITY:                                        1.040
    FLUID VAPOR PRESSURE, psia:                                    4.000
    VOLUMETRIC FLOWRATE:, gpm:                                    250.000
    PRESSURE AT EQUIPMENT, psia:                                   27.700
    SUCTION LINE LOSSES, psi:                                        .220
    OTHER LOSSES (e.g. STRAINER/FILTER), psi:                        .000
    SUCTION STATIC HEAD, ft.:                                      12.000
    SUCTION STATIC HEAD, psi:                                       5.403
    TOTAL PUMP SUCTION PRESSURE, psig:                             18.183
    TOTAL PUMP SUCTION PRESSURE, psia:                             32.883
    AVAILABLE NET POSITIVE SUCTION HEAD, ft.:                      64.153
    DELIVERY PRESSURE, psia.:                                      28.200
    DISCHARGE STATIC HEAD, ft.:                                    33.000
    DISCHARGE STATIC HEAD, psi:                                    14.857
    CONTROL VALVE PRESSURE DROP, psi.:                             10.000
    EXCHANGER PRESSURE DROP, psi.:                                  5.000
    ORIFICE PRESSURE DROP, psi.:                                    2.000
    FURNACE PRESSURE DROP, psi.:                                     .000
    DISCHARGE LINE LOSSES, psi.:                                    4.380
    OTHER LOSSES, psi.:                                              .000
    TOTAL PUMP DISCHARGE PRESSURE, psig:                           49.737
    TOTAL PUMP DISCHARGE PRESSURE, psia:                           64.437
    TOTAL PUMP PRESSURE DROP, psi.:                                31.555
    TOTAL PUMP PRESSURE DROP, ft.:                                 70.088
    HYDRAULIC BRAKE HORSEPOWER REQUIRED BY THE PUMP, bhp:           4.600
    ACTUAL BRAKE HORSEPOWER REQUIRED FOR PUMP OPERATION bhp:        6.809
    PUMP EFFICIENCY, (%):                                          67.557
-------------------------------------------------------------------------------
```

Problem 6.3

A 6-inch pump delivers the following heads when rotating at 1750 rpm and at varying flow rates as shown in Table 6-8. For a geometrically similar 8-inch pump running at 1450 rpm, calculate:

1. the heads developed by the 8-inch pump.
2. the brake horsepower for the flow rates.
3. the pump efficiencies for the 6- and 8-inch pumps.
4. develop the characteristic curves for the 6-inch and the 8-inch pumps.

Solution

Using the affinity law (Equation 6-76), the corresponding values for the head at varying flow rates are shown in Table 6-8. The computer program PROG63 calculates both the brake horsepower and pump efficiencies of the 6- and 8-inch pumps. Tables 6-9 and 6-10 show the input data and the computer results of these pumps. The characteristic curves are shown in Figure 6-6.

Table 6-8
Total Heads and Flow Rates for the 6-inch and 8-inch Centrifugal Pumps

6 inch @ Q (gpm)	1750 rpm H (ft)	8 inch @ Q (gpm)	1450 rpm H (ft)
0	160	0	195.3
100	158	100	192.8
200	155	200	189.2
300	152	300	185.5
400	146	400	178.2
500	140	500	170.9
600	132	600	161.1
700	118	700	144.0
800	104	800	126.9
900	84	900	102.5
1000	60	1000	73.2

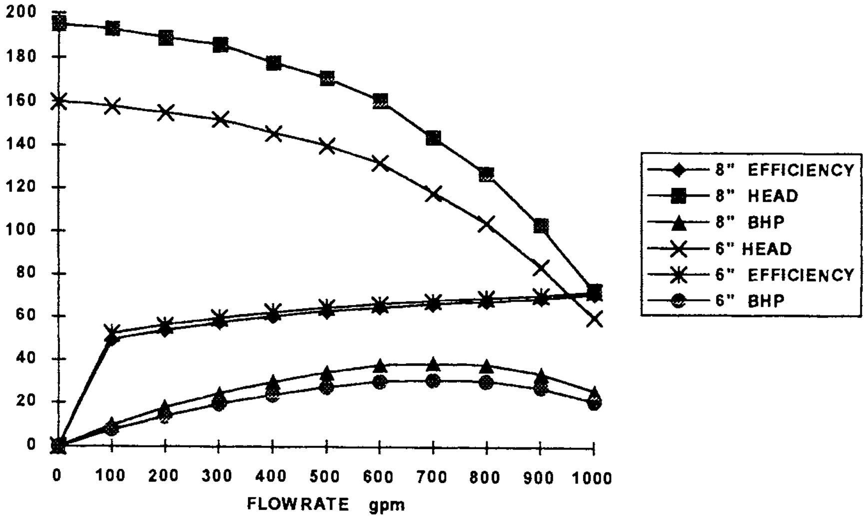

Figure 6-6. Characteristic curves of the 6-inch and the 8-inch centrifugal pumps.

Table 6-9
Efficiency and Brake Horsepower Calculations for the 6-inch Centrifugal Pump Program Inputs and Outputs

```
DATA63.DAT
-------------
11
0.0  160.0
100.0  158.0
200.0  155.0
300.0  152.0
400.0  146.0
500.0  140.0
600.0  132.0
700.0  118.0
800.0  104.0
900.0  84.0
1000.0  60.0
```

```
                        EFFICIENCY AND BRAKE HORSEPOWER CALCULATIONS
******************************************************************************

    FLOWRATE gpm          HEAD ft.      EFFICIENCY  %       BRAKE HORSEPOWER Bhp
******************************************************************************
          .0              160.0              .0                   .0
       100.0              158.0            52.4                  7.6
       200.0              155.0            56.3                 13.9
       300.0              152.0            59.4                 19.4
       400.0              146.0            62.2                 23.7
       500.0              140.0            64.4                 27.4
       600.0              132.0            66.2                 30.2
       700.0              118.0            67.8                 30.8
       800.0              104.0            69.0                 30.5
       900.0               84.0            70.4                 27.1
      1000.0               60.0            72.3                 20.9
------------------------------------------------------------------------------
```

Table 6-10
Efficiency and Brake Horsepower Calculations for the 8 inch Centrifugal Pump Program Inputs and Outputs

```
DATA63.DAT
-------------
11
0.0  195.3
100.0  192.8
200.0  189.2
300.0  185.5
400.0  178.2
500.0  170.9
600.0  161.1
700.0  144.0
800.0  126.9
900.0  102.5
1000.0  73.2
```

```
                        EFFICIENCY AND BRAKE HORSEPOWER CALCULATIONS
******************************************************************************

    FLOWRATE gpm            HEAD ft.      EFFICIENCY  %       BRAKE HORSEPOWER Bhp
******************************************************************************
          .0                195.3              .0                 .0
       100.0                192.8            49.6                9.8
       200.0                189.2            53.8               17.8
       300.0                185.5            57.3               24.5
       400.0                178.2            60.3               29.8
       500.0                170.9            62.7               34.4
       600.0                161.1            64.5               37.8
       700.0                144.0            66.2               38.5
       800.0                126.9            67.4               38.0
       900.0                102.5            68.9               33.8
      1000.0                 73.2            71.0               26.1
------------------------------------------------------------------------------
```

References

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11. Hughson, R. V., "Programs Predict Pump Performance," *Chem. Eng. Prog.,* Nov. 1992, pp. 43–46.
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```
        PROGRAM PROG61

C       ******************************************************************
C       THIS PROGRAM CALCULATES EITHER POLYTROPIC OR ADIABATIC HEADS,
C       THE ASSOCIATED GAS HORSEPOWER AND GAS DISCHARGE TEMPERATURE,
C       AS LONG AS THE POLYTROPIC OR ADIABATIC EFFICIENCY IS USED
C       WITH THE COMPANION HEAD CALCULATION.  THE PROGRAM ALSO CALCULATES
C       ADIABATIC EFFICIENCY FROM POLYTROPIC EXPONENT "K" FROM THE
C       MOLAL HEAT CAPACITY (MCp).
C
C
C
C       **********************************************************************
C
C
C       Hpoly(PH)   = POLYTROPIC HEAD, ft
C       ZAV         = AVERAGE COMPRESSIBILITY FACTOR FOR GAS FROM SUCTION TO
C                     DISCHARGE CONDITIONS. A VALUE OF 1.0 WILL GIVE
C                     CONSERVATIVE RESULTS.
C       R           = GAS CONSTANT= 1544.
C       TS          = SUCTION TEMPERATURE, oF
C       MW          = MOLECULAR WEIGTH OF GAS
C       N           = POLYTROPIC EXPONENT
C       RC          = COMPRESSION RATIO (DISCHARGE PRESSURE/SUCTION PRESSURE)
C                     P2/P1
C       T11         = INLET TEMPERATURE, oF
C       T12         = DISCHARGE TEMPERATURE, oF
C       K           = ADIABATIC EXPONENT, Cp/Cv
C       Epoly (PE)  = POLYTROPIC EFFICIENCY (TRY 0.75 FOR PRELIMINARY WORK)
C       HP          = GAS HORSEPOWER, bhp.
C       W           = GAS FLOW, lb/h
C       Had (AH)    = ADIABATIC HEAD, ft
C       T21         = SUCTION TEMPERATURE, oF
C       T22         = DISCHARGE TEMPERATURE, oF
C       Ead (AE)    = ADIABATIC EFFICIENCY
C       MCp (MCP)   = MOLAL SPECIFIC HEAT OF GAS AT CONSTANT PRESSURE,
C                     Btu/(lb mol)(oF).
C       P1          = SUCTION PRESSURE, psia.
C       P2          = DISCHARGE PRESSURE, psia.
C       CHOICE      = CHOOSE WHETHER THE PROCESS IS ADIABATIC OR POLYTROPIC
C       **********************************************************************

        CHARACTER*14 CHOICE
        REAL K,MW,N
        COMMON/PROG1/W,P1,P2,T11,T12,T21,T22,K,MW,N,ZAV,AE,AECAL,RC
        COMMON/PROG2/POLYH,ADIAH,HPPOLY,HPADIA,PE,PECAL,BHPP,BHPA
        COMMON/PROG3/WORK,PROD

        OPEN (UNIT=3,FILE='DATA61.DAT',STATUS='OLD',ERR=18)
        OPEN (UNIT =1, FILE ='PRN')

C
C       DETERMINE WHETHER THE COMPRESSOR CALCULATION IS POLYTROPIC
C       OR ADIABATIC.

        READ (3, 15, ERR=19) CHOICE

 15     FORMAT (A)

        IF (CHOICE .EQ. 'POLYTROPIC' .OR. CHOICE .EQ. 'polytropic') THEN
```

```
        READ (3, *, ERR=19) W, P1, P2
        READ (3, *, ERR=19) T11, K, MW
        READ (3, *, ERR=19) ZAV, PE


        GO TO 40

      ELSEIF (CHOICE .EQ. 'ADIABATIC' .OR. CHOICE .EQ. 'adiabatic') THEN

        READ (3, *, ERR=19) W, P1, P2
        READ (3, *, ERR=19) T11, K, MW
        READ (3, *, ERR=19) ZAV, AE


        GO TO 50
        ENDIF


18      WRITE (*, 10)
10      FORMAT (3X, 'FILE DOES NOT EXIST')

        GO TO 999
19      WRITE (*, 20)
20      FORMAT (3X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

40      WRITE (1, 30)
30      FORMAT (///,26X,'POLYTROPIC COMPRESSOR CALCULATION', /, 78(1H*))

        CALL POLYTR

        WRITE (1, 60) CHOICE, W, P1, P2, RC
60      FORMAT (5X,'TYPE OF SERVICE:', T60, A,/,
    *           5X,'GAS FLOWRATE, lb/hr.:',T60, F12.3,/,
    *           5X,'SUCTION PRESSURE, psia:', T60, F12.3,/,
    *           5X,'DISCHARGE PRESSURE, psia:', T60, F12.3,/,
    *           5X,'COMPRESSION RATIO:', T60, F12.3)

        WRITE (1, 70) T11, K, MW
70      FORMAT (5X,'INLET TEMPERATURE, oF:',T60, F12.3,/,
    *           5X,'RATIO OF SPECIFIC HEAT CAPACITIES, k:',T60,F12.3,/,
    *           5X,'MOLECULAR WEIGHT OF GAS, lb/lb-mole:',T60,F12.3)

        WRITE (1, 80) ZAV, PE
80      FORMAT (5X,'AVERAGE COMPRESSIBILITY FACTOR, Z:',T60, F8.4,/,
    *           5X,'POLYTROPIC EFFICIENCY:',T60,F8.2)


        WRITE (1, 90) POLYH, T12, HPPOLY
90      FORMAT (5X,'POLYTROPIC HEAD, ft:',T60,F12.3,/,
    *           5X,'GAS DISCHARGE TEMPERATURE, oF:',T60, F12.3, /,
    *           5X,'GAS HORSEPOWER, hp:', T60, F12.3)

        WRITE (1, 100) PROD, BHPP, WORK
100     FORMAT (5X,'MECHANICAL LOSSES, hp:', T60, F12.3,/,
    *           5X,'TOTAL BRAKE HORSEPOWER, hp:',T60, F12.3,/,
    *           5X,'WORK DONE, lb-mole/hr.:', T60, F12.3)

        WRITE (1, 105)
```

```
 105      FORMAT (78(1H-))

C         FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

          WRITE (1, *) CHAR(12)


          GO TO 999

 50       WRITE (1, 110)
 110      FORMAT (///,26X,'ADIABATIC COMPRESSOR CALCULATION', /, 78(1H*))

          CALL ADIAB

          WRITE (1, 120) CHOICE, W, P1, P2, RC
 120      FORMAT (5X,'TYPE OF SERVICE:', T60, A,/,
     *            5X,'GAS FLOWRATE, lb/hr.:', T60, F12.3,/,
     *            5X,'SUCTION PRESSURE, psia:', T60, F12.3,/,
     *            5X,'DISCHARGE PRESSURE, psia:', T60, F12.3,/,
     *            5X,'COMPRESSION RATIO:', T60, F12.3)

          WRITE (1, 130) T11, K, MW
 130      FORMAT (5X,'INLET TEMPERATURE, oF:',T60, F12.3,/,
     *            5X,'RATIO OF SPECIFIC HEATS CAPACITIES, K:',T60,F12.3,/,
     *            5X,'MOLECULAR WEIGHT OF GAS, lb/lb-mole:',T60, F12.3)

          WRITE (1, 140) ZAV, AE
 140      FORMAT (5X,'AVERAGE COMPRESSIBILITY FACTOR, Z:',T60, F8.4,/,
     *            5X,'ADIABATIC EFFICIENCY:',T60, F12.3)

          WRITE (1, 150) ADIAH, T22, HPADIA
 150      FORMAT (5X,'ADIABATIC HEAD, ft.:',T60, F12.3,/,
     *            5X,'GAS DISCHARGE TEMPERATURE, oF:', T60, F12.3,/,
     *            5X, 'GAS HORSEPOWER, hp:', T60, F12.3)

          WRITE (1, 160) PROD
 160      FORMAT (5X,'MECHANICAL LOSSES, hp:',T60, F12.3)

          WRITE (1, 170) BHPA, WORK
 170      FORMAT (5X,'TOTAL BRAKE HORSEPOWER, hp:',T60, F12.3,/,
     *            5X,'WORK DONE, ft/lb-mole:',T60,F12.3)

          WRITE (1, 180) AECAL
 180      FORMAT (5X,'CALCULATED ADIABATIC EFFICIENCY FROM',/,
     *            5X,'POLYTROPIC EFFICIENCY:',T60, F12.3)

          WRITE (1, 190)
 190      FORMAT (1H ,78(1H-))

C         FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

          WRITE (1, *) CHAR(12)

          CLOSE (3,STATUS='KEEP')
          CLOSE (1)
  999     STOP
          END

C         *****************************************************************
```

```
C        THIS PROGRAM CALCULATES THE POLYTROPIC HEAD,THE ASSOCIATED GAS
C        HORSEPOWER AND GAS DISCHARGE TEMPERATURE IN POLYTROPIC MACHINES
C        *****************************************************************

         SUBROUTINE POLYTR
         REAL K,MW,N,MLOSS
         COMMON/PROG1/W,P1,P2,T11,T12,T21,T22,K,MW,N,ZAV,AE,AECAL,RC
         COMMON/PROG2/POLYH,ADIAH,HPPOLY,HPADIA,PE,PECAL,BHPP,BHPA
         COMMON/PROG3/WORK, PROD

         R = 1545.0
         T11 = T11 + 460.


C        CALCULATE THE COMPRESSION RATIO (DISCHARGE PRESS./SUCTION PRESS.)

         RC = P2/P1
         N = (K*PE)/(K*PE-K+1.0)


C        CALCULATE THE POLYTROPIC HEAD, POLYH: ft.

         VAL1 = (ZAV*R*T11)/MW
         VAL2 = (N/(N-1.0))*(RC**((N-1.0)/N)-1.0)
         POLYH = VAL1*VAL2

C        CALCULATE THE GAS HORSEPOWER, HPPOLY: hp.

         HPPOLY = (W*POLYH)/(1.98*(10.0**6)*PE)

C        CALCULATE THE APPROXIMATE MECHANICAL LOSSES AS A PERCENTAGE OF GAS
C        POWER REQUIREMENT, PROD: hp.

         CALL MECHL (HPPOLY, MLOSS)

C        CALCULATE THE TOTAL BRAKE HORSEPOWER, BHPP: hp.

         BHPP = HPPOLY + PROD

C        CALCULATE THE GAS DISCHARGE TEMPERATURE, T12: oF.

         VAL3 = (POLYH*MW)/(ZAV*R)
         T12 = VAL3*((N-1.0)/N) + T11

C        CALCULATE THE WORK DONE  lb- mole/hr.
C        CALCULATE THE BASIS IN moles.

         B = W/MW

C        CALCULATE THE WORK DONE

         WORK = (N/(N-1.0))*(R*T11*((P2/P1)**((N-1.0)/N)-1.0))
         WORK = (WORK*B)/(1.98*(10.0**6))

         T11 = T11 - 460.0
         T12 = T12 - 460.0

         RETURN
         END
C
```

```
C       ******************************************************************
C       THIS PROGRAM CALCULATES THE ADIABATIC HEAD,THE ASSOCIATED GAS
C       HORSEPOWER AND GAS DISCHARGE TEMPERATURE
C       ******************************************************************

        SUBROUTINE ADIAB
        REAL K,MW,N,MLOSS
        COMMON/PROG1/W,P1,P2,T11,T12,T21,T22,K,MW,N,ZAV,AE,AECAL,RC
        COMMON/PROG2/POLYH,ADIAH,HPPOLY,HPADIA,PE,PECAL,BHPP,BHPA
        COMMON/PROG3/WORK, PROD

        PE = 0.75
        R = 1545.0
        T21 = T11 + 460.

C       CALCULATE THE COMPRESSION RATIO (DISCHARGE PRESS./SUCTION PRESS.)

        RC = P2/P1


C       CALCULATE THE ADIABATIC HEAD, ADIAH: ft.

        VAL4 = (ZAV*R*T21)/MW
        VAL5 = (K/(K-1.0))*(RC**((K-1.0)/K)-1.0)
        ADIAH = VAL4*VAL5

C       CALCULATE THE GAS HORSEPOWER, HPADIA: hp.

        HPADIA = (W*ADIAH)/(1.98*(10.0**6)*AE)


C       CALCULATE THE APPROXIMATE MECHANICAL LOSSES AS A PERCENTAGE OF GAS
C       POWER REQUIREMENT, PROD: hp.

        CALL MECHL (HPADIA, MLOSS)

C       CALCULATE THE TOTAL BRAKE HORSEPOWER, BHPA: hp.

        BHPA = HPADIA + PROD

C       CALCULATE THE GAS DISCHARGE TEMPERATURE, oF.

        T22 = T21*(RC**((K-1.0)/K))
        T22 = T22 - 460.0

C       CALCULATE THE ADIABATIC EFFICIENCY FROM THE POLYTROPIC EFFICIENCY

        N = (K*PE)/(K*PE-K+1.0)
        VAL6 = (RC**((K-1.0)/K))-1.0
        VAL7 = (RC**((N-1.0)/N))-1.0
        AECAL = VAL6/VAL7

C       CALCULATE THE WORK DONE, hp

C       CALCULATE THE BASIS IN lb-moles per hr.

        B = W/MW

C       CALCULATE THE WORK DONE
```

```
        WORK = (K/(K-1.0))*(R*T21)*((P2/P1)**((K-1.0)/K)-1.0)
        WORK = (WORK*B)/(1.98*(10.0**6))

        RETURN
        END

C       ***************************************************************
C       THIS PROGRAM CALCULATES THE MECHANICAL LOSSES DUE TO
C       FRICTION IN BEARINGS.
C       ***************************************************************

        SUBROUTINE MECHL (POLYL, MLOSS)

        COMMON/PROG3/WORK,PROD
        REAL MLOSS

        IF (POLYL .LT. 3000.0 ) THEN
        MLOSS = 0.03
        PROD = POLYL*MLOSS
        ELSEIF (POLYL .GT. 3000.0 .AND. POLYL .LT. 6000.0) THEN
        MLOSS = 0.025
        PROD = POLYL*MLOSS
        ELSEIF (POLYL .GT. 6000.0 .AND. POLYL .LT. 10000.0) THEN
        MLOSS = 0.02
        PROD = POLYL*MLOSS
        ELSEIF (POLYL .GT. 10000.0) THEN
        MLOSS = 0.015
        PROD = POLYL*MLOSS
        ENDIF

        RETURN
        END
```

```
      PROGRAM PROG62

C     ******************************************************************
C     THIS PROGRAM CALCULATES ALL PUMP HEAD CALCULATIONS REQUIRED TO WRITE
C     A PUMP SPECIFICATION SUITABLE FOR A VENDOR INQUIRY OR PURCHASE
C     ORDER.  THE PROGRAM FURTHER CALCULATES THE CENTRIFUGAL PUMP
C     EFFICIENCY AND PUMP HORSEPOWER USING AN EQUATION DEVELOPED BY
C     BY C. BRANAN (The Process Engineer's Pocket Handbook, Gulf Publishing
C     Company, Houston 1976.)
C     ******************************************************************
C
C     FLUID   =  FLUID NAME
C     TEMP    =  FLUID OPERATING TEMPERATURE, oF.
C     VIS     =  FLUID VISCOSITY, cP.
C     GPM     =  FLOWRATE, gpm
C     SPG     =  SPECIFIC GRAVITY OF LIQUID
C     VP      =  VAPOR PRESSURE OF PUMPED FLUID AT PUMP SUCTION
C                TEMPERATURE, psia.
C     VESP    =  PRESSURE AT EQUIPMENT ON PUMP SUCTION, psia.
C     SLL     =  SUCTION LINE LOSSES (PRESSURE DROP IN PIPING), psi.
C     SSHD    =  SUCTION STATIC HEAD OF LIQUID ON PUMP SUCTION OR
C                DISCHARGE, ft.
C     NPSH    =  NET POSITIVE SUCTION HEAD ON PUMP, ft.
C     DELP    =  PRESSURE AT EQUIPMENT ON PUMP DISCHARGE, psia.
C     DSHD    =  DISCHARGE STATIC HEAD, ft.
C     CVPD    =  CONTROL VALVE PRESSURE DROP, psi.
C     EXPD    =  HEAT EXCHANGER PRESSURE DROP, psi.
C     ORPD    =  ORIFICE PRESURE DROP, psi.
C     FURPD   =  FURNACE PRESSURE DROP, psi.
C     DLL     =  DISCHARGE LINE LOSSES (PRESSURE DROP IN PIPING), psi.
C     OTLD    =  OTHER LOSSES (DISCHARGE:-e.g. FURNACE), psi.
C     OTLS    =  OTHER LOSSES (SUCTION:- e.g. STRAINER/FILTER), psi
C     DELTAP  =  PRESSURE DROP ACROSS PUMP, psi.
C     DELPHT  =  PRESSURE DROP ACROSS PUMP, ft.
C     HBHP    =  HYDRAULIC BRAKE HORSEPOWER REQUIRED BY PUMP, bhp.
C                (FOR HBHP CALCULATION, ASSUME PUMP EFFICIENCY=1.0)
C     EFF     =  PUMP EFFICIENCY (%).
C     F       =  DEVELOPED PUMP HEAD, ft.
C     G       =  FLOW RATE THROUGH PUMP, gpm.
C     BHP     =  ACTUAL BRAKE HORSEPOWER REQUIRED FOR PUMP OPERATION
C     psi     =  ft(0.433 x sp.gr.)
C     ft      =  psi/(0.433 x sp.gr.)
C     *****************************************************************

      CHARACTER*14 FLUID
      REAL  NPSH, ORPD, OTLD, OTLS

      COMMON/DATA1/ FLUID, TEMP, VIS, SPG, VP
      COMMON/DATA2/ GPM, VESP, SLL, SSHD, SSHDP
      COMMON/DATA3/ DELP, DSHD, DSHDP, CVPD, EXPD
      COMMON/DATA4/ ORPD, FURPD, DLL, OTLS, OTLD
      COMMON/DATA5/ SP, SPGAGE, NPSH, DISP, DISPG
      COMMON/DATA6/ DELTAP,DELPHT,HBHP,BHP,EFF


      OPEN(UNIT=3,FILE='DATA62.DAT',STATUS='OLD',ERR=18)
      OPEN (UNIT =1, FILE='PRN')
```

```
      READ (3, 5, ERR=19) FLUID
5     FORMAT (A)

      READ (3, *, ERR=19) TEMP, VIS, SPG
      READ(3, *, ERR=19) VP, GPM
      READ(3, *, ERR=19) VESP, SLL, SSHD
      READ(3, *, ERR=19) DELP, DSHD,CVPD
      READ(3, *, ERR=19) EXPD, ORPD, FURPD
      READ(3, *, ERR=19) DLL, OTLS, OTLD

      GO TO 15

18    WRITE(*, 11)
11    FORMAT(6X,'FILE DOES NOT EXIST')
      GO TO 999

19    WRITE(*, 12)
12    FORMAT(6X,'ERROR MESSAGE IN THE DATA VALUE')
      GO TO 999

15    CALL PUMPHA

      WRITE(1, 10)
10    FORMAT(26X,'CENTRIFUGAL PUMP SIZING',/,1H ,78(1H*))


      WRITE (1, 20) FLUID, TEMP, VIS, SPG, VP, GPM
20    FORMAT (5X,'FLUID NAME:', T65, A,/,
    *         5X,'FLUID OPERATING TEMPERATURE, oF:', T65, F9.3,/,
    *         5X,'FLUID VISCOSITY, cP:', T65, F9.4,/,
    *         5X,'FLUID SPECIFIC GRAVITY:', T65, F9.3,/,
    *         5X,'FLUID VAPOR PRESSURE, psia:', T65, F9.3,/,
    *         5X,'VOLUMETRIC FLOWRATE:, gpm:', T65, F9.3)


      WRITE (1, 30) VESP, SLL, OTLS, SSHD
30    FORMAT (5X,'PRESSURE AT EQUIPMENT, psia:', T65, F9.3,/,
    *         5X,'SUCTION LINE LOSSES, psi:', T65, F9.3,/,
    *         5X,'OTHER LOSSES (e.g. STRAINER/FILTER), psi:',T65,F9.3,
    *       /,5X,'SUCTION STATIC HEAD, ft.:', T65, F9.3)

      WRITE (1, 40) SSHDP, SPGAGE, SP
40    FORMAT (5X,'SUCTION STATIC HEAD, psi:', T65, F9.3,/,
    *         5X,'TOTAL PUMP SUCTION PRESSURE, psig:', T65, F9.3,/,
    *         5X,'TOTAL PUMP SUCTION PRESSURE, psia:', T65, F9.3)

      WRITE (1, 50) NPSH
50    FORMAT (5X,'AVAILABLE NET POSITIVE SUCTION HEAD, ft.:', T65, F9.3)

      WRITE (1, 60) DELP, DSHD, DSHDP, CVPD
60    FORMAT (5X,'DELIVERY PRESSURE, psia.:', T65, F9.3,/,
    *         5X,'DISCHARGE STATIC HEAD, ft.:', T65, F9.3,/,
    *         5X,'DISCHARGE STATIC HEAD, psi:', T65, F9.3,/,
    *         5X,'CONTROL VALVE PRESSURE DROP, psi.:', T65, F9.3)

      WRITE (1, 70) EXPD, ORPD, FURPD, DLL, OTLD
70    FORMAT (5X,'EXCHANGER PRESSURE DROP, psi.:', T65, F9.3,/,
    *         5X,'ORIFICE PRESSURE DROP, psi.:', T65, F9.3,/,
    *         5X,'FURNACE PRESSURE DROP, psi.:', T65, F9.3,/,
```

```
     *          5X,'DISCHARGE LINE LOSSES, psi.:', T65, F9.3,/,
     *          5X,'OTHER LOSSES, psi.:', T65, F9.3)


        WRITE(1, 80)DISPG,DISP
 80     FORMAT(5X,'TOTAL PUMP DISCHARGE PRESSURE, psig:', T65, F9.3,/,
     *         5X,'TOTAL PUMP DISCHARGE PRESSURE, psia:', T65, F9.3)


        WRITE(1, 90)DELTAP,DELPHT
 90     FORMAT(5X,'TOTAL PUMP PRESSURE DROP, psi.:', T65, F9.3,/,
     *         5X,'TOTAL PUMP PRESSURE DROP, ft.:', T65, F9.3)

        WRITE(1, 100)HBHP
 100    FORMAT(5X,'HYDRAULIC BRAKE HORSEPOWER REQUIRED BY THE PUMP,'\,
     *         ' bhp:', T65, F9.3)

        WRITE(1, 110)BHP
 110    FORMAT(5X,'ACTUAL BRAKE HORSEPOWER REQUIRED FOR PUMP OPERATION',
     *         \,' bhp:', T65, F9.3)

        WRITE  (1, 120) EFF
 120    FORMAT (5X,'PUMP EFFICIENCY, (%):', T65, F9.3)

        WRITE (1, 130)
 130    FORMAT (1H ,78(1H-))


C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE(3,STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END

C       ********************************************************************
C       THIS PROGRAM CALCULATES THE SUCTION PRESSURE AND THE NET POSITIVE
C       SUCTION HEAD
C       ********************************************************************

        SUBROUTINE PUMPHA

        CHARACTER*14 FLUID

        REAL NPSH, OTLS, OTLD, ORPD

        COMMON/DATA1/ FLUID, TEMP, VIS, SPG, VP
        COMMON/DATA2/ GPM, VESP, SLL, SSHD, SSHDP
        COMMON/DATA3/ DELP, DSHD, DSHDP, CVPD, EXPD
        COMMON/DATA4/ ORPD, FURPD, DLL, OTLS, OTLD
        COMMON/DATA5/ SP, SPGAGE, NPSH, DISP, DISPG
        COMMON/DATA6/ DELTAP, DELPHT, HBHP, BHP, EFF


        VAL1 = 0.4329*SPG
        SSHDP = SSHD*VAL1
        SP = VESP + SSHDP- SLL- OTLS
```

```
         SPGAGE = SP-14.7

C        AVAILABLE NET POSITIVE SUCTION HEAD

         SLL1 = SLL/VAL1
         VESP1 = VESP/VAL1
         VP1 = VP/VAL1
         DEF = VESP1-VP1
         NPSH = DEF + SSHD - SLL1


C        PUMP DISCHARGE PRESSURE

         DSHDP = DSHD*VAL1
         DISP = DELP+DSHDP+CVPD+EXPD+ORPD+FURPD+DLL+OTLD
         DISPG = DISP-14.7


C        TOTAL PUMP DELTAP = PUMP DISCH. PRES. - PUMP SUC. PRES.

         DELTAP = DISP-SP
         DELPHT = DELTAP/VAL1

C        HYDRAULIC BRAKE HORSEPOWER REQUIRED BY PUMP
C        PUMP EFFICIENCY IS ASSUMED = 1.0

         HBHP = (DELTAP*GPM)/(1715.0*1.0)

C        THIS PROGRAM CALCULATES EFFICIENCY AND PUMP HORSEPOWER USING
C        C. BRANAN'S EQUATION (e.g. C Brannan: The Process Engineer's
C        Pocket Handbook, Gulf publishing Co.)


         F = DELPHT
         G = GPM
         VAL2=0.2855*F
         VAL3=3.78*F*G*(10.0**(-4))
         VAL4=2.38*F*(G**2)*(10.0**(-7))
         VAL5=5.39*(F**2)*(10.0**(-4))
         VAL6=6.39*(F**2)*G*(10.0**(-7))
         VAL7=4.0*(F**2)*(G**2)*(10.0**(-10))
         EFF=(80.0-VAL2+VAL3-VAL4+VAL5-VAL6+VAL7)
         BHP=(100.0*HBHP)/EFF

         RETURN
         END
```

```
      PROGRAM PROG63

C     ****************************************************************
C     THIS PROGRAM WILL CALCULATE THE PUMP EFFICIENCY BASED ON
C     THE FLUID FLOW RATE AND THE HEAD USING THE EQUATIONS
C     DEVELOPED BY C. BRANAN (The Process Engineer's Pocket Handbook,
C     Gulf Publishing Company, Houston 1976).
C     *****************************************************************
C
C     H       =   HEAD, ft.
C     Q       =   VOLUMETRIC FLOWRATE, gpm.
C     HBHP    =   HYDRAULIC HORSEPOWER, bhp.
C     BHP     =   BRAKE HORSEPOWER, bhp.
C     *****************************************************************

      DIMENSION EFF(20), H(20), Q(20), HBHP(20), BHP(20)


      OPEN (UNIT=3, FILE='DATA63.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT=1, FILE='PRN')


      READ (3, *, ERR=19) N

      DO 10 I=1, N
      READ (3, *, ERR=19) Q(I), H(I)

 10   CONTINUE

      GO TO 44


 18   WRITE (*, 20)
 20   FORMAT (6X, 'FILE DOES NOT EXIST')
      GO TO 999

 19   WRITE (*, 21)
 21   FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
      GO TO 999

 44   WRITE (1, 90)
 90   FORMAT (///,25X,'EFFICIENCY AND BRAKE HORSEPOWER CALCULATIONS',/
     *        1H ,78(1H*),//)

      WRITE(1, 95)
 95   FORMAT (5X,'FLOWRATE gpm', 10X,'HEAD ft.', 6X,'EFFICIENCY  %',
     * 6X,'BRAKE HORSEPOWER Bhp',/1H , 78(1H*))

      SPGR=1.0


      DO 35 I=1,N
      IF (Q(1) .EQ. 0.0) THEN
      EFF(1) = 0.0
      HBHP(1) = 0.0
      ELSE
      ENDIF
```

```
        VAL1 = 0.2855*H(I)
        VAL2 = 3.78*H(I)*Q(I)*(10.0**(-4))
        VAL3 = 2.38*H(I)*(Q(I)**2)*(10.0**(-7))
        VAL4 = 5.39*(H(I)**2)*(10.0**(-4))
        VAL5 = 6.39*(H(I)**2)*Q(I)*(10.0**(-7))
        VAL6 = 4.0*(H(I)**2)*(Q(I)**2)*(10.0**(-10))
        EFF(I)=(80.0-VAL1+VAL2-VAL3+VAL4-VAL5+VAL6)


C       HYDRAULIC BRAKE HORSEPOWER REQUIRED BY THE PUMP
C       PUMP EFFICIENCY IS ASSUMED = 1.0


        HBHP(I)=(Q(I)*H(I)*SPGR)/(3960.0*1.0)
        BHP(I)=HBHP(I)/(EFF(I)/100.0)

 35     CONTINUE

        DO I =1, N

        WRITE (1, 96)Q(I),H(I),EFF(I),BHP(I)
  96    FORMAT (5X, F8.1, 10x, F8.1, 10X, F8.1, 10X, F8.1)

        ENDDO

        WRITE(*, 100)
 100    FORMAT (5X , 'FLOWRATE gpm', 10X, 'HEAD ft.', 6X 'EFFICIENCY  %',
     *  6X,'BRAKE HORSEPOWER  Bhp',/1H ,78(1H*))

        DO 45 I =1, N
        WRITE(*, 110)Q(I), H(I), EFF(I) ,BHP(I)
 110    FORMAT (5X, F8.1, 10X, F8.1, 10X, F8.2, 10X, F8.1)
 45     CONTINUE

        WRITE (1,120)
 120    FORMAT (1H ,78(1H-))

C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE (3, STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END
```

CHAPTER 7

Mass Transfer

INTRODUCTION

Unit operation techniques in the chemical process industries (CPI) effect the separation of a mixture or mixtures into their components. These operations are called diffusional or mass transfer operations. Techniques employed in the CPI to effect these separations are: distillation, absorption, liquid extraction, drying, leaching, crystallization, and gas adsorption. These processes account for 40% to 70% of both the capital and operating costs in the CPI. Separation operations significantly affect energy consumption, product costs, and manufacturing profits. About 43% of the energy consumed by the U.S. chemical process industries is used for separation processes [1]. The method depends on the state (such as liquid, solid, or gaseous) of the components.

The engineer must adequately size equipment for separating and recovering products from multicomponent feed streams. In addition, he or she should consider whether the design is either stagewise or continuous, tray or packed. The trays act as individual stages and produce stepwise changes in concentration, while packed towers give gradual changes in concentration. Designing distillation equipment requires knowledge of vapor-liquid equilibria in multi-component mixtures.

This chapter considers the vapor-liquid equilibrium of mixtures, conditions for bubble and dew points of gaseous mixtures, isothermal equilibrium flash calculations, the design of distillation towers with valve trays, packed tower design, Smoker's equation for estimating the number of plates in a binary mixture, and finally, the computation of multicomponent recovery and minimum trays in distillation columns.

VAPOR-LIQUID EQUILIBRIUM

A common operation in the CPI for the separation of fluid mixtures into their components is distillation. The distillation process is a separation technique that depends on the difference between the compositions of liquid and vapor phases at equilibrium. This implies that the temperatures and pressures of the phases must be the same, and no composition change occurs with time. Equilibrium can be achieved after a long period of thorough mixing and contact between the two phases.

An ideal gas is, by definition, one that follows the ideal gas laws:

$$PV = nRT \tag{7-1}$$

where P = absolute pressure
V = total volume
n = number of moles of gas
R = ideal gas constant
T = absolute temperature

The conditions under which a given component or mixture approaches ideal behavior depend on the critical temperature and critical pressure. Other principles of gas behavior are Dalton's law of additive pressures and Amagat's law of additive volumes. These are:

$$\pi = p_A + p_B + \ldots \tag{7-2}$$

and

$$V_T = V_A + V_B + \ldots \tag{7-3}$$

where π = total system pressure
p = partial pressure
V_A = volume of component A
V_B = volume of component B
V_t = total volume of system
A,B = components

These laws are correct when conditions are such that each component and the mixture obey the ideal gas law. The equilibrium between two phases can be related to the equality of the chemical potential and defined in terms of the Gibbs free energy as

$$\mu_i = \left[\frac{\partial G}{\partial \mu_i}\right]_{T,P,n_j} = \overline{G}_i \tag{7-4}$$

where $\overline{G}_i$ is the partial molar Gibbs free energy. From the thermodynamic relationship between Gibbs free energy, temperature and pressure, and at constant temperature,

$$dG = VdP \tag{7-5}$$

where G is the molar Gibbs free energy and V is the molar volume.

Considering a pure fluid of component i and substituting Equation 7-1 into Equation 7-5,

$$\begin{aligned} dG &= RT\frac{dP}{p} \\ &= RTd(\ln P) \end{aligned} \tag{7-6}$$

The free energy from Equation 7-6 is restricted to ideal gases, but can be modified to include real fluids by introducing a new function defined as the fugacity. Equation 7-6 becomes

$$dG_i = RTd(1n\ f_i) \tag{7-7}$$

where f_i is the fugacity of pure i with units of pressure. The fugacity becomes equal to the pressure as the pressure approaches zero.

Thus,

$$\lim_{P \to 0} \frac{f_i}{P} = 1.0 \tag{7-8}$$

For a single component in a mixture at constant temperature, the fugacity is defined by

$$d\overline{G}_i = RTd(\ln \bar{f}_i) \tag{7-9}$$

and

$$\lim_{P \to 0} \frac{\bar{f}_i}{y_i P} = 1.0 \tag{7-10}$$

If a liquid mixture at temperature T and pressure P is in equilibrium with a vapor mixture at the same temperature and pressure, therefore at an equilibrium condition, the thermodynamic criterion will be

$$f_i^V = f_i^L \tag{7-11}$$

where f_i^V = fugacity of component i in the vapor phase
f_i^L = fugacity of component i in the liquid phase

The fugacity of a component in a mixture depends on the temperature, pressure, and composition of that mixture. The fugacity, f_i^L, of any component, i, in the liquid phase is related to the composition (mole fraction) of the component in that phase by

$$f_i^L = \gamma_i x_i f_i^{oL} \tag{7-12}$$

where γ_i = the activity coefficient of component i
x_i = mole fraction of component i
f_i^{oL} = the fugacity of component i in the reference (or standard) state

The fugacity of pure liquid **i** at temperature T and pressure P is given by

$$f_i^{oL} = P_{vp,i}(T)\phi_i^s(T)\exp\left[\int_{P_{vp,i}}^{P} \frac{V_i^L(T,P)}{RT}\,dP\right] \tag{7-13}$$

where $P_{vp,i}$ = the vapor pressure of component i
ϕ_i^s = the vapor phase fugacity coefficient of pure saturated vapor of component i

The exponential term in Equation 7-13 is a correction factor for the effect of pressure on liquid-phase fugacity and is known as the **Poynting factor**. In Equation 7-13, V_i^L can be replaced by the partial molar volume of component i in the liquid solution for greater accuracy. For low to moderate pressure, V_i^L is assumed as the saturated liquid molar volume at the specified temperature. Equation 7-13 is simplified to give

$$f_i^{oL} = P_{vp,i}\phi_i^s \exp\left[\frac{V_i^{Ls}(P - P_{vp,i})}{RT}\right] \tag{7-14}$$

Equation 7-14 is used to calculate the reference state fugacity of liquids. Any equation of state can be used to evaluate ϕ_i^s. For low to moderate pressures, the virial equation is the simplest to use. The fugacities of pure gases and gas mixtures are needed for estimating many thermodynamic properties, such as entropy, enthalpy, and fluid phase equilibria. For pure gases, the fugacity is

$$\ln f = \frac{1}{RT}\int_0^P VdP \tag{7-15}$$

The fugacity can be calculated from Equation 7-15 once the P-V-T behavior of the fluid is known from an equation of state. The fugacity coefficient is the ratio of the fugacity of a substance to its pressure. For a pure substance,

$$\phi = \frac{f}{P} \tag{7-16}$$

For the vapor phase, the composition is nearly always expressed by the mole fraction, y_i

$$\phi_i = \frac{f_i^V}{y_i P} \tag{7-17}$$

For a mixture of ideal gases, $\phi_i = 1$. The fugacity coefficient, ϕ_i, depends on temperature and pressure. The fugacity coefficient is normalized, such that as $P \to 0$, $\phi_i \to 1$ for all components. At a low pressure, ϕ_i is assumed to be unity.

When the volume is known as a function of the pressure, either from direct measurement or from an empirical equation of state, changes in fugacity may be found by integration. Thus

$$\ln \frac{f_2}{f_1} = \frac{1}{RT}\int_{P_1}^{P_2} VdP \tag{7-18}$$

Since $\phi = 1$ when $P = 0$, absolute values of the fugacity coefficient can be determined. Therefore,

$$\begin{aligned}\ln \phi = \ln \frac{f}{P} &= \frac{1}{RT}\int_0^P \left(V - \frac{RT}{P}\right)dP \\ &= \int_0^P (Z-1)\frac{dP}{P}\end{aligned} \tag{7-19}$$

Methods for estimating fugacities of liquid and vapor phases are given by Reid, *et al.* [2], and by Walas [3].

Raoult's law states that the partial pressure in the liquid phase can be expressed as

$$p_A = x_A p_A^o \tag{7-20}$$

where x_A is the mole fraction of component A, and p_A^o is the vapor pressure of component A.

For the vapor phase, Dalton's law can be expressed as:

$$p_A = \pi y_A \tag{7-21}$$

where y_A is the mole fraction of component A. Combining Equation 7-20 and Equation 7-21

$$x_A p_A^o = \pi y_A$$

$$K = \frac{y_A}{x_A} = \frac{p_A^o}{\pi} \tag{7-22}$$

where K is the equilibrium constant.

Few multicomponent systems exist for which completely generalized equilibrium data are available. The most widely available data are those for vapor-liquid systems, and these are frequently referred to as vapor-liquid equilibrium distribution coefficients or K value. The K values vary with temperature and pressure, and a selectivity that is equal to the ratio of the K values is used. For vapor-liquid systems, this is referred to as the relative volatility and is expressed for a binary system as

$$\alpha = \frac{K_A}{K_B} \tag{7-23}$$

where

$$K_A = y_A/x_A$$

and

$$K_B = y_B/x_B$$

$$\alpha_{A-B} = \frac{y_A \cdot x_B}{x_A \cdot y_B} \tag{7-24}$$

Equation 7-24 can be expressed in terms of the more volatile component A, as

$$y_A = \frac{\alpha x_A}{1 + (\alpha - 1)x_A} \tag{7-25}$$

where

$$x_A + x_B = 1$$

and

$$y_A + y_B = 1$$

Equation 7-25 relates equilibrium compositions x_A and y_A in terms of the relative volatility. If the assumption is that α is independent of temperature and composition, then Equation 7-25 becomes the equation of the equilibrium line or the x-y curve, as shown in Figure 7-1. Figure 7-1 can be used to determine the compositions of vapor and liquid in equilibrium.

BUBBLE POINT OF GAS MIXTURES

An equilibrium between a liquid and a vapor implies that the liquid is on the point of boiling, is producing bubbles of vapor within it, and the

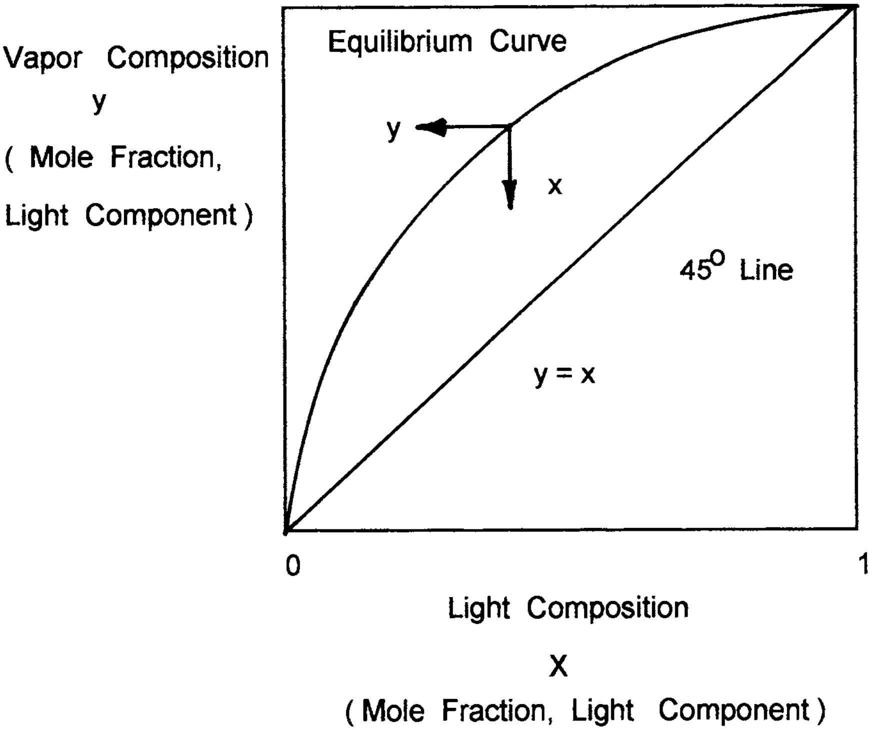


Figure 7-1. X-Y diagram for a binary system.

vapor is on the point of condensing or forming a dew. These conditions are referred to as saturated liquid and saturated vapor. For the particular total pressure, the liquid is at its bubble point temperature and the vapor at its dew point temperature. The amount of vapor formed is assumed to be so small as to have no effect on the liquid composition. For a binary system,

$$x_1 = \frac{1 - K_2}{K_1 - K_2} \tag{7-26}$$

and

$$x_2 = 1.0 - x_1 \tag{7-27}$$

In many cases where there are more than two components in the liquid mixture, no direct solution as Equation 7-26 exists. The basic definition of the equilibrium coefficient is

$$y_i = K_i x_i \tag{7-28}$$

For a stable system, the total mole fraction is unity, which is

$$\sum y_i = 1.0 = \sum K_i x_i \tag{7-29}$$

Equation 7-29 is used to determine the bubble point temperature and pressure. In using Equation 7-29, the temperature or pressure is fixed, while the other parameter is varied until the criterion for a stable system is satisfied. A combination of temperature and pressure is altered, if the summation of the calculated vapor composition is different from unity. There is no known direct method that will allow a reasonable estimation of the amount of change required. However, Dodge [4], Hines and Maddox [5] have provided techniques for reducing the number of trials that is required.

DEW POINT CALCULATIONS

The dew point of a vapor is that combination of temperature and pressure at which the first drop of liquid condenses. The dew point criterion can be expressed as:

$$\sum x_i = 1.0 = \sum \frac{y_i}{K_i} \tag{7-30}$$

For binary mixtures of components 1 and 2, then

$$y_i = \frac{K_1(1 - K_2)}{K_1 - K_2} \qquad (7\text{-}31)$$

and

$$y_2 = 1.0 - y_1 \qquad (7\text{-}32)$$

These two equations can be used to calculate the composition of a binary vapor that will begin to condense at a given temperature and pressure.

EQUILIBRIUM FLASH COMPUTATIONS

Flash vaporization calculations involving multicomponent mixtures are essential to the design and successful operation of many processes. These calculations are often required to determine the condition of the feed to a fractionating column or to determine the flow of vapor from a reboiler or condenser.

Flash calculations often involve trial-and-error solutions that are time consuming, tedious, and subject to error if performed manually. Coker [6] has developed an improved iterative convergence method first suggested by Oliver [7] and later modified by Kostecke [8], for isothermal equilibrium flash computations. Multicomponent flash (isothermal and adiabatic) computations are incorporated as part of overall process simulation and equipment design. However, single-stage flash fractionation processes are also employed to obtain a separation of the light components in a feed and as a preliminary step before a multicomponent fractionation column, such as crude oil distillation. Table 7-1 lists ways of producing two-phase mixtures from a single phase at appropriate conditions. The last process in the table typifies the well head separation that takes place in an oil field. It is known as a flash process because the

Table 7-1
Ways to Produce Two-Phase Mixture

Initial	Action to Produce Two-Phase Mixture
Gas	Cool, possibly after initial compression
Gas	Expand through a valve or an engine
Liquid	Heat to achieve partial vaporization
Liquid	Reduce pressure through a valve, if close to saturation

vapor forms due to the rapid drop in the pressure.

Fundamentals

To carry out an appropriate flash calculation, the pressure, P, and the temperature, T, must be known. If the values of P and T in the separating vessel are fixed, the value of P must not be so high that the two phases cannot exist at any value of T. Nor must T lie outside the bubble point and dew point range corresponding to P. For a valid two-phase equilibrium calculation, the following relationship must be satisfied:

$$T_{bp} < T_s < T_{dp} \qquad (7\text{-}33)$$

where T_{bp} = the bubble point temperature
T_s = the specified temperature
T_{dp} = the dew point temperature

The existence of a valid two-phase flash can be verified with the design equations for the bubble point, dew point, and equilibrium data calculated at the specified pressure and temperature. The design equations for the bubble and dew points are:

Bubble point

$$f_1 = \sum_{i=1}^{n} K_i X_i \qquad (7\text{-}34)$$

Dew point

$$f_2 = \sum_{i=1}^{n} Y_i / K_i \qquad (7\text{-}35)$$

Table 7-2 illustrates the phase condition using the liquid-vapor data associated with the specified pressure and temperature.

From Table 7-2, the conditions for a valid two-phase equilibrium flash are:

$$f_1 = \sum_{i=1}^{n} K_i n_i > 1.0 \qquad (7\text{-}36)$$

and

$$f_2 = \sum_{i=1}^{n} n_i / K_i > 1.0 \qquad (7\text{-}37)$$

Table 7-2
Equilibrium Flash Criteria

	$f_1 = \sum_{i=1}^{n} K_i n_i$	$f_2 = \sum_{i=1}^{n} n_i/K_i$
Subcooled liquid	<1	>1
Bubble point	=1	>1
Two-phase condition	>1	>1
Dew point	>1	=1
Superheated vapor	>1	<1

Feed analyses of component concentrations are normally not available for complex hydrocarbon mixtures with a final boiling point of more than about 38°C (e.g. n-pentane), unless such a feed is broken down into pseudo-components (narrow boiling fractions). This enables the mole fraction and equilibrium constant, K, to be estimated, and consequently, flash calculation of the mixture can be carried out. A source of K values for light hydrocarbon systems is the De-Priester [9] charts, which are shown in Figures 7-2 and 7-3. These charts give the K values over a wide range of temperature and pressure. Because the charts are nomographs, a straight edge connecting the temperature and pressure for which K values are required will intersect curves for each compound at its K value. These K values have been obtained by calculating fugacities from an equation of state. Use of these charts for exact determination of K values requires trial-and-error calculations. Hadden and Grayson [10] have presented correlations for hydrocarbon vapor-liquid distribution ratios, and the charts from their work are shown in Figures 7-4 and 7-5. These charts can be readily used for determining the vapor-liquid distribution coefficients. Figure 7-6 shows a continuous equilibrium flash fractionation process.

The Equations

The following equations are used for the multicomponent equilibrium flash calculations.

$$f_1 = \sum_{i=1}^{n} n_i K_i < 1 \quad \text{all liquid} \tag{7-38}$$

(text continued on page 484)

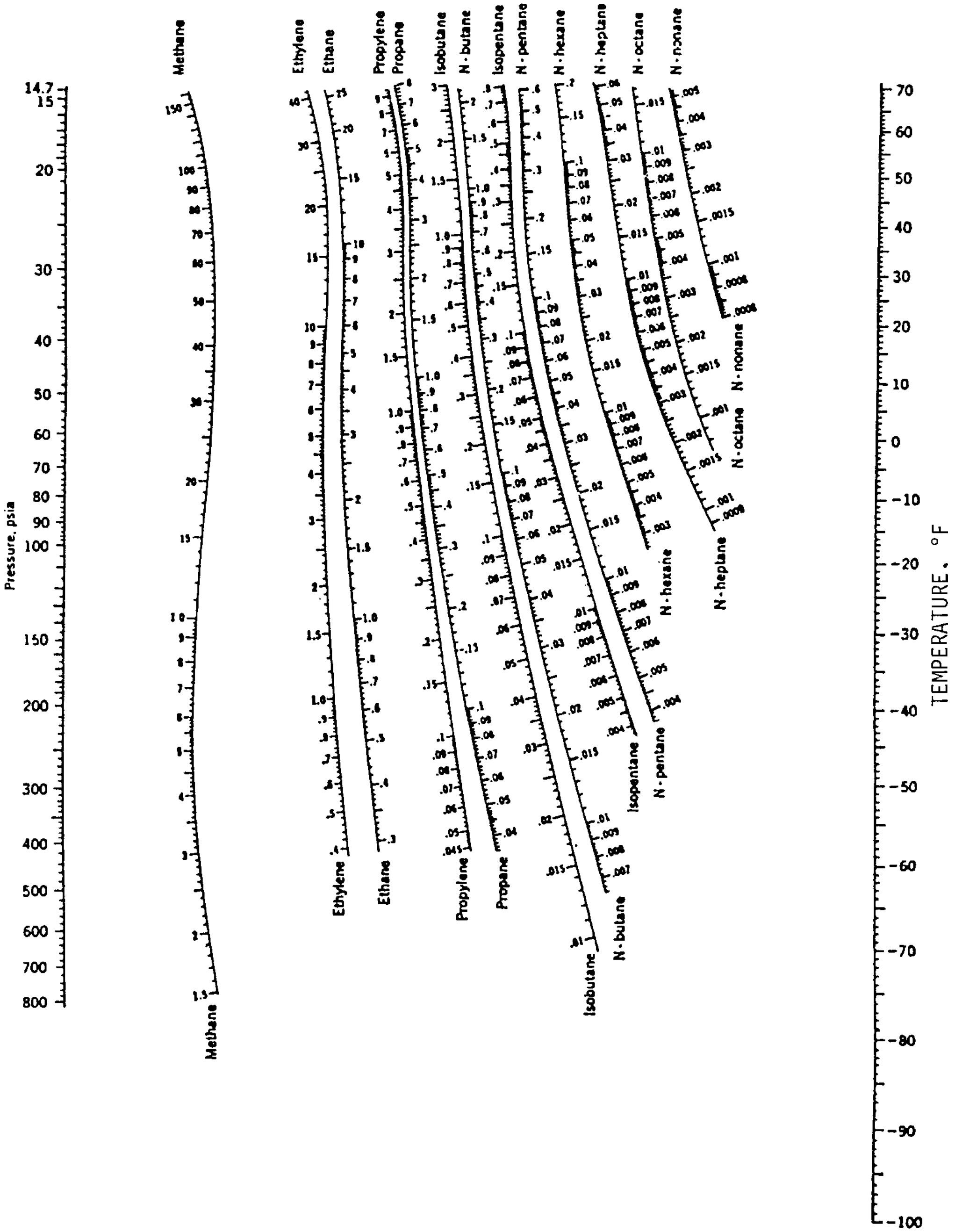


Figure 7-2. K-values for hydrocarbons, low temperature. Source: De-Priester [9].

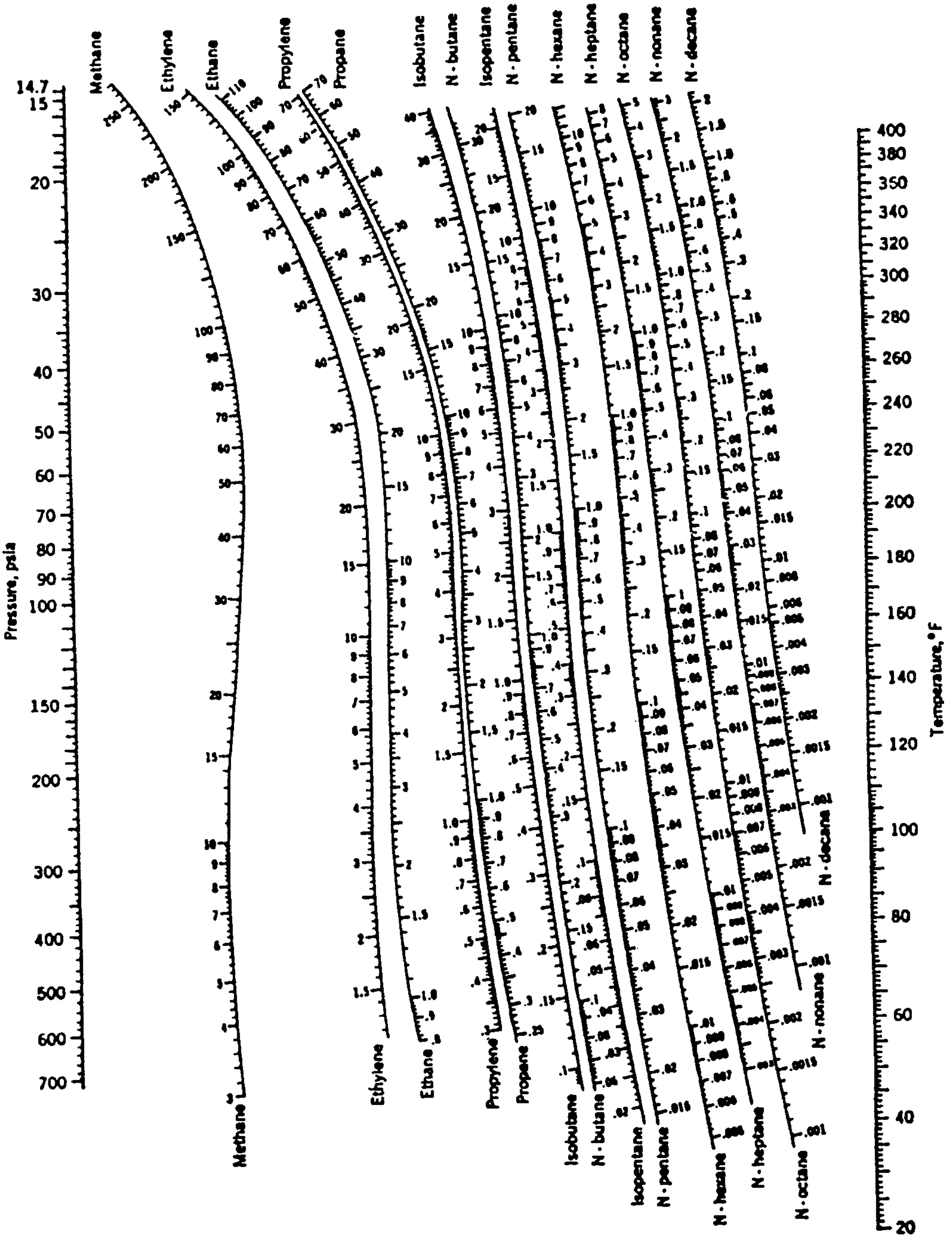
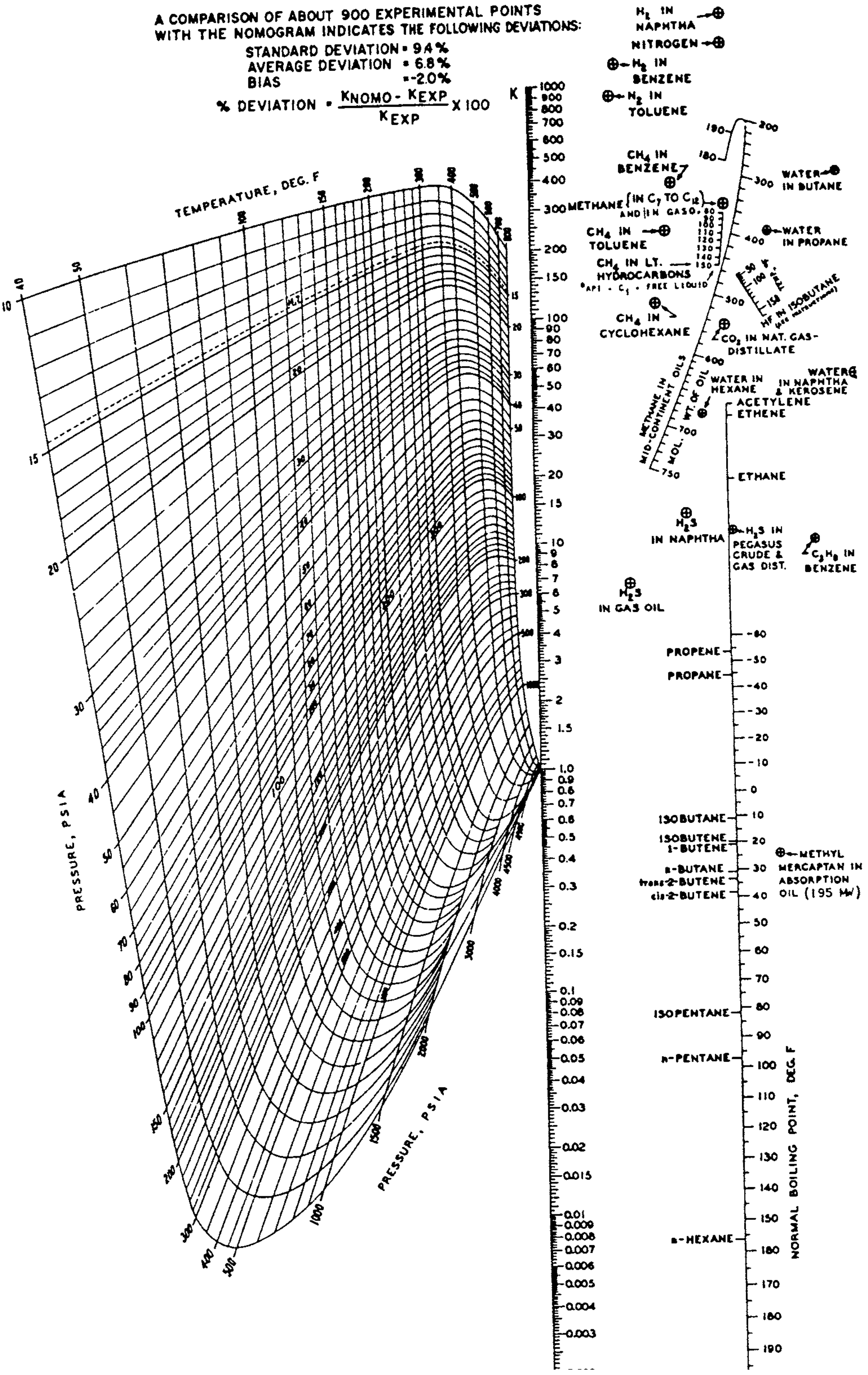


Figure 7-3. K-values for hydrocarbons, high temperature. Source: De-Priester [9].



A COMPARISON OF ABOUT 900 EXPERIMENTAL POINTS WITH THE NOMOGRAM INDICATES THE FOLLOWING DEVIATIONS:

STANDARD DEVIATION = 9.4%
AVERAGE DEVIATION = 6.8%
BIAS = -2.0%

$$\% \text{ DEVIATION} = \frac{K_{NOMO} - K_{EXP}}{K_{EXP}} \times 100$$

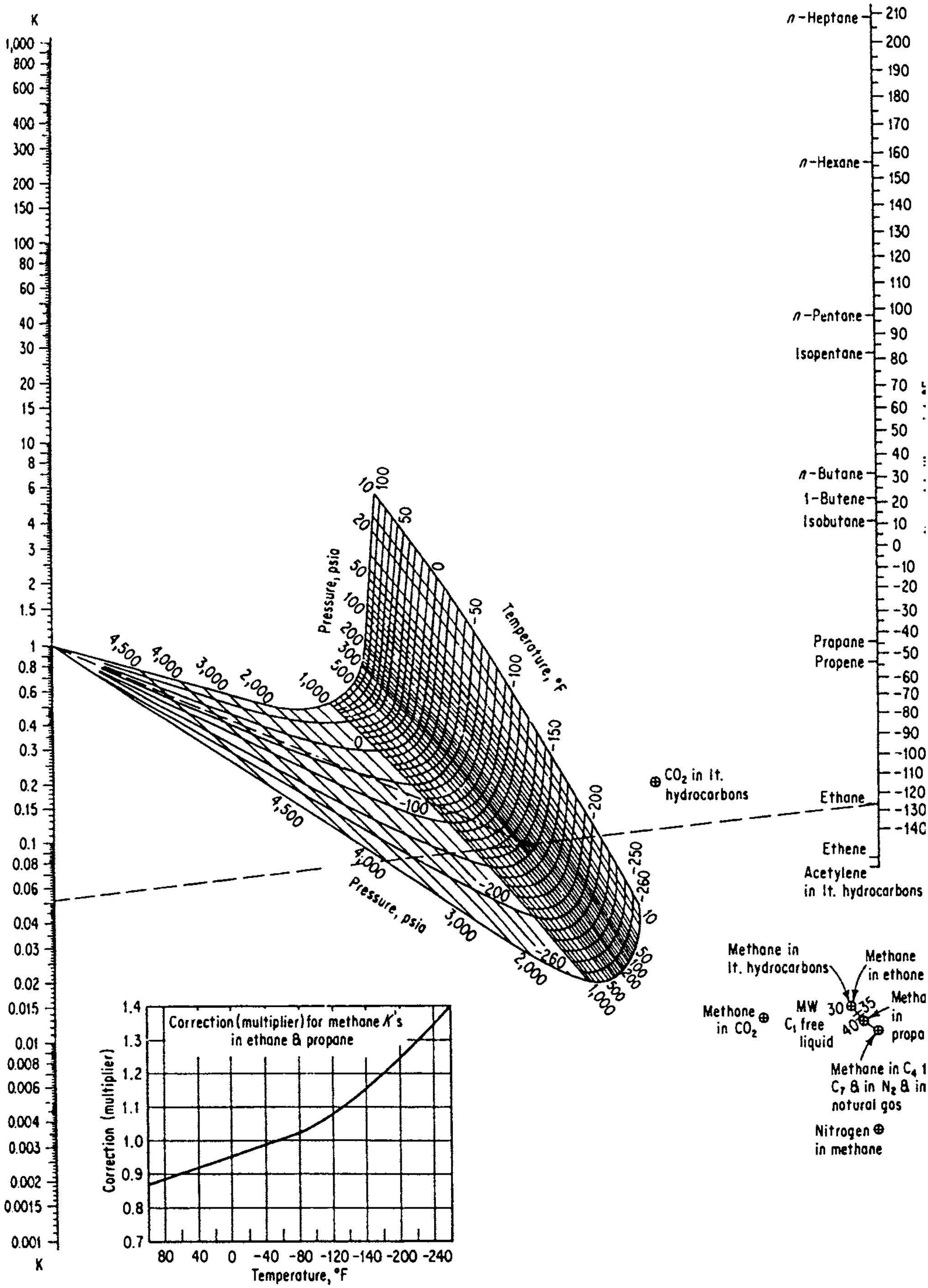


Figure 7-5. Vapor-liquid equilibrium constants, –260 to +100°F. Source: Hadden and Grayson [10].

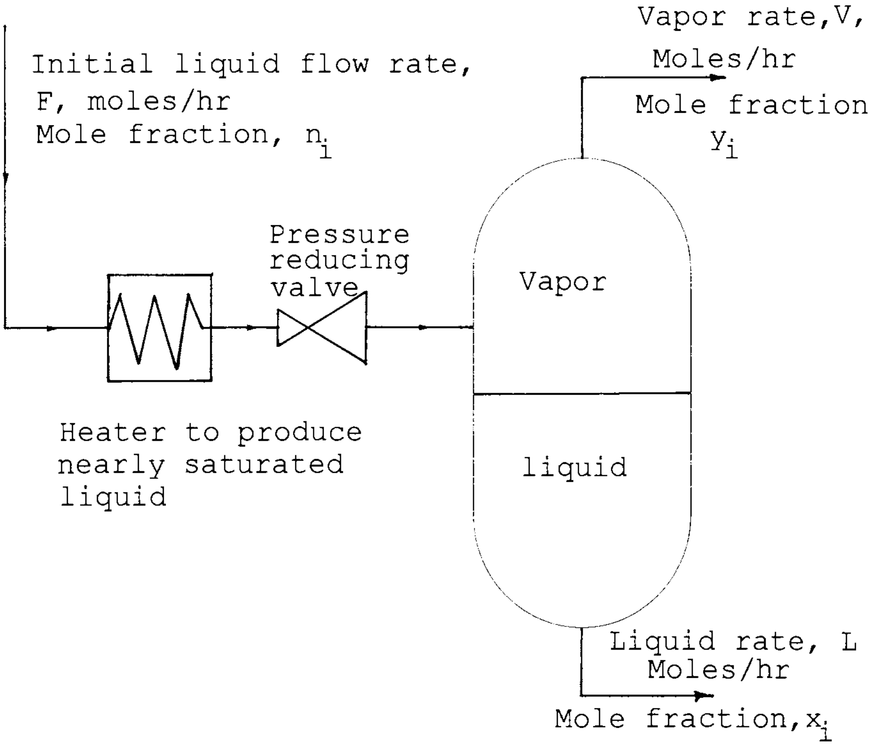


Figure 7-6. Continuous equilibrium flash fractionation.

(text continued from page 479)

$$f_2 = \sum_{i=1}^{n} n_i/K_i < 1 \quad \text{all vapor} \tag{7-39}$$

$$C_i = \frac{[M_i(K_i - 1)(R + 1)]}{(K_i + R)} \tag{7-40}$$

where R = the liquid-vapor (L/V) ratio. The new L/V ratio for each iterative calculation, R′, is determined from:

$$R' = \frac{[FR - E(R + 1)]}{[F + E(R + 1)]} \tag{7-41}$$

The constants E and F are determined by

$$E = \sum_{i=1}^{n} C_i \tag{7-42}$$

$$F = \sum_{i=1}^{n} (C_i)^2 / M_i \tag{7-43}$$

The Algorithm

The computation then determines whether $|E| < 0.001$. If $|E|$ is not less than 0.001, R is set equal to R' and the calculations of Equations 7-40, 7-41, 7-42 and 7-43 are repeated until $|E| < 0.001$.

Once $|E| < 0.001$, the calculation proceeds to find the total moles of component i in both the liquid and the vapor phases, that is, L_i and V_i. These are given by

$$L_i = \frac{M_i R}{(K_i + R)} \tag{7-44}$$

and

$$V_i = M_i - L_i \tag{7-45}$$

The mole fractions of components in the feed, the liquid and vapor phases are evaluated as follows:

$$n_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{7-46}$$

$$X_i = \frac{L_i}{\sum_{i=1}^{n} L_i} \tag{7-47}$$

and

$$Y_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \tag{7-48}$$

where

$$\sum_{i=1}^{n} n_i = \sum_{i=1}^{n} X_i = \sum_{i=1}^{n} Y_i = 1 \tag{7-49}$$

The method described here is based on the vapor-liquid equilibrium relationships given in handbooks available from the Gas Processors Suppliers Association. This technique will handle flash calculations with feed streams containing up to 15 components. As an added feature, the calculation will check the feed composition at flash conditions for dew point or bubble point condition (i.e., whether the feed is either all vapor or all liquid). These checks are done before the flash calculations are started. If the feed is above the dew point or below the bubble point, an appropriate message is displayed on the computer screen. A default value for R (L/V) = 1.0 is used to start the iterative process.

Nomenclature

E,F = constants
K_i = equilibrium flash constant for each component in the feed stream
L_i = total moles of component i in the liquid phase
L = total moles of liquid at equilibrium conditions
M_i = total moles of component i in the feed stream
n_i = mole fraction of component i in the feed stream
R = liquid-vapor (L/V) ratio
R′ = new L/V ratio for each iteration calculation
V = total moles of vapor at equilibrium conditions
V_i = total moles of component i in the vapor phase
X_i = mole fraction of component i in the liquid phase
Y_i = mole fraction of component i in the vapor phase

TOWER SIZING FOR VALVE TRAYS

Introduction

Many types of trays are used in both fractionating and absorption columns. In a fractionating column, the bubble caps with the weirs and downcomers maintain a liquid level on the trays. The liquid flows across the tray via the downcomer and across the next tray in the opposite direction, and the vapor flows up through the caps and the slots, thus mixing with the liquid. Figures 7-7 and 7-8 show a section of the column distributor and different types of packings. Figure 7-9 illustrates the vapor flows through bubble cap, sieve, and valve trays. The riser in the bubble cap can aid the design of the tray to prevent liquid from “weeping” through the vapor passage. Sieve or valve trays control weeping by vapor velocity. The bubble cap tray has the highest turn down

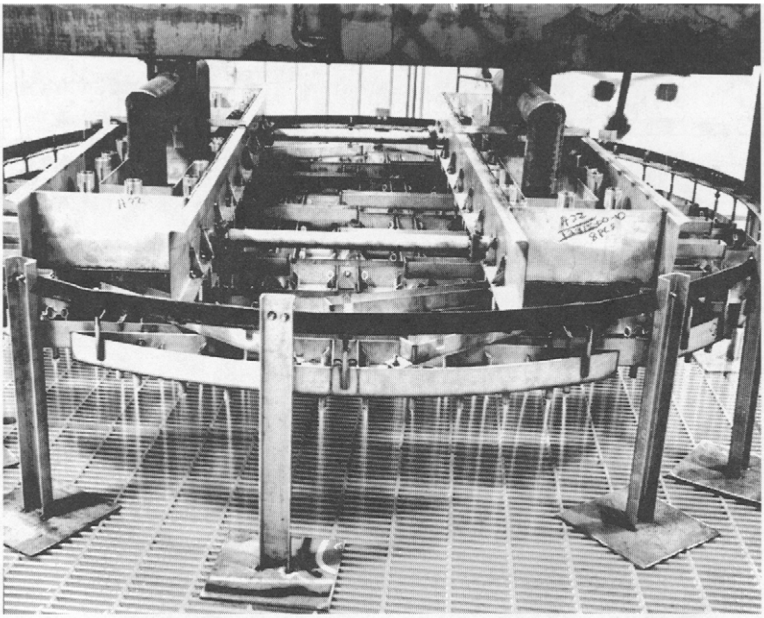


Figure 7-7. Nutter Engineering MTS-109 multi-pan two-stage liquid distributor Courtesy of Nutter Engineering.

Figure 7-8. Nutter ring random packing. Courtesy of Nutter Engineering.

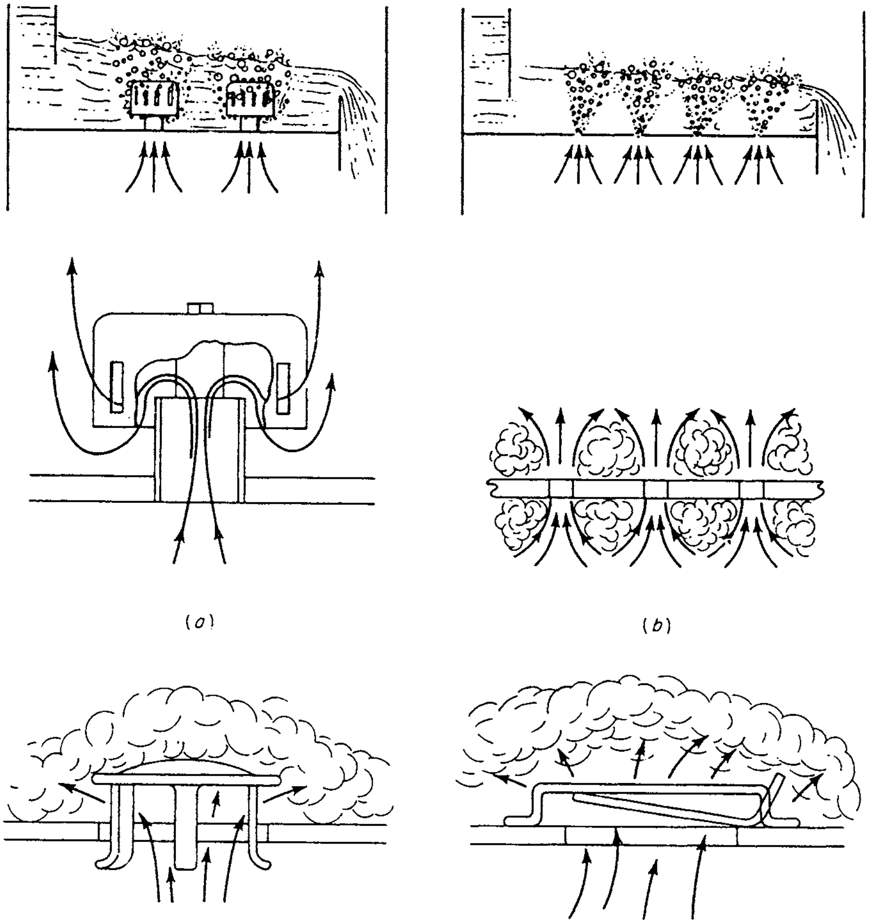


Figure 7-9. Flow through vapor passages. (a) Vapor flow through bubble cap. (b) Vapor flow through perforations. (c) Vapor flow through valves. Source: Van-Winkle [11].

ratio with the design of 8:1 to 10:1 ratio. Such trays are commonly used in glycol dehydrating columns [11].

Valve and sieve trays are favored because of lower cost and increased capacity over bubble cap trays for a given tower diameter. Sieves or perforated trays are plates with holes for vapor passage. It is simple to construct and the least expensive of the three designs. Generally, the sieve tray has a higher capacity. At low vapor rates, it is susceptible to "weeping" or dumping of the liquid through the holes. Furthermore, sieve trays are very good in fouling applications or when solids are present. They can have large holes because they are highly resistant to clogging and are easy to clean. In addition, their turndown ratio is limited.

Trayed columns give satisfactory operation over a wide range of liquid and vapor loadings. Correspondingly, valve trays can maintain high efficiencies over a wider range of operating liquid and gas rates than with sieve trays. Valve units are more complex mechanically than sieve trays, and therefore are more expensive to fabricate. The liquid and vapor rates can vary independently over a broad range in the column resulting in a satisfactory operation. At low vapor rates, unsatisfactory tray dynamics may be characterized by dumping of liquid, uneven distribution, and vapor pulsation. Alternatively, at high vapor rates, the tower floods, as the liquid is backed-up in the downcomers. At low liquid rates, poor vapor-liquid contact can result. Correspondingly, at high liquid rates, flooding and dumping can also result as the liquid capacities are exceeded in the downcomers. Valve trays are designed to have better turndown properties than sieve trays, and therefore are more flexible for varying feed rate. At the design vapor rate, valve trays have about the same efficiency as sieve trays. They can be designed for a lower pressure drop (ΔP) than sieve trays. However, they are susceptible to fouling or plugging, if dirty solutions are distilled.

Here, valve trays are used for sizing the columns. The procedure uses the Tower sizing graphs and tables from Nutter [12] and Blackwell's [13] correlation.

The Equations

The following expressions are used for the design of valve trays columns:

The density radical, R_D, is defined by

$$R_D = \left(\frac{\rho_V}{\rho_V - \rho_L} \right)^{0.5} \tag{7-50}$$

The velocity at zero liquid load is:

$$V = \exp\left\{A + B(\ln X) - C(\ln X)^2 + D(\ln X)^3 - E(\ln X)^4\right\} \tag{7-51}$$

where

$$X = \frac{\sigma}{\rho_V} \tag{7-52}$$

A, B, C, D, and E are constants:

$A = 0.22982$

$B = 0.46605$

$C = 0.03452$

$D = 0.00415$

$E = 0.00017$

Equation 7-51 is valid for $0.1 \leq X \leq 3000$.

The tray spacing factor, T_{SF}, is defined by

$$T_{SF} = G + H(\ln X) \tag{7-53}$$

where Equation 7-53 is valid for $0.1 \leq X \leq 5000$. The constants G and H for different tray spacing are given in Table 7-3. Figure 7-10 illustrates the plots of T_{SF} versus $X(\sigma/\rho_V)$ for different tray spacing.

The operating volumetric vapor flow rate, Q_V, is determined by

$$Q_V = \frac{W_V}{(3600)(\rho_V)}, \quad ft^3/s \tag{7-54}$$

The operating volumetric liquid flow rate, Q_L, is determined by

$$Q_L = \frac{W_L}{(3600)(\rho_L)}, \quad ft^3/s \tag{7-55}$$

The bubbling area, A_b, is given by

Table 7-3
Values of G and H for Each Tray Spacing

Tray Spacing (inches)	G	H
12	0.77174	–0.02964
18	0.93655	–0.02310
24	$T_{SF} = 1.0$ for all values of X	
30	0.98057	0.03220
	$T_{SF} = 1.0$ when $X < 1.85$	
36	0.96583	0.06162
	$T_{SF} = 1.0$ when $X < 1.85$	

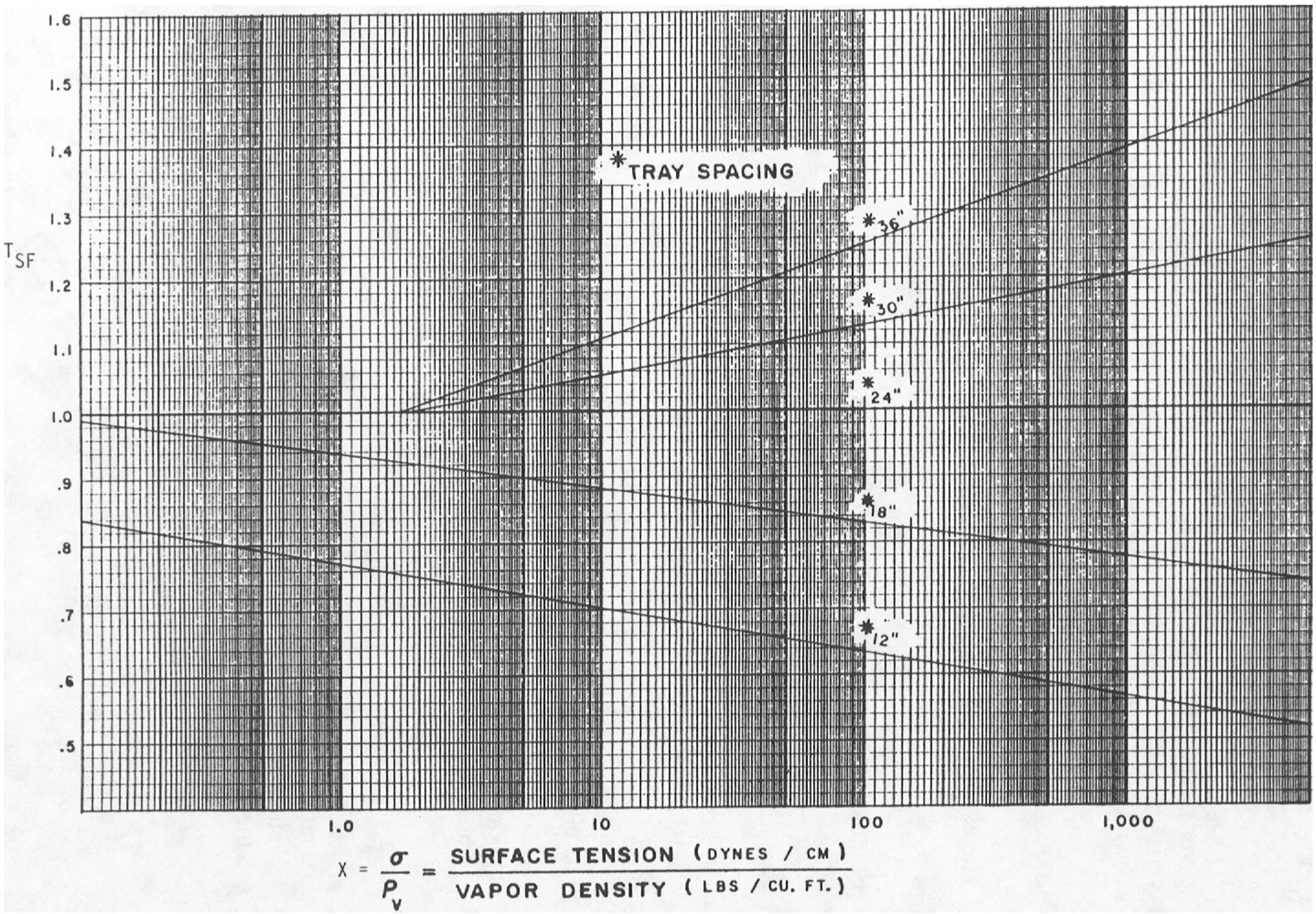


Figure 7-10. Plots of tray spacing. vs. ratio of surface tension to vapor density. By permission of Nutter Engineering.

$$A_b = \frac{(Q_V)(R_D) + Q_L}{(T_{SF})(V)(R_D)(\text{Foam fac})}, \quad \text{ft}^2 \tag{7-56}$$

If $(V)(R_D) > 0.5$, then replace 0.5 for $(V)(R_D)$ in Equation 7-56. Table 7-4 gives recommended values of the foam factor and residence time.

Using Table 7-4 to obtain both the foam factor (Foam fac) and the downcomer residence time, τ, the downcomer area, A_{DC}, is determined by

$$A_{DC} = \frac{(\tau)(Q_L)(12)}{(\text{Foam fac})(T_S)}, \quad \text{ft}^2 \tag{7-57}$$

The expression for the safety factor, S_{Fac}, is given by

$$S_{Fac} = K(X)^M \tag{7-58}$$

Equation 7-58 is valid for $3.0 \le X \le 50{,}000$.

where $K = 0.91146$
$M = -0.03821$

The tower area, A_T, is determined by

$$A_T = \frac{2(A_{DC}) + A_b}{S_{Fac}}, \quad \text{ft}^2 \tag{7-59}$$

Table 7-5 shows the tower diameter versus its cross-sectional areas, and Tables 7-6 to 7-9 give the recommended downcomer area and bubbling area distribution ratios.

The column diameter, D, is given by

$$D = \left(\frac{4.\,A_T}{\pi}\right)^{0.5} \tag{7-60}$$

The number of tray passes required is determined from Table 7-10.

Figures 7-11 and 7-12 show the dimensions of the various downcomers and the distribution area for the number of passes.

Nomenclature

A_b = bubbling area, ft^2
A_{DC} = downcomer area, ft^2
A_T = tower area, ft^2

(text continued on page 501)

Table 7-4
Recommended Values for Foam Factor and Residence Time

Fractionators	Foam factor	Downcomer Res. Time, Sec.
Straight Run		
Hydrocarbon	1.0	4.0
Low MW Alcohols	1.0	3.5
Crude Fractionator	1.0	4.5
Special		
Rich Oil (Top) Demeth. or Deeth.	0.85	4.5
Rich Oil (BTM) Demeth. or Deeth.	1.0	4.5
Hydrocarbon Still (Top)	1.0	4.0
Hydrocarbon Still (BTM)	1.0	4.5
MEA-DEA Still	0.85	4.5
Glycol-DGA Still	0.8	4.5
Sulfinol Still	1.0	5.0
H_2S Stripper	0.9	4.0
Sour Water Stripper	0.5–0.7	4.5
O_2 Stripper	1.0	3.0
Refrigerated Demeth. or Deeth. (Top)	0.8	8.0
Refrigerated Demeth. or Deeth. (BTM)	1.0	5.0
Absorbers		
Oil-Ambient Temp. (Above 0°F)	0.85	4.5
Oil-Low Temp. (Below 0°F)	0.95	4.5
DGA-DEA-MEA (Contactor)	0.75	4.5
Glycol Contactor	0.65	5.0
Sulfinol Contactor	1.0	5.0
Vacuum Towers		
Crude Vacuum	1.0	5.0

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Table 7-5
Tower Diameter Versus Cross Sectional Areas

Tower Diameter		Area	Tower Diameter		Area
Feet	Inches	Sq. Ft.	Feet	Inches	Sq. Ft.
2'-0"	24"	3.142	21'-0"	252"	346.361
2'-6"	30"	4.909	21'-6"	258"	363.050
3'-0"	36"	7.069	22'-0"	264"	380.133
3'-6"	42"	9.621	22'-6"	270"	397.608
4'-0"	48"	12.566	23'-0"	276"	415.476
4'-6"	54"	15.904	23'-6"	282"	433.736
5'-0"	60"	19.635	24'-0"	288"	452.389
5'-6"	66"	23.758	24'-6"	294"	471.435
6'-0"	72"	28.274	25'-0"	300"	490.874
6'-6"	78"	33.183	25'-6"	306"	510.705
7'-0"	84"	38.485	26'-0"	312"	530.929
7'-6"	90"	44.179	26'-6"	318"	551.546
8'-0"	96"	50.266	27'-0"	324"	572.555
8'-6"	102"	56.745	27'-6"	330"	593.957
9'-0"	108"	63.617	28'-0"	336"	615.752
9'-6"	114"	70.882	28'-6"	342"	637.940
10'-0"	120"	78.540	29'-0"	348"	660.520
10'-6"	126"	86.590	29'-6"	354"	683.493
11'-0"	132"	95.033	30'-0"	360"	706.858
11'-6"	138"	103.869	30'-6"	366"	730.617
12'-0"	144"	113.098	31'-0"	372"	754.768
12'-6"	150"	122.719	31'-6"	378"	779.311
13'-0"	156"	132.733	32'-0"	384"	804.248
13'-6"	162"	143.139	32'-6"	390"	829.577
14'-0"	168"	153.938	33'-0"	396"	855.299
14'-6"	174"	165.130	33'-6"	402"	881.413
15'-0"	180"	176.715	34'-0"	408"	907.920
15'-6"	186"	188.692	34'-6"	414"	934.820
16'-0"	192"	201.062	35'-0"	420"	962.113
16'-6"	198"	213.825	35'-6"	426"	989.798
17'-0"	204"	226.980	36'-0"	432"	1017.876
17'-6"	210"	240.528	36'-6"	438"	1046.347
18'-0"	216"	254.469	37'-0"	444"	1075.210
18'-6"	222"	268.803	37'-6"	450"	1104.466
19'-0"	228"	283.529	38'-0"	456"	1134.115
19'-6"	234"	298.648	38'-6"	462"	1164.156
20'-0"	240"	314.159	39'-0"	468"	1194.591
20'-6"	246"	330.064	39'-6"	476"	1225.417

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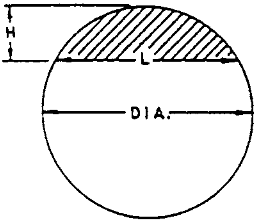
Table 7-6
Downcomer Dimensions



TABLES OF DOWNCOMER DIMENSIONS

H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t
.0000	.0000	.0000	.0200	.2800	.0048	.0400	.3919	.0134	.0600	.4750	.0245	.0800	.5426	.0375
.0005	.0447	.0000	.0205	.2834	.0050	.0405	.3943	.0137	.0605	.4768	.0248	.0805	.5441	.0378
.0010	.0632	.0001	.0210	.2868	.0051	.0410	.3966	.0139	.0610	.4787	.0251	.0810	.5457	.0382
.0015	.0774	.0001	.0215	.2901	.0053	.0415	.3989	.0142	.0615	.4805	.0254	.0815	.5472	.0385
.0020	.0894	.0002	.0220	.2934	.0055	.0420	.4012	.0144	.0620	.4823	.0257	.0820	.5487	.0389
.0025	.0999	.0002	.0225	.2966	.0057	.0425	.4035	.0147	.0625	.4841	.0260	.0825	.5502	.0392
.0030	.1094	.0003	.0230	.2998	.0059	.0430	.4057	.0149	.0630	.4859	.0263	.0830	.5518	.0396
.0035	.1181	.0004	.0235	.3030	.0061	.0435	.4080	.0152	.0635	.4877	.0266	.0835	.5533	.0399
.0040	.1262	.0004	.0240	.3061	.0063	.0440	.4102	.0155	.0640	.4895	.0270	.0840	.5548	.0403
.0045	.1339	.0005	.0245	.3092	.0065	.0445	.4124	.0157	.0645	.4913	.0273	.0845	.5563	.0406
.0050	.1411	.0006	.0250	.3122	.0067	.0450	.4146	.0160	.0650	.4931	.0276	.0850	.5578	.0410
.0055	.1479	.0007	.0255	.3153	.0069	.0455	.4168	.0162	.0655	.4948	.0279	.0855	.5592	.0413
.0060	.1545	.0008	.0260	.3183	.0071	.0460	.4190	.0165	.0660	.4966	.0282	.0860	.5607	.0417
.0065	.1607	.0009	.0265	.3212	.0073	.0465	.4211	.0168	.0665	.4983	.0285	.0865	.5622	.0421
.0070	.1667	.0010	.0270	.3242	.0075	.0470	.4233	.0171	.0670	.5000	.0288	.0870	.5637	.0424
.0075	.1726	.0011	.0275	.3271	.0077	.0475	.4254	.0173	.0675	.5018	.0292	.0875	.5651	.0428
.0080	.1782	.0012	.0280	.3299	.0079	.0480	.4275	.0176	.0680	.5035	.0295	.0880	.5666	.0431
.0085	.1836	.0013	.0285	.3328	.0081	.0485	.4296	.0179	.0685	.5052	.0298	.0885	.5680	.0435
.0090	.1889	.0014	.0290	.3356	.0083	.0490	.4317	.0181	.0690	.5069	.0301	.0890	.5695	.0439
.0095	.1940	.0016	.0295	.3384	.0085	.0495	.4338	.0184	.0695	.5086	.0304	.0895	.5709	.0442
.0100	.1990	.0017	.0300	.3412	.0087	.0500	.4359	.0187	.0700	.5103	.0308	.0900	.5724	.0446
.0105	.2039	.0018	.0305	.3439	.0090	.0505	.4379	.0190	.0705	.5120	.0311	.0905	.5738	.0449
.0110	.2086	.0020	.0310	.3466	.0092	.0510	.4400	.0193	.0710	.5136	.0314	.0910	.5752	.0453
.0115	.2132	.0021	.0315	.3493	.0094	.0515	.4420	.0195	.0715	.5153	.0318	.0915	.5766	.0457
.0120	.2178	.0022	.0320	.3520	.0096	.0520	.4441	.0198	.0720	.5170	.0321	.0920	.5781	.0460
.0125	.2222	.0024	.0325	.3546	.0098	.0525	.4461	.0201	.0725	.5186	.0324	.0925	.5795	.0464
.0130	.2265	.0025	.0330	.3573	.0101	.0530	.4481	.0204	.0730	.5203	.0327	.0930	.5809	.0468
.0135	.2308	.0027	.0335	.3599	.0103	.0535	.4501	.0207	.0735	.5219	.0331	.0935	.5823	.0472
.0140	.2350	.0028	.0340	.3625	.0105	.0540	.4520	.0210	.0740	.5235	.0334	.0940	.5837	.0475
.0145	.2391	.0030	.0345	.3650	.0108	.0545	.4540	.0212	.0745	.5252	.0337	.0945	.5850	.0479
.0150	.2431	.0031	.0350	.3676	.0110	.0550	.4560	.0215	.0750	.5268	.0341	.0950	.5864	.0483
.0155	.2471	.0033	.0355	.3701	.0112	.0555	.4579	.0218	.0755	.5284	.0344	.0955	.5878	.0486
.0160	.2510	.0034	.0360	.3726	.0115	.0560	.4598	.0221	.0760	.5300	.0347	.0960	.5892	.0490
.0165	.2548	.0036	.0365	.3751	.0117	.0565	.4618	.0224	.0765	.5316	.0351	.0965	.5906	.0494
.0170	.2585	.0037	.0370	.3775	.0119	.0570	.4637	.0227	.0770	.5332	.0354	.0970	.5919	.0498
.0175	.2622	.0039	.0375	.3800	.0122	.0575	.4656	.0230	.0775	.5348	.0358	.0975	.5933	.0501
.0180	.2659	.0041	.0380	.3824	.0124	.0580	.4675	.0233	.0780	.5363	.0361	.0980	.5946	.0505
.0185	.2695	.0042	.0385	.3848	.0127	.0585	.4694	.0236	.0785	.5379	.0364	.0985	.5960	.0509
.0190	.2730	.0044	.0390	.3872	.0129	.0590	.4712	.0230	.0790	.5395	.0368	.0990	.5973	.0513
.0195	.2765	.0046	.0395	.3896	.0132	.0595	.4731	.0242	.0795	.5410	.0371	.0995	.5987	.0517

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Table 7-7
Downcomer Dimensions

H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t
.1000	.6000	.0520	.1275	.6671	.0743	.1550	.7238	.0986	.1825	.7725	.1249	.2100	.8146	.1527
.1005	.6013	.0524	.1280	.6682	.0747	.1555	.7248	.0991	.1830	.7733	.1253	.2105	.8153	.1532
.1010	.6027	.0528	.1285	.6693	.0751	.1560	.7257	.0996	.1835	.7742	.1258	.2110	.8160	.1537
.1015	.6040	.0532	.1290	.6704	.0755	.1565	.7267	.1000	.1840	.7750	.1263	.2115	.8167	.1542
.1020	.6053	.0536	.1295	.6715	.0760	.1570	.7276	.1005	.1845	.7758	.1268	.2120	.8174	.1547
.1025	.6066	.0540	.1300	.6726	.0764	.1575	.7285	.1009	.1850	.7766	.1273	.2125	.8182	.1553
.1030	.6079	.0544	.1305	.6737	.0768	.1580	.7295	.1014	.1855	.7774	.1278	.2130	.8189	.1558
.1035	.6092	.0547	.1310	.6748	.0773	.1585	.7304	.1019	.1860	.7782	.1283	.2135	.8196	.1563
.1040	.6105	.0551	.1315	.6759	.0777	.1590	.7314	.1023	.1865	.7790	.1288	.2140	.8203	.1568
.1045	.6118	.0555	.1320	.6770	.0781	.1595	.7323	.1028	.1870	.7798	.1293	.2145	.8210	.1573
.1050	.6131	.0559	.1325	.6781	.0785	.1600	.7332	.1033	.1875	.7806	.1298	.2150	.8216	.1579
.1055	.6144	.0563	.1330	.6791	.0790	.1605	.7341	.1037	.1880	.7814	.1303	.2155	.8223	.1584
.1060	.6157	.0567	.1335	.6802	.0794	.1610	.7351	.1042	.1885	.7822	.1308	.2160	.8230	.1589
.1065	.6170	.0571	.1340	.6813	.0798	.1615	.7360	.1047	.1890	.7830	.1313	.2165	.8237	.1594
.1070	.6182	.0575	.1345	.6824	.0803	.1620	.7369	.1051	.1895	.7838	.1318	.2170	.8244	.1600
.1075	.6195	.0579	.1350	.6834	.0807	.1625	.7378	.1056	.1900	.7846	.1323	.2175	.8251	.1605
.1080	.6208	.0583	.1355	.6845	.0811	.1630	.7387	.1061	.1905	.7854	.1328	.2180	.8258	.1610
.1085	.6220	.0587	.1360	.6856	.0816	.1635	.7396	.1066	.1910	.7862	.1333	.2185	.8265	.1615
.1090	.6233	.0591	.1365	.6866	.0820	.1640	.7406	.1070	.1915	.7870	.1338	.2190	.8271	.1621
.1095	.6245	.0595	.1370	.6877	.0825	.1645	.7415	.1075	.1920	.7877	.1343	.2195	.8278	.1626
.1100	.6258	.0598	.1375	.6887	.0829	.1650	.7424	.1080	.1925	.7885	.1348	.2200	.8285	.1631
.1105	.6270	.0602	.1380	.6898	.0833	.1655	.7433	.1084	.1930	.7893	.1353	.2205	.8292	.1636
.1110	.6283	.0606	.1385	.6908	.0838	.1660	.7442	.1089	.1935	.7901	.1358	.2210	.8298	.1642
.1115	.6295	.0610	.1390	.6919	.0842	.1665	.7451	.1094	.1940	.7909	.1363	.2215	.8305	.1647
.1120	.6307	.0614	.1395	.6929	.0847	.1670	.7460	.1099	.1945	.7916	.1368	.2220	.8312	.1652
.1125	.6320	.0619	.1400	.6940	.0851	.1675	.7468	.1103	.1950	.7924	.1373	.2225	.8319	.1658
.1130	.6332	.0623	.1405	.6950	.0855	.1680	.7477	.1108	.1955	.7932	.1378	.2230	.8325	.1663
.1135	.6344	.0627	.1410	.6960	.0860	.1685	.7486	.1113	.1960	.7939	.1383	.2235	.8332	.1668
.1140	.6356	.0631	.1415	.6971	.0864	.1690	.7495	.1118	.1965	.7947	.1388	.2240	.8338	.1674
.1145	.6368	.0635	.1420	.6981	.0869	.1695	.7504	.1122	.1970	.7955	.1393	.2245	.8345	.1679
.1150	.6380	.0639	.1425	.6991	.0873	.1700	.7513	.1127	.1975	.7962	.1398	.2250	.8352	.1684
.1155	.6392	.0643	.1430	.7001	.0878	.1705	.7521	.1132	.1980	.7970	.1403	.2255	.8358	.1689
.1160	.6404	.0647	.1435	.7012	.0882	.1710	.7530	.1137	.1985	.7977	.1409	.2260	.8365	.1695
.1165	.6416	.0651	.1440	.7022	.0886	.1715	.7539	.1142	.1990	.7985	.1414	.2265	.8371	.1700
.1170	.6428	.0655	.1445	.7032	.0891	.1720	.7548	.1146	.1995	.7992	.1419	.2270	.8378	.1705
.1175	.6440	.0659	.1450	.7042	.0895	.1725	.7556	.1151	.2000	.8000	.1424	.2275	.8384	.1711
.1180	.6452	.0663	.1455	.7052	.0900	.1730	.7565	.1156	.2005	.8007	.1429	.2280	.8391	.1716
.1185	.6464	.0667	.1460	.7062	.0904	.1735	.7574	.1161	.2010	.8015	.1434	.2285	.8397	.1721
.1190	.6476	.0671	.1465	.7072	.0909	.1740	.7582	.1166	.2015	.8022	.1439	.2290	.8404	.1727
.1195	.6488	.0676	.1470	.7082	.0913	.1745	.7591	.1171	.2020	.8030	.1444	.2295	.8410	.1732
.1200	.6499	.0680	.1475	.7092	.0918	.1750	.7599	.1175	.2025	.8037	.1449	.2300	.8417	.1738
.1205	.6511	.0684	.1480	.7102	.0922	.1755	.7608	.1180	.2030	.8045	.1454	.2305	.8423	.1743
.1210	.6523	.0688	.1485	.7112	.0927	.1760	.7616	.1185	.2035	.8052	.1460	.2310	.8429	.1748
.1215	.6534	.0692	.1490	.7122	.0932	.1765	.7625	.1190	.2040	.8059	.1465	.2315	.8436	.1754
.1220	.6546	.0696	.1495	.7132	.0936	.1770	.7633	.1195	.2045	.8067	.1470	.2320	.8442	.1759
.1225	.6557	.0701	.1500	.7141	.0941	.1775	.7642	.1200	.2050	.8074	.1475	.2325	.8449	.1764
.1230	.6569	.0705	.1505	.7151	.0945	.1780	.7650	.1204	.2055	.8081	.1480	.2330	.8455	.1770
.1235	.6580	.0709	.1510	.7161	.0950	.1785	.7659	.1209	.2060	.8089	.1485	.2335	.8461	.1775
.1240	.6592	.0713	.1515	.7171	.0954	.1790	.7667	.1214	.2065	.8096	.1490	.2340	.8467	.1781
.1245	.6603	.0717	.1520	.7180	.0959	.1795	.7675	.1219	.2070	.8103	.1496	.2345	.8474	.1786
.1250	.6614	.0721	.1525	.7190	.9063	.1800	.7684	.1224	.2075	.8110	.1501	.2350	.8480	.1791
.1255	.6626	.0726	.1530	.7200	.0968	.1805	.7692	.1229	.2080	.8118	.1506	.2355	.8486	.1797
.1260	.6637	.0730	.1535	.7209	.0973	.1810	.7700	.1234	.2085	.8125	.1511	.2360	.8492	.1802
.1265	.6648	.0734	.1540	.7219	.0977	.1815	.7709	.1239	.2090	.8132	.1516	.2365	.8499	.1808
.1270	.6659	.0738	.1545	.7229	.0982	.1820	.7717	.1244	.2095	.8139	.1521	.2370	.8505	.1813

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Table 7-8
Downcomer Dimensions

H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t
.2375	.8511	.1818	.2650	.8827	.2122	.2925	.9098	.2436	.3200	.9330	.2759	.3475	.9524	.3089
.2380	.8517	.1824	.2655	.8832	.2128	.2930	.9103	.2442	.3205	.9333	.2765	.3480	.9527	.3095
.2385	.8523	.1829	.2660	.8837	.2133	.2935	.9107	.2448	.3210	.9337	.2771	.3485	.9530	.3101
.2390	.8529	.1835	.2665	.8843	.2139	.2940	.9112	.2453	.3215	.9341	.2777	.3490	.9533	.3107
.2395	.8536	.1840	.2670	.8848	.2145	.2945	.9116	.2459	.3220	.9345	.2782	.3495	.9536	.3113
.2400	.8542	.1845	.2675	.8853	.2150	.2950	.9121	.2465	.3225	.9349	.2788	.3500	.9539	.3119
.2405	.8548	.1851	.2680	.8858	.2156	.2955	.9125	.2471	.3230	.9352	.2794	.3505	.9543	.3125
.2410	.8554	.1856	.2685	.8864	.2161	.2960	.9130	.2477	.3235	.9356	.2800	.3510	.9546	.3131
.2415	.8560	.1862	.2690	.8869	.2167	.2965	.9134	.2482	.3240	.9360	.2806	.3515	.9549	.3137
.2420	.8566	.1867	.2695	.8874	.2173	.2970	.9139	.2488	.3245	.9364	.2812	.3520	.9552	.3143
.2425	.8572	.1873	.2700	.8879	.2178	.2975	.9143	.2494	.3250	.9367	.2818	.3525	.9555	.3150
.2430	.8578	.1878	.2705	.8884	.2184	.2980	.9148	.2500	.3255	.9371	.2824	.3530	.9558	.3156
.2435	.8584	.1884	.2710	.8890	.2190	.2985	.9152	.2506	.3260	.9375	.2830	.3535	.9561	.3162
.2440	.8590	.1889	.2715	.8895	.2195	.2990	.9156	.2511	.3265	.9379	.2511	.3540	.9564	.3168
.1445	.8596	.1895	.2720	.8900	.2201	.2995	.9161	.2517	.3270	.9382	.2842	.3545	.9567	.3174
.2450	.8602	.1900	.2725	.8905	.2207	.3000	.9165	.2523	.3275	.9386	.2848	.3550	.9570	.3180
.2455	.8608	.1906	.2730	.8910	.2212	.3005	.9170	.2529	.3280	.9390	.2854	.3555	.9573	.3186
.2460	.8614	.1911	.2735	.8915	.2218	.3010	.9174	.2535	.3285	.9393	.2860	.3560	.9576	.3192
.2465	.8619	.1917	.2740	.8920	.2224	.3015	.9178	.2541	.3290	.9397	.2866	.3565	.9579	.3198
.2470	.8625	.1922	.2745	.8925	.2229	.3020	.9138	.2547	.3295	.9401	.2872	.3570	.9582	.3204
.2475	.8631	.1927	.2750	.8930	.2235	.3025	.9187	.2552	.3300	.9404	.2878	.3575	.9585	.3211
.2480	.8637	.1933	.2755	.8935	.2241	.3030	.9191	.2558	.3305	.9408	.2884	.3580	.9588	.3217
.2485	.8643	.1938	.2760	.8940	.2246	.3035	.9195	.2564	.3310	.9411	.2890	.3585	.9591	.3223
.2490	.8649	.1944	.2765	.8945	.2252	.3040	.9200	.2570	.3315	.9415	.2896	.3590	.9594	.3229
.2495	.8654	.1949	.2770	.8950	.2258	.3045	.9204	.2576	.3320	.9419	.2902	.3595	.9597	.3235
.2500	.8660	.1955	.2775	.8955	.2264	.3050	.9208	.2582	.3325	.9422	.2908	.3600	.9600	.3241
.2505	.8666	.1961	.2780	.8960	.2269	.3055	.9212	.2588	.3330	.9426	.2914	.3605	.9603	.3247
.2510	.8672	.1966	.2785	.8965	.2275	.3060	.9217	.2593	.3335	.9429	.2920	.3610	.9606	.3253
.2515	.8678	.1972	.2790	.8970	.2281	.3065	.9221	.2599	.3340	.9433	.2926	.3615	.9609	.3259
.2520	.8683	.1977	.2795	.8975	.2286	.3070	.9225	.2605	.3345	.9436	.2932	.3620	.9612	.3265
.2525	.8689	.1983	.2800	.8980	.2292	.3075	.9229	.2611	.3350	.9440	.2938	.3625	.9614	.3272
.2530	.8695	.1988	.2805	.8985	.2298	.3080	.9233	.2617	.3335	.9443	.2944	.3630	.9617	.3278
.2535	.8700	.1994	.2810	.8990	.2304	.3085	.9237	.2623	.3360	.9447	.2950	.3635	.9620	.3284
.2540	.8706	.1999	.2815	.8995	.2309	.3090	.9242	.2629	.3365	.9450	.2956	.3640	.9623	.3290
.2545	.8712	.2005	.2820	.8999	.2315	.3095	.9246	.2635	.3370	.9454	.2962	.3645	.9626	.3296
.2550	.8717	.2010	.2825	.9004	.2321	.3100	.9250	.2640	.3375	.9457	.2968	.3650	.9629	.3302
.2555	.8723	.2016	.2830	.9009	.2326	.3105	.9254	.2646	.3380	.9461	.2974	.3655	.9631	.3308
.2560	.8728	.2021	.2835	.9014	.2332	.3110	.9258	.2652	.3385	.9464	.2980	.3660	.9634	.3315
.2565	.8734	.2027	.2840	.9019	.2338	.3115	.9262	.2658	.3390	.9467	.2986	.3665	.9637	.3321
.2575	.8745	.2038	.2850	.9028	.2349	.3125	.9270	.2670	.3400	.9474	.2998	.3675	.9642	.3333
.2580	.8751	.2044	.2855	.9033	.2355	.3130	.9274	.2676	.3405	.9478	.3004	.3680	.9645	.3339
.2585	.8756	.2049	.2860	.9038	.2361	.3135	.9278	.2682	.3410	.9481	.3010	.3685	.9648	.3345
.2590	.8762	.2055	.2865	.9043	.2367	.3140	.9282	.2688	.3415	.9484	.3016	.3690	.9651	.3351
.2595	.8767	.2060	.2870	.9047	.2872	.3145	.9286	.2693	.3420	.9488	.3022	.3695	.9653	.3357
.2600	.8773	.2066	.2875	.9052	.2378	.3150	.9290	.2699	.3425	.9491	.3028	.3700	.9656	.3364
.2605	.8778	.2072	.2880	.9057	.2384	.3155	.9294	.2705	.3430	.9494	.3034	.3705	.9659	.3370
.2610	.8784	.2077	.2885	.9061	.2390	.3160	.9298	.2711	.3435	.9498	.3040	.3710	.9661	.3376
.2615	.8789	.2083	.2890	.9066	.2395	.3165	.9302	.2717	.3440	.9501	.3046	.3715	.9664	.3382
.2620	.8794	.2088	.2895	.9071	.2401	.3170	.9306	.2723	.3445	.9504	.3053	.3720	.9667	.3388
.2625	.8800	.2094	.2900	.9075	.2407	.3175	.9310	.2729	.3450	.9507	.3059	.3750	.9669	.3394
.2630	.8805	.2100	.2905	.9080	.2413	.3180	.9314	.2735	.3455	.9511	.3065	.3730	.9672	.3401
.2635	.8811	.2105	.2910	.9084	.2419	.3185	.9318	.2741	.3460	.9514	.3071	.3735	.9676	.3407
.2640	.8816	.2111	.2915	.9089	.2424	.3190	.9322	.2747	.3465	.9517	.3077	.3740	.9677	.3413
.2645	.8821	.2116	.2920	.9094	.2430	.3195	.9326	.2753	.3470	.9520	.3083	.3745	.9680	.3419

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Table 7-9
Downcomer Dimensions

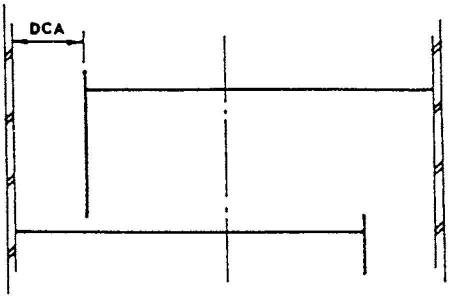
H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t	H/DIA	L/DIA	A_d/A_t
.3750	.9682	.3425	.4000	.9798	.3735	.4250	.9887	.4049	.4500	.9950	.4364	.4750	.9987	.4682
.3755	.9685	.3431	.4005	.9800	.3742	.4255	.9888	.4055	.4505	.9951	.4371	.4755	.9988	.4688
.3760	.9688	.3438	.4010	.9802	.3748	.4260	.9890	.4061	.4510	.9952	.4377	.4760	.9988	.4695
.3765	.9690	.3444	.4015	.9804	.3754	.4265	.9891	.4068	.4515	.9953	.4383	.4765	.9989	.4701
.3770	.9693	.3450	.4020	.9806	.3760	.4270	.9893	.4074	.4520	.9954	.4390	.4770	.9989	.4707
.3775	.9695	.3456	.4025	.9808	.3767	.4275	.9894	.4080	.4525	.9955	.4396	.4775	.9990	.4714
.3780	.9698	.3462	.4030	.9810	.3773	.4280	.9896	.4086	.4530	.9956	.4402	.4780	.9990	.4720
.3785	.9700	.3468	.4035	.9812	.3779	.4285	.9897	.4093	.4535	.9957	.4409	.4785	.9991	.4726
.3790	.9703	.3475	.4040	.9814	.3785	.4290	.9899	.4099	.4540	.9958	.4415	.4790	.9991	.4733
.3795	.9705	.3481	.4045	.9816	.3791	.4295	.9900	.4105	.4545	.9959	.4421	.4795	.9992	.4739
.3800	.9708	.3487	.4050	.9818	.3798	.4300	.9902	.4112	.4550	.9959	.4428	.4800	.9992	.4745
.3805	.9710	.3493	.4055	.9802	.3804	.4305	.9903	.4118	.4555	.9960	.4434	.4805	.9992	.4752
.3810	.9713	.3499	.4060	.9822	.3810	.4310	.9904	.4124	.4560	.9961	.4440	.4810	.9993	.4758
.3815	.9715	.3505	.4065	.9824	.3816	.4315	.9906	.4131	.4565	.9962	.4447	.4815	.9993	.4765
.3820	.9718	.3512	.4070	.9825	.3823	.4320	.9907	.4137	.4570	.9963	.4453	.4820	.9994	.4771
.3825	.9720	.3518	.4075	.9827	.3829	.4325	.9908	.4143	.4575	.9964	.4460	.4825	.9994	.4777
.3830	.9722	.3524	.4080	.9829	.3835	.4330	.9910	.4149	.4580	.9965	.4466	.4830	.9994	.4784
.3835	.9725	.3530	.4085	.9831	.3842	.4335	.9911	.4156	.4585	.9965	.4472	.4835	.9995	.4790
.3840	.9727	.3536	.4090	.9833	.3848	.4340	.9912	.4162	.4590	.9966	.4479	.4840	.9995	.4796
.3845	.9730	.3543	.4095	.9835	.3854	.4345	.9914	.4168	.4595	.9967	.4485	.4845	.9995	.4803
.3850	.9732	.3549	.4100	.9837	.3860	.4350	.9915	.4175	.4600	.9968	.4491	.4850	.9995	.4809
.3855	.9734	.3555	.4105	.9838	.3867	.4355	.9916	.4181	.4605	.9969	.4498	.4855	.9996	.4815
.3860	.9737	.3561	.4110	.9840	.3873	.4360	.9918	.4187	.4610	.9970	.4505	.4860	.9996	.4822
.3865	.9739	.3567	.4115	.9842	.3879	.4365	.9919	.4194	.4615	.9970	.4510	.4865	.9996	.4828
.3870	.9741	.3574	.4120	.9844	.3885	.4370	.9920	.4200	.4620	.9971	.4517	.4870	.9997	.4834
.3875	.9744	.3580	.4125	.9846	.3892	.4375	.9922	.4206	.4625	.9972	.4523	.4875	.9997	.4841
.3880	.9746	.3586	.4130	.9847	.3898	.4380	.9923	.4213	.4630	.9973	.4529	.4880	.9997	.4847
.3885	.9748	.3592	.4135	.9849	.3904	.4385	.9924	.4219	.4635	.9973	.4536	.4885	.9997	.4854
.3890	.9750	.3598	.4140	.9851	.3910	.4390	.9925	.4225	.4640	.9974	.4542	.4890	.9998	.4860
.3895	.9753	.3605	.4145	.9853	.3917	.4395	.9927	.4232	.4645	.9975	.4548	.4895	.9998	.4866
.3900	.9755	.3611	.4150	.9854	.3923	.4400	.9928	.4238	.4650	.9975	.4555	.4900	.9998	.4873
.3905	.9757	.3617	.4155	.9856	.3929	.4405	.9929	.4244	.4655	.9976	.4561	.4905	.9998	.4879
.3910	.9759	.3623	.4160	.9858	.3936	.4410	.9930	.4251	.4660	.9977	.4567	.4910	.9998	.4885
.3915	.9762	.3629	.4165	.9860	.3942	.4415	.9931	.4257	.4665	.9978	.4574	.4915	.9999	.4892
.3920	.9764	.3636	.4170	.9861	.3948	.4420	.9932	.4263	.4670	.9978	.4580	.4920	.9999	.4898
.3925	.9766	.3642	.4175	.9863	.3642	.4425	.9934	.4270	.4675	.9979	.4568	.4925	.9999	.4905
.3930	.9768	.3648	.4180	.9865	.3961	.4430	.9935	.4276	.4680	.9979	.4593	.4930	.9999	.4911
.3935	.9771	.3654	.4185	.9866	.3967	.4435	.9936	.4282	.4685	.9980	.4599	.4935	.9999	.4917
.3940	.9773	.3661	.4190	.9868	.3973	.4440	.9937	.4288	.4690	.9981	.4606	.4940	.9999	.4924
.3945	.9775	.3667	.4195	.9870	.3979	.4445	.9938	.4295	.4695	.9981	.4612	.4945	.9999	.4930
.3950	.9777	.3673	.4200	.9871	.3986	.4450	.9939	.4301	.4700	.9982	.4618	.4950	1.0000	.4936
.3955	.9779	.3679	.4205	.9873	.3992	.4455	.9940	.4307	.4705	.9983	.4625	.4955	1.0000	.4943
.3960	.9781	.3685	.4210	.9874	.3998	.4460	.9942	.4314	.4710	.9983	.4631	.4960	1.0000	.4949
.3965	.9783	.3692	.4215	.9876	.4005	.4465	.9943	.4320	.4715	.9984	.4637	.4965	1.0000	.4955
.3970	.9786	.3698	.4220	.9878	.4011	.4470	.9944	.4326	.4720	.9984	.4644	.4970	1.0000	.4962
.3975	.9788	.3704	.4225	.9879	.4017	.4475	.9945	.4333	.4725	.9985	.4650	.4975	1.0000	.4968
.3980	.9790	.3710	.4230	.9881	.4023	.4480	.9946	.4339	.4730	.9985	.4656	.4980	1.0000	.4975
.3985	.9792	.3717	.4235	.9882	.4030	.4485	.9947	.4345	.4735	.9986	.4663	.4985	1.0000	.4981
.3990	.9794	.3723	.4240	.9884	.4036	.4490	.9948	.4352	.4740	.9986	.4669	.4990	1.0000	.4987
.3995	.9796	.3729	.4245	.9885	.4042	.4495	.9949	.4358	.4745	.9987	.4675	.4995	1.0000	.4994
												.5000	1.0000	.5000

(By Permission of Nutter Engineering)

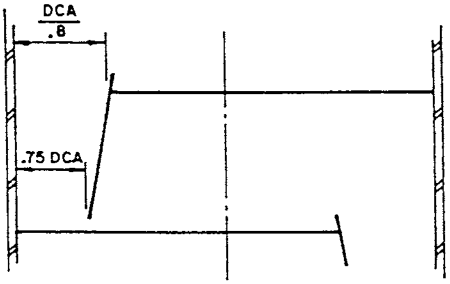
Table 7-10
Determining Number of Passes

Tray Spacing (inch)	Increase No. of Passes gpm/in. of Weir Exceeds
12	3
18	18

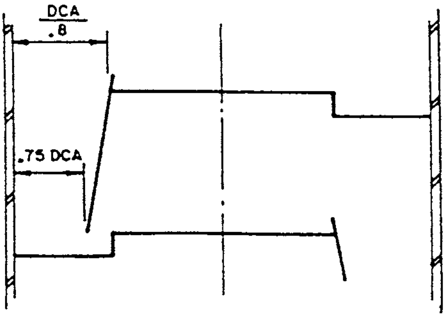
DOWNCOMER TYPES



Vertical Downcomer — Flat Deck: Used as a standard unless process reasons dictate otherwise



Sloped Downcomer — Flat Deck: Used in high pressure systems where vapor disengagement out of the top portion of the downcomer is critical.

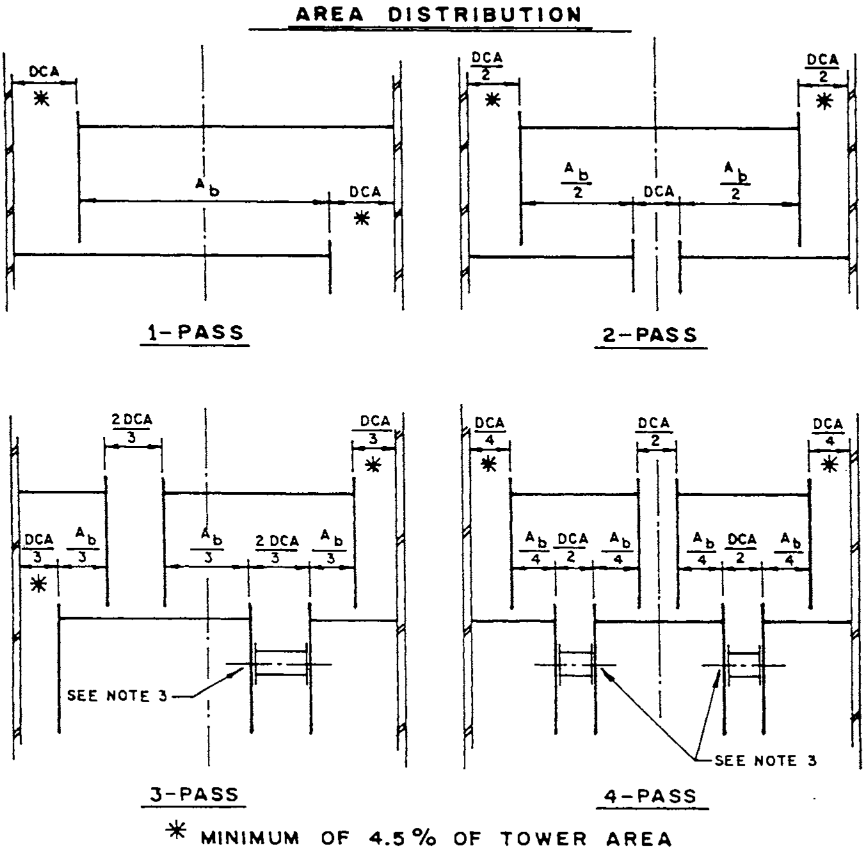


Sloped Downcomer — Recessed Pan:

(1) Used in high liquid rate systems to help alleviate hydraulic problems

(2) Used in low liquid rate systems to maintain positive downcomer seal

Figure 7-11. Dimensions of downcomer types. By permission of Nutter Engineering.



NOTES:

(1) Trays are designed using as few passes as possible. Increasing number of passes decreases efficiency and increases cost.

(2) Multipass trays are designed with equal-bubbling areas. Weir lengths or heights can be adjusted to provide uniform tray hydraulics.

(3) Vapor equalizers are a recommended option to guarantee vapor equalization between compartments.

Figure 7-12. Area distribution for different pass types. By permission of Nutter Engineering.

(text continued from page 492)

D = tower diameter, ft
Foam fac. = foam factor (see Table 7-4)
Q_L = volumetric liquid flow rate, ft^3/s
Q_V = volumetric vapor flow rate, ft^3/s
R_D = density radical
S_{fac} = safety factor
T_{SF} = tray spacing factor
V = velocity at zero liquid load, ft/sec
W_L = liquid flow rate, lb/h
W_V = vapor flow rate, lb/h

Greek Letters

ρ_L = liquid density, lb/ft^3
ρ_V = vapor density, lb/ft^3
σ = surface tension, dynes/cm

PACKED TOWER DESIGN

Introduction

Packed towers are used increasingly in a variety of applications in the chemical process industries. The reasons for this are an increase in the availability of design information, the evolution of higher-capacity and higher-efficiency mass-transfer packings, and improvements in distributors and support plates. Today, packings can be considered for most services where high numbers of theoretical stages are required for mass transfer.

Most of the fractionating columns in gas-processing plants that were previously equipped with trays can now be filled with packings. Packings, such as slotted rings in metal and plastic and plastic saddles, offer large improvements in capacity for absorption and heat transfer applications. An example of this is the use of slotted rings in a gas-plant demethanizer, which resulted in a significant capacity improvement over trays.

Packed towers are used increasingly in small fractionating towers and absorbers where accessibility is restricted. Their use is also advantageous where corrosion control is essential. Because of liquid-distribution concerns, packing still is usually not recommended for large-diameter columns or where a high turndown ratio is required. All packings tend to spread liquid as it flows downwards. This characteristic is adequate in dispersing the liquid between distribution points, but not to correct poor distribution across a tower without considerable loss of efficiency. Studies of liquid spread in tower packing have been reported by Hoak [14]. Figure 7-13 illustrates the sections of a packed tower.

Pressure Drop

The pressure drop (ΔP) through a packed bed represents the frictional loss, kinetic energy loss through the packing, and the force exerted by the operating liquid holdup. At constant ΔP, the packed bed has less volumetric liquid holdup in high-liquid-density systems. But with low-density liquids, the volumetric liquid holdup can be significantly greater than for water at the same ΔP. At atmospheric pressure and in vacuum services, the static head produced by the gas is negligible. In high-pressure fractionators requiring large number of theoretical stages, the static head of vapor can be considerable from the condenser to the reboiler. Here, the value should be added to the calculated ΔP in determining the bottom column pressure and reboiler temperature. Pressure drop may be estimated from Figure 7-14 for the particular packing system properties and operating conditions [15], or may be calculated by the following equation as represented by Leva [16].

$$\Delta P = \alpha 10^{\beta L}\left(\frac{G_I^2}{\rho_G}\right) \tag{7-61}$$

The equation was originally developed for air-water systems. For other liquids, however, L is multiplied by the ratio of the density of water to the density of liquid. Table 7-11 shows ΔP correlations for different types of packing material [17].

Flooding

In packed columns, flooding is caused when the energy potential of the vapor is greater than that of the liquid (that is, when all the void spaces in the packing are filled with liquid), so that the liquid travels up and the column floods. This gives a ΔP of 2–3 in. H_2O/ft of packing depth, and a column cannot be operated successfully under these conditions. Flooding depends on a number of parameters, and empirical correlations of the variables have been presented by Bain and Hougen [18], Lobo *et al.* [19], Sherwood *et al.* [20], and Eckert [21].

Eckert's modification of Sherwood's flooding correlation has been widely applied for designing packed columns. Blackwell [13] developed

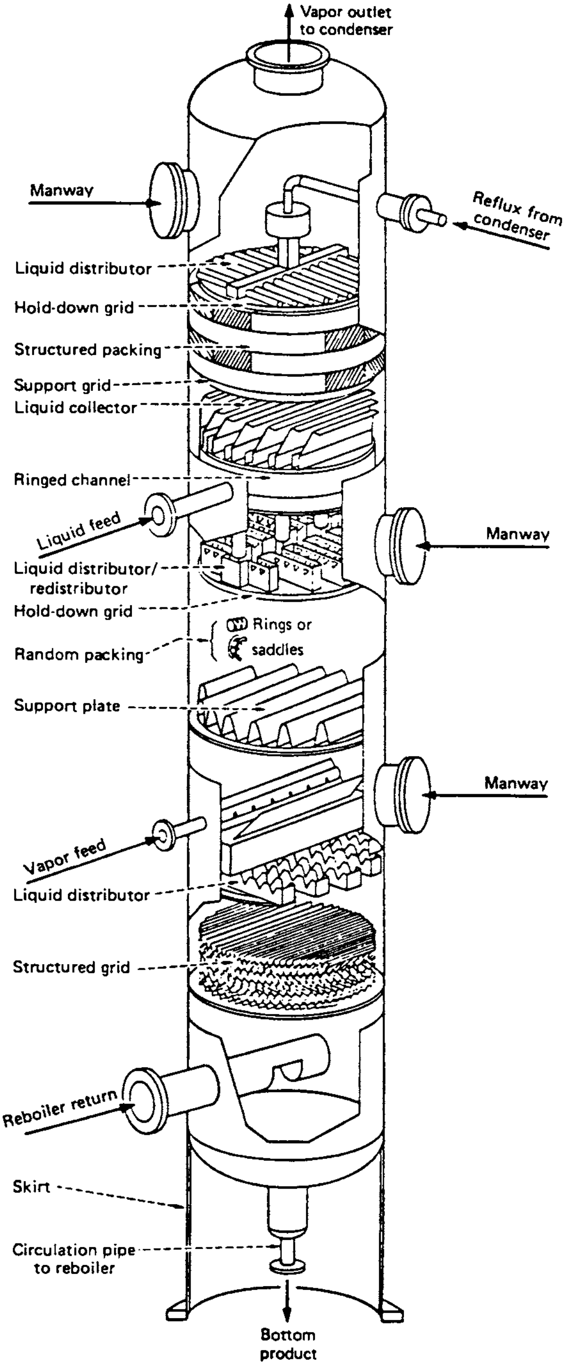


Figure 7-13. Packed tower and internals. By permission of Chemical Engineering.

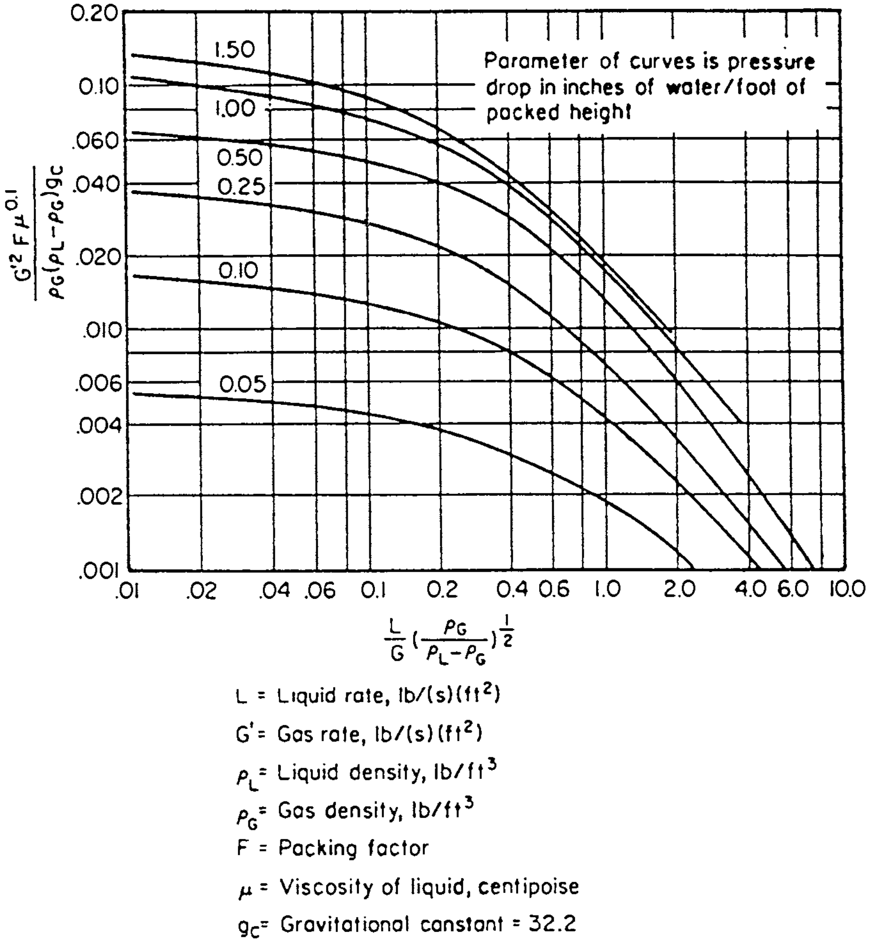


Figure 7-14. Correlation of flow rate and pressure drop in packed towers. Source: Eckert [15].

mathematical models representing the generalized pressure-drop curves excluding the flooding condition. Kessler and Wankat [22] formulated a model to represent Eckert's flooding curve within the range of the original data.

Operating and Design Conditions

Packed towers are typically operated at a gas velocity that corresponds to about 50-80% of flooding condition. This usually results in a ΔP of 0.5–1.0 in. H_2O/ft of packing. Alternatively, a large decrease in flow

Table 7-11
Pressure-Drop Correlations for Packed Towers

Packing		Constants	
Type	Nominal Size, in.	α	β
Raschig rings	3/8	4.70	0.41
Ceramic	1/2	3.10	0.41
	5/8	2.35	0.26
	3/4	1.34	0.26
	1	0.97	0.25
	1 1/4	0.57	0.23
	1 1/2	0.39	0.23
	2	0.24	0.17
Raschig rings	5/8	1.20	0.28
Metal, 1/32 in.	1	0.42	0.21
Wall, 1/16 in.	1 1/2	0.29	0.20
	2	0.23	0.135
Pall rings, metal	5/8	0.43	0.17
	1	0.15	0.16
	1 1/2	0.08	0.15
	2	0.06	0.12
Berl saddles	1/2	1.2	0.21
	3/4	0.62	0.17
	1	0.39	0.17
	1 1/2	0.21	0.13
Intalox saddles	1/2	0.82	0.20
	3/4	0.28	0.16
	1	0.31	0.16
	1 1/2	0.14	0.14

SOURCE: Van Winkle [11].

rate causes channeling through the packed bed, and could result in poor column performance.

Two principal design methods have often been employed in sizing packed towers. One is the selection of an allowable ΔP, and the other is to select some fraction of the flooding capacity. Nguyen [23,24] uses the latter and employs Chen's least-square method to determine the tower diameter at 50% of the superficial flooding rate. This means that the ΔPs are 2 in. H_2O/ft of bed, or greater. Here, an allowable ΔP is selected to determine the diameter of a packed tower. Kessler and Wankat's model is employed to determine the vapor rate at 70% of the flooding condition.

The maximum recommended design ΔP is 1.0 in. H_2O/ft for liquids with a specific gravity of 0.8 or more. A lower maximum design ΔP is recommended for lighter liquids. The recommended design ΔP criterion for sizing a packed tower should fall within the ranges as shown in Table 7-12 [25]. Packed beds may be scaled up using the modified Sherwood correlation as illustrated in Figure 7-14. The packing factor for various types of packing is as shown in Table 7-13 [26], because the capacity of the bed is independent of tower diameter and height. Packings that have sizes that are too large for the tower diameter will show a greater contact caused by the extra voidage, (that is, where the pieces of packing contact the tower wall) and a lower ΔP than that predicted by their published packing factors. This effect reduces to zero for most packings when the ratio of packing size to diameter exceeds 10:1 [15]. This factor is necessary when data from a pilot plant tower, which is filled with large packings, are used for scale up.

Design Equations

The packed tower sizing method is based upon the generalized ΔP correlation as shown in Figure 7-14.

Table 7-12
Generalized Pressure Drop Rules

Service	Design Pressure Drop in. H_2O/ft. of Packed Depth
Absorbers and Regenerators (Non-foaming System)	0.25–0.40
Absorbers and Regenerators	0.10–0.25
Atmospheric or Pressure Stills and Fractionators	0.40–0.80
Vacuum Stills and Fractionators	0.10–0.40

Source: Branan [25].

Table 7-13
Packing Factors

Type of Packing	Mat'l.	Nominal Packing Size, in										
		¼	⅜	½	⅝	¾	1	1¼	1½	2	3	3½
Super Intalox	Ceramic	—	—	—	—	—	60	—	—	30	—	—
Super Intalox	Plastic	—	—	—	—	—	33	—	—	21	16	—
Intalox saddles	Ceramic	725	330	200	—	145	98	—	52	40	22	—
Hy-Pak rings	Metal	—	—	—	—	—	42	—	—	18	15	—
Pall rings	Plastic	—	—	—	97	—	52	—	40	25	—	16
Pall rings	Metal	—	—	—	70	—	48	—	28	20	—	16
Berl saddles	Ceramic	900^{x}	—	240^{x}	—	170^{h}	110^{h}	—	65^{h}	45^{x}	—	—
Raschig rings	Ceramic	1,600^{b,x}	1,000^{b,x}	580^{c}	380^{c}	255^{c}	155^{d}	125^{e,x}	95^{e}	65^{f}	37^{g,x}	—
Raschig rings $\frac{1}{32}$-in wall	Metal	700^{x}	390^{x}	300^{x}	170	155	115^{x}	—	—	—	—	—
Raschig rings $\frac{1}{16}$-in wall	Metal	—	—	410	290	220	137	110^{x}	83	57	32^{x}	—
Tellerettes	Plastic	—	—	—	—	—	40	—	—	20	—	—
Maspak	Plastic	—	—	—	—	—	—	—	—	32	20	—
Lessing exp.	Metal	—	—	—	—	—	—	—	30	—	—	—
Cross partition	Ceramic	—	—	—	—	—	—	—	—	—	70	—

[a] $\frac{1}{32}$ Wall
[b] $\frac{1}{16}$ Wall
[c] $\frac{3}{32}$ Wall
[d] $\frac{1}{8}$ Wall
[e] $\frac{3}{16}$ Wall
[f] $\frac{1}{4}$ Wall
[g] $\frac{3}{8}$ Wall
[h] Packing factors obtained in 16- and 30-in. I.D. towers.
[x] Extrapolated

Source: Eckert [26].

The abscissa on the generalized ΔP curve is expressed as:

$$X = \left(\frac{L}{G}\right)\left[\frac{\rho_G}{(\rho_L - \rho_G)}\right]^{0.5} \tag{7-62}$$

where $0.01 < X < 2.0$ and the ordinate is expressed as:

$$Y = \frac{(G_1^2 F_p \mu_L^{0.1})}{[\rho_G(\rho_L - \rho_G)g]} \tag{7-63}$$

where $0.001 < Y < 0.15$

$$Y = \exp[C_0 + C_1 \ln X + C_2(\ln X)^2 + C_3(\ln X)^3 + C_4(\ln X)^4] \tag{7-64}$$

and $C_0 - C_4$ are constants derived for each ΔP. The values of these constants for each ΔP correlation are shown in Table 7-14 [13].

The mass vapor rate, G_1, is expressed as:

$$G_1 = \left\{\frac{[Y\rho_G(\rho_L - \rho_G)g]}{F_p \mu_L^{0.1}}\right\}^{0.5} \frac{lb}{ft^2 . s} \tag{7-65}$$

The tower area is

$$A = \frac{G}{(3600)(G_1)} \tag{7-66}$$

$$= \frac{\pi D^2}{4} \tag{7-67}$$

The tower diameter is defined by

$$D = \left(\frac{4A}{\pi}\right)^{0.5}, \quad ft \tag{7-68}$$

At flooding condition, Eckert's flooding curve is represented as:

$$\log\left(\frac{G_2^2 F_p \Psi \mu_L^{0.2}}{\rho_G \rho_L g}\right) \quad \text{versus} \quad \log(F_{LG}) \tag{7-69}$$

Table 7-14
Constants for Each Pressure Drop Correlation

Pressure Drop in. $H_2O/ft.$ of Packed Depth	Constants	Pressure Drop in. $H_2O/ft.$ of Packed Depth	Constants
0.05	C_0= -6.30253	0.50	C_0= -4.39918
	C_1= -0.60809		C_1= -0.99404
	C_2= -0.11932		C_2= -0.16983
	C_3= -0.00685		C_3= 0.00873
	C_4= 0.00032		C_4= 0.00343
0.10	C_0= -5.50093	1.0	C_0= -4.09505
	C_1= -0.78508		C_1= -1.00120
	C_2= -0.13496		C_2= -0.15871
	C_3= 0.00134		C_3= 0.00797
	C_4= 0.00174		C_4= 0.00318
0.25	C_0= -5.00319	1.5	C_0= -4.02555
	C_1= -0.95299		C_1= -0.98945
	C_2= -0.13930		C_2= -0.08291
	C_3= 0.01264		C_3= 0.03237
	C_4= 0.00334		C_4= 0.00532

Source: Blackwell [13]

where

$$F_{LG} = \left(\frac{L}{G}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \tag{7-70}$$

Using Kessler and Wankat's model to represent the flooding condition,

$$X_1 = F_{LG} \tag{7-71}$$

$$Y_1 = \frac{(G_2^2 F_p \Psi \mu_L^{0.2})}{(\rho_G \cdot \rho_L \cdot g)} \tag{7-72}$$

At flooding condition,

$$\log(Y_1) = -1.6678 - 1.085 \log(X_1) - 0.29655(\log X_1)^2 \qquad (7\text{-}73)$$

The mass vapor rate lb/(sft^2) at 70% flooding condition can be expressed as:

$$G_2 = 0.7\left(\frac{Y_1 \cdot \rho_G \cdot \rho_L \cdot g}{F_p . \Psi . \mu_L^{0.2}}\right)^{0.5} \qquad (7\text{-}74)$$

The vapor velocity (ft/sec) at 70% flooding condition is expressed as:

$$V_{GF} = \frac{G_2}{\rho_G} \qquad (7\text{-}75)$$

Guidelines for Selecting Packed Towers

Use the following rules of thumb for selecting packed towers:

1. Structured and random packings are suited to packed towers under 3 ft diameter and when low ΔP is desirable. In such cases, volumetric efficiences, given adequate liquid distribution throughout the column, can exceed trayed towers.
2. Replacing trays with packing allows greater throughput or separation in existing tower shells.
3. For gas rates of 500 ft^3/min, use 1-inch packing. For gas rates of 200 ft^3/min, or more, use 2-inch packing.
4. The ratio of the diameter of the tower to the packing should be at least 15.
5. Because of deformability, plastic packing is limited to an unsupported depth of 10–15 ft, metal to 20–25 ft.
6. Liquid redistributors are required every 5–10 tower diameters with pall rings, and at least every 20ft for other types of dumped packings. The number of liquid streams should be 3–5/ft^2 in towers larger than 3 ft diameter. Some experts advocate 9–12/ft^2 [27].
7. The height equivalent to a theoretical plate (HETP) for vapor-liquid contacting is 1.3–1.8 ft for 1-inch rings, 2.5–3.0 ft for 2-inch rings.
8. Packed towers should operate near 70% of the flooding rate given by the correlation of Lobo *et al.* [19] and Sherwood.

9. Limit the tower height to about 175 ft maximum because of wind load and foundation considerations. Also, L/D should be less than 30.

Packed Towers Versus Trayed Towers

Both trays and packings are used to provide intimate contact between the ascending vapor and descending liquid without a great reduction in the throughput or capacity of a fractionating column. The most striking difference between trays and packings is the percentage opening of each phase-contacting device. A tray has an opening of 8–15% of the tower cross-sectional area, while the projected opening of a typical packing design is usually more than 50% of tower cross section. The void fraction of a packed column is even higher, and is usually more than 90% of the tower volume. In addition, with packing, contact is readily achieved between the vapor and the liquid phases throughout the column, rather than at specific points as with trays.

The following further illustrates the advantages of using packed towers over trays.

High capacity with high liquid rates or high viscosity. Trayed columns employ the energy of the vapor to create a mass-transfer surface area by bubbling through the liquid. Packed towers, with the aid of gravity, create a mass-transfer surface area by the action of the liquid falling over the packing. Thus, there are no downcomers in a packed tower, and 100% of the tower cross section is used for mass transfer.

High capacity/efficiency combinations. Because the capacity of a packed tower is greater than a comparable sized trayed one, a smaller, more efficient packing can be used to handle the same capacity. The range of packing sizes and types allows the combination of efficiency and capacity to be optimized.

High capacity in foaming system. Trayed columns use the continuous liquid phase to create a froth that is difficult to separate. Packed towers make the vapor phase continuous, and the liquid phase discontinuous.

Low pressure drop. Packed towers have a low ΔP per theoretical stage or transfer unit, which is beneficial in low-pressure and vacuum applications.

Low residence time. Packed towers offer low liquid holdup. This gives lower residence time for materials that are sensitive to high processing temperature. In contrast, trayed columns typically impose a holdup volume of 20–30%.

Economic Trade-Offs

In the design of industrial-scale packed towers, an economic balance is important between the capital cost of the column, its ancillary equipment, and the operating cost. If the diameter of the tower is reduced, the capacity cost will also be reduced, but the cost of pumping the gas through the column will increase because of the higher ΔP.

For columns operating at high pressures, the capital cost of the column shell is more significant, and it may be more economic to operate at gas velocities above the loading conditions. Morris and Jackson [28] suggest that a gas velocity 75–80% of the flooding velocity for normal systems, and less than 40% of the flooding rate if foaming is present.

In general, the actual operating vapor rate is some percentage of $G_{2_{flood}}$. The usual range is 65–90% of flooding, with 70-80% being most common. Because the flooding correlation is not always accurate, some confidence limit is used. For a 95% confidence, Bolles and Fair [29,30] recommend a safety factor of 1.32 for the calculated cross-sectional area. The tower diameter is calculated once the tower area is known. Because the liquid and vapor properties and gas and liquid flow rates all vary, the designer must calculate the diameter at several locations, and then use the largest value. Sizing the column diameter has often been influenced by changes in the vapor flow rate.

Eckert [21] develops an economic characterization number for various types of packing. Usually, the most suitable choice of packing is dependent on the material of construction of the equipment. In distillation towers when low-carbon steel is used, 2-inch metal rings are often favored because they give a low ΔP, high capacity, and efficiency. Alternatively, saddles are the most frequently selected plastic and ceramic packing.

Troubleshooting packed towers is well illustrated in the literature [31].

Nomenclature

A = tower area, ft^2
$C_0 - C_4$ = packed drop correlation constants
D = packed tower diameter, ft
F_{LG} = flow parameter (Equation 7-67)
F_p = packing factor for packing material

G = vapor rate, lb/h
G_1 = vapor mass velocity, lb/(ft^2 sec tower cross section)
G_2 = vapor mass velocity, lb/(ft^2 sec tower cross section)
g = gravitational constant, 32.2 ft/s^2
L = liquid rate, lb/h
L_1 = liquid mass velocity, lb/(ft^2 sec tower cross section)
X = abscissa in the generalized plot
Y = ordinate in the generalized plot
Y_1 = ordinate in Eckert's flooding curve
V_{GF} = vapor velocity at 70% of flooding conditions, ft/s

Greek Letters

α = constant in Table 7-11
β = constant in Table 7-11
μ_L = liquid viscosity, cP
ρ_L = liquid density, lb/ft^3
ρ_G = vapor density, lb/ft^3
Ψ = ratio of water density to liquid density

DETERMINATION OF PLATES IN FRACTIONATING COLUMNS BY THE SMOKER EQUATIONS

Introduction

Smoker [32] developed an analytical equation that determines the number of stages when the relative volatility is constant (that is α is constant). Smoker's method can be used in preference to the McCabe-Thiele [33] graphical method for calculating the number of theoretical plates. This is because the accuracy of the McCabe-Thiele depends on the care given to the construction of the plots. The graphical construction for the number of stages becomes more difficult at very low concentrations. Also, if the relative volatility is close to one, the number of stages required will be very large, and the McCabe-Thiele diagram will be difficult to construct.

The Equations

Smoker's equations start by considering Raoult's law for a binary mixture, where α is a constant and represents the vapor-liquid equilibrium relationship. From Equation 7-25

$$y = \frac{\alpha x}{1 + (\alpha - 1)x} \tag{7-25}$$

Any operating line that is either above or below the feed plate can be represented by the general equation of a straight line.

$$y = mx + b \tag{7-76}$$

Eliminating y from Equations 7-25 and 7-76 gives a quadratic equation in x.

$$m(\alpha - 1)x^2 + [m + (\alpha - 1)b - \alpha]x + b = 0 \tag{7-77}$$

For any particular distillation problem, Equation 7-77 will have only one real root k, between 0 and 1. Representing this root k, and substituting in Equation 7-77 gives

$$m(\alpha - 1)k^2 + [m + (\alpha - 1)b - \alpha]k + b = 0 \tag{7-78}$$

k is the value of the x-ordinate at the point where the extended operating lines intersect the vapor-liquid equilibrium curve.

Smoker shows that the number of stages required is given by

$$N = \log\left[\frac{x_0^*(1 - \beta x_n^*)}{x_n^*(1 - \beta x_0^*)}\right] \Bigg/ \log\left(\frac{\alpha}{mc^2}\right) \tag{7-79}$$

where

$$\beta = \frac{mc(\alpha - 1)}{\alpha - mc^2} \tag{7-80}$$

N = number of stages required effecting the separation represented by the concentration change from

$$x_n^* \text{ to } x_0^*;\ x^* = (x - k) \text{ and } x_0^* > x_n^*;\ c = 1 + (\alpha - 1)k \tag{7-81}$$

k = composition of the liquid where the operating line intersects the equilibrium line

m = slope of the operating line between x_n^* and x_0^*

α = average relative volatility, assumed constant over x_n^* to $x_0^* = (\alpha_{top} + \alpha_{bottom})/2$

Application to a Distillation Column

Apply Smoker's equation to actual distillation conditions with a single feed and no side streams.

Rectifying Section:

For a rectifying column, the number of plates required to enrich from the feed composition, z_F, to the distillate (product) composition, x_D, at fixed reflux ratio, R, is required by

$$m = \frac{R}{R+1} \tag{7-82}$$

and

$$b = \frac{x_D}{R+1} \tag{7-83}$$

Also

$$m(\alpha - 1)k^2 + [m + (\alpha - 1)b - \alpha]k + b = 0$$

where k is the root between 0 and 1

$$x_0 = x_D \tag{7-84}$$

$$x_0^* = X_D - k \tag{7-85}$$

$$x_n = z_F \tag{7-86}$$

$$x_n^* = z_F - k \tag{7-87}$$

Stripping Section:

For the stripping section, the bottoms composition, x_B, the feed, z_F, the overhead composition, x_D and the reflux ratio, R, all fix the operating line. The values of m and b are

$$m = \frac{Rz_F + x_D - (R+1)x_B}{(R+1)(z_F - x_B)} \tag{7-88}$$

and

$$b = \frac{(z_F - x_D)x_B}{(R+1)(z_F - x_B)} \tag{7-89}$$

$$x_0^* = z_F - k \tag{7-90}$$

$$x_n^* = x_B - k \tag{7-91}$$

If the feed stream is not at its bubble point, z_F is replaced by the value of x at the intersection of operating lines given by

$$z_F^* = \frac{b + z_F/(q - 1)}{q/(q - 1) - m} \tag{7-92}$$

For distillation at total reflux R = ∞, m = 1, b = 0, k = 0, c = 1 and Equation 7-79 becomes

$$N = \log\left\{\frac{x_0(1 - x_n)}{x_n(1 - x_0)}\right\} \Big/ \log \alpha \tag{7-93}$$

Equation 7-79 simplifies to the equation derived by Underwood [34].

Smoker's equation is not limited to the range of small concentrations, but can be used for stage calculation over the entire range. In such instances, the equation is written twice, one for each section of the tower. The average relative volatilities for the rectifying section and for the stripping section are determined.

Nomenclature

b = intercept of a straight line with the y-axis
c = constant defined by Equation 7-81
k = composition of the liquid where the operating line intersects the equilibrium line
n = number of plates between any two points in the column under consideration
R = reflux ratio, reflux per unit time divided by moles of distillate per unit time
x_B = mole fraction in the bottoms
x_D = mole fraction in the distillate
z_F = mole fraction in the feed

MULTICOMPONENT DISTRIBUTION AND MINIMUM TRAYS IN DISTILLATION COLUMNS

Determining the number of stages and reflux ratio for multicomponent distillations is more complex than for binary mixtures. In multicomponent distillation with the feed containing more than two components, it is often difficult to specify the complete composition of the top and bottoms products. The separation between the top and bottoms products is specified by setting limits on two key components between which it is desired to effect separation. Also, fixing one component composition does not uniquely determine the other component compositions and the stage temperature.

Key Components

Before the start of the column design, the process designer must select the two key components between which it is desired to effect the separation. In cases where pure components are being produced, the key components are the compounds boiling adjacent to one another on the temperature scale. The material having the lower boiling point is known as the light key component and the next heavier as the heavy key component. The light key component is the component that is desired to keep out the bottoms product, and the heavy key is the component that is desired to keep out the top product. Specifications are often set on the maximum concentrations of the keys in the top and bottoms products.

The keys are known as "adjacent keys" if they are adjacent in a listing of the components in order of volatility. Sometimes, the keys selected are not adjacent but have an intermediate boiling component between them. They are known as "light key," "heavy," key and "intermediate" (boiling) or "distributed key." The non-key components that appear in both top and bottoms products are known as "distributed" components. Those that are not present to any significant extent, in one or other product, are known as the "non-distributed" components.

Equations Surveyed

The increasing availability of personal computers with acquired simulation software packages has helped design engineers to optimize a number of equilibrium stages in multipurpose fractionating towers and absorbers. Designers adept in mathematical modeling are still engaged in the use of vigorous, iterative plate-to-plate computation to study a wide range of process conditions. However, preliminary design with graphical correlations has often helped to arrive at an approximate optimum number of stages before reverting to established design methods. Figure 7-15 shows a schematic of a fractionating column with two or more multicomponent and associated equipment items. Alternatives to the preliminary design are the short-cut methods to achieve a realistic optimum number of theoretical stages. Generally, short-cut methods were proposed to establish the minimum number of stages at total reflux, and

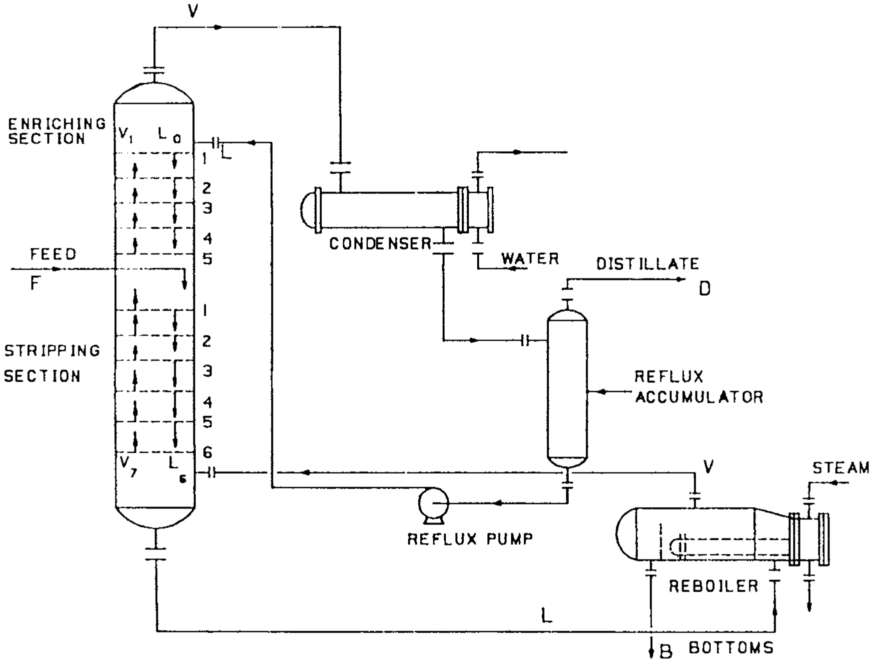


Figure 7-15. Factionation column with a reboiler and refluxing auxiliaries.

also the minimum reflux at an infinite number of theoretical stages. Many authors have correlated the minimum reflux and minimum stages with operating reflux and corresponding theoretical equilibrium stages required. These methods have enabled designers to vary the reflux ratio and plates in order to achieve an optimum relationship based on investment and operating costs.

Mathematical Modeling

The distribution of components between the distillate and bottoms is given by the Hengstebeck-Geddes equation [35,36].

$$\log\left[\frac{d_i}{b_i}\right] = A_i + B_l \log \alpha_i \qquad (7\text{-}94)$$

where d_i = moles of component i in the distillate
b_i = moles of component i in the bottoms
α_i = relative volatility of component i
A_l, B_l = correlation constants

A material balance for the ith component in the feed is:

$$f_i = d_i + b_i \tag{7-95}$$

The quantity of component i in the distillate can be expressed as mole fraction recovered, or d_i/f_i. Alternatively, in the bottoms, the mole fraction of component i recovered is b_i/f_i.

If Equation 7-94 is expressed with respect to the heavy key component, then

$$\log\left[\frac{d_{HK}}{b_{HK}}\right] = A_1 + B_1 \log \alpha_{HK} \tag{7-96}$$

The relative volatility of the heavy key component (that is, α_{HK}) is 1.0

Therefore,

$$A_1 = \log\left[\frac{d_{HK}}{b_{HK}}\right] \tag{7-97}$$

but

$$f_{HK} = d_{HK} + b_{HK} \tag{7-98}$$

and

$$f_{LK} = d_{LK} + b_{LK} \tag{7-99}$$

Therefore

$$A_1 = \log\left[\frac{f_{HK} - b_{HK}}{b_{HK}}\right] \tag{7-100}$$

Equation 7-100 can be expressed in terms of mole fraction recovered as:

$$A_1 = \log\left[\frac{(1.0 - b_{HK}/f_{HK})}{(b_{HK}/f_{HK})}\right] \tag{7-101}$$

Substituting Equation 7-97 into Equation 7-94 and expressing in terms of the light key component.

$$\log\left[\frac{d_{LK}}{b_{LK}}\right] = \log\left[\frac{d_{HK}}{b_{HK}}\right] + B_1 \log \alpha_{LK} \tag{7-102}$$

Therefore

$$B_1 = \frac{\log\left[\left(\dfrac{d_{LK}}{b_{LK}}\right)\Big/\left(\dfrac{d_{HK}}{b_{HK}}\right)\right]}{\log \alpha_{LK}} \tag{7-103}$$

Expressing Equation 7-103 in terms of fractional recoveries.

$$B_1 = \frac{\log\left[\left(\dfrac{d_{LK}/f_{LK}}{\dfrac{f_{LK} - d_{LK}}{f_{LK}}}\right)\left(\dfrac{bH_{LK}/f_{HK}}{\dfrac{f_{HK} - d_{HK}}{f_{HK}}}\right)\right]}{\log \alpha_{LK}} \tag{7-104}$$

$$B_1 = \frac{\log\left[\left(\dfrac{d_{LK}/f_{LK}}{1 - \dfrac{d_{LK}}{f_{LK}}}\right)\left(\dfrac{bH_{LK}/f_{HK}}{1 - \dfrac{b_{HK}}{f_{HK}}}\right)\right]}{\log \alpha_{LK}} \tag{7-105}$$

The recoveries of the ith component in the distillate and bottoms: Equation 7-94 and Equation 7-95 are

$$\log\left[\frac{d_i}{b_i}\right] = A_1 + B_1 \log \alpha_i \tag{7-94}$$

$$f_i = d_i + b_i \tag{7-95}$$

Expressing Equations 7-94 and 7-95 in terms of the recoveries of the ith component.

That is

$$\log\left[\frac{d_i/f_i}{1 - d_i/f_i}\right] = A_1 + B_1 \log \alpha_i \tag{7-106}$$

Hence,

$$\left[\frac{d_i/f_i}{1-d_i/f_i}\right] = 10^{A_i}.10^{(\log_{10}\alpha_i^{B_i})} \tag{7-107}$$

$$= 10^{A_i}.\alpha_i^{B_i}$$

$$\frac{d_i}{f_i} = 10^{A_i}.\alpha_i^{B_i}\left(1-\frac{d_i}{f_i}\right) \tag{7-108}$$

The recovery of the ith component in the distillate is given by

$$\frac{d_i}{f_i} = \frac{(10^{A_i}.\alpha^{B_i})}{(1+10^{A_i}.\alpha^{B_i})} \tag{7-109}$$

And the recovery of the ith component in the bottoms is

$$\frac{b_i}{f_i} = 1-\frac{d_i}{f_i} \tag{7-110}$$

$$= 1-\frac{(10^{A_i}.\alpha_i^{B_i})}{(1+10^{A_i}.\alpha_i^{B_i})} \tag{7-111}$$

$$\frac{b_i}{f_i} = \frac{1}{1+10^{A_i}.\alpha_i^{B_i}} \tag{7-112}$$

The Fenske's Method for Total Reflux

Fenske's [37] equation for determining the minimum equilibrium stages at total reflux was based on an ideal mixture. This suggests that the ratio of vapor pressures or the ratio of equilibrium vaporization of the key components is constant over the range of temperatures (that is, the relative volatilities are constant). Fenske expressed the minimum number of equilibrium stages as:

$$N_{\min} = \frac{\log\left[\left(\frac{x_{LK}}{x_{HK}}\right)_D\left(\frac{x_{HK}}{x_{LK}}\right)_B\right]}{\log\left[\frac{\alpha_{LK}}{\alpha_{HK}}\right]} \tag{7-113}$$

The Gilliland Method for Number of Equilibrium Stages

The number of theoretical equilibrium stages required for a given separation at a given reflux ratio is often determined by empirical correlations [38,39]. The abscissa, X, represents a reflux function as:

(7-114)

Correspondingly, the ordinate, Y, represents a stage function as given by

$$Y = \frac{(N - N_m)}{(N + 1)} \qquad (7\text{-}115)$$

The ratios used for the axes of abscissa and ordinate were chosen because they provide fixed end points for the curve ($X = 0.0$, $Y = 1.0$ and at $X = 1.0$, $Y = 0.0$). The two functions were found to give good correlations. These correlations are shown in Figures 7-16 and 7-17.

Gilliland's correlation has produced relevant results that offer the following advantages:

- They represent an optimum solution concerning the location of the feed plate.
- The splitting for the two key components is verified.
- The maximum deviation using Gilliland's correlation in terms of tray number is within the7% range [39].

The Gilliland correlation tends to be conservative for feeds with low values of the thermal condition of the feed (q). It can give inaccurate results when there is a large difference in tray requirements above and below the feed. The correlation is adequate for preliminary designs before a detailed analysis is carried out. Great caution should be exercised when used for final designs. Hines and Maddox [5] have described an improved correlation for determining the number of theoretical stages.

Underwood's Method

If an infinite or nearly infinite number of equilibrium stages is involved, a zone of constant composition must exist in the fractionating column. In this instance, there is no measurable change in the composition of liquid or vapor from stage to stage. Under these conditions, the reflux ratio can be defined as the minimum reflux ratio, R_{min}, with

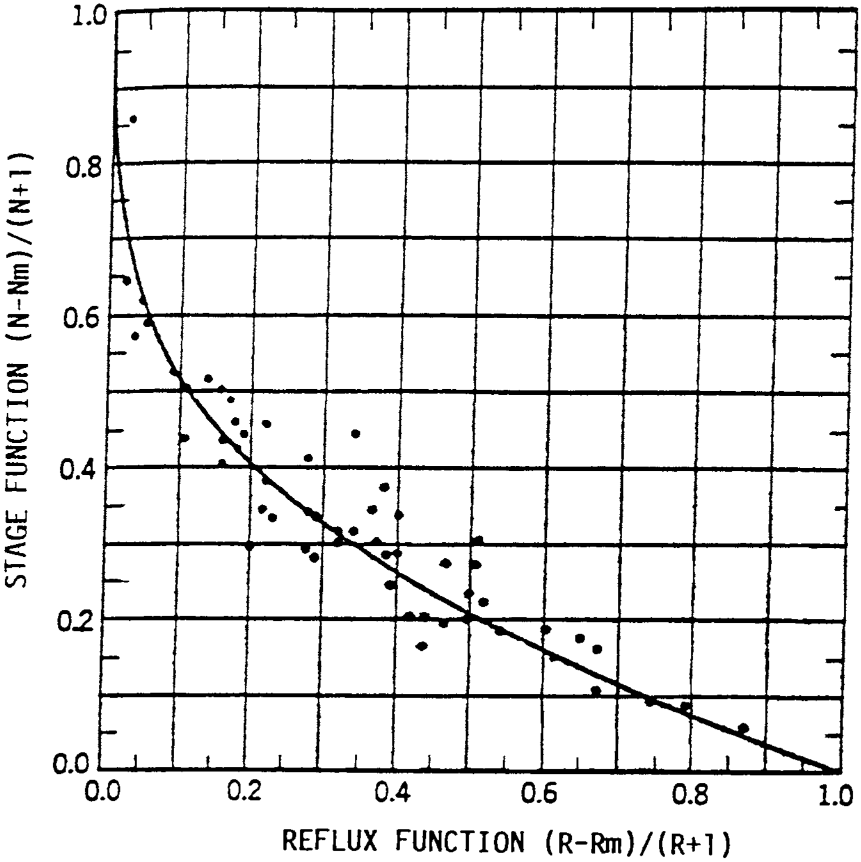


Figure 7-16. Linear coordinates based on Gilliland's correlation.

respect to a given separation of two key components (that is, the light key and heavy key) [40].

Therefore, for component i, in the distillate

$$R_{min} + 1 = \sum_{i=1}^{n} \frac{(\alpha_i - x_{i,D})}{(\alpha_i - \theta)} \tag{7-116}$$

where θ is Underwood's constant (or root of the equation), and must lie between the relative volatilities of the light and heavy keys (α_{LK} and α_{HK}). The number of components is n.

Correspondingly, for the feed,

$$1 - q = \sum_{i=1}^{n} \frac{(\alpha_i . x_{i,F})}{(\alpha_i - \theta)} \tag{7-117}$$

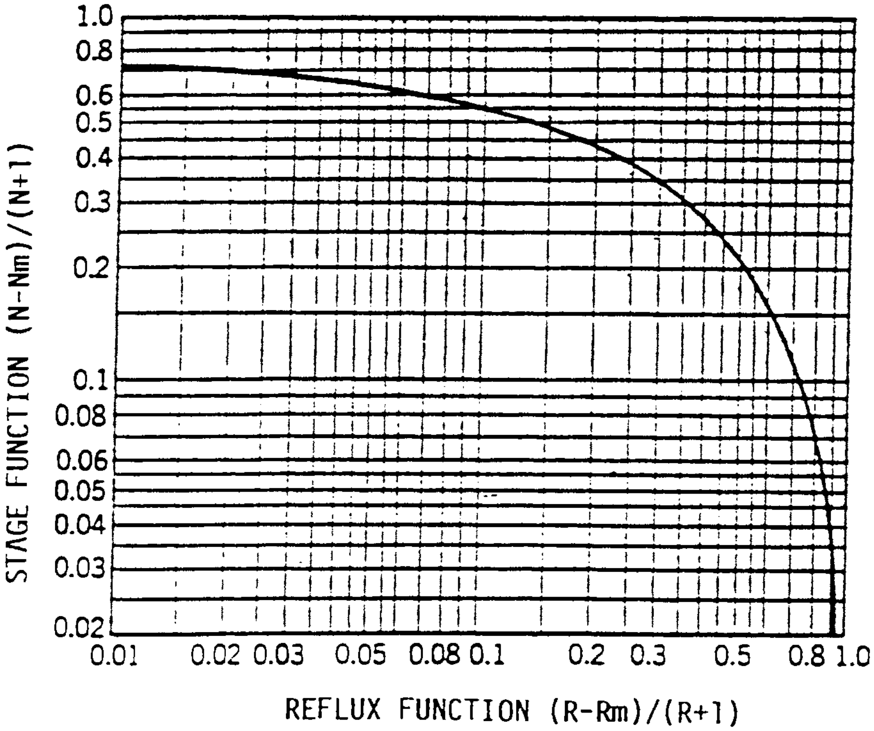


Figure 7-17. Logarithmic coordinates based on Gilliland's correlation.

Equation 7-117 shows the relationship for the feed, where q is the fraction of feed that is liquid at the feed tray temperature and pressure. For a bubble point feed, q =1, and for a dew point feed, q = 0. The minimum reflux ratio is determined from Equation 7-117 by substituting into Equation 7-116. Coker [41] developed a numerical method for computing θ and R_{min} respectively. However, other methods should be tried, if R_{min} gives a negative value. Also, it may be that the separation between the feed and the overhead can be accomplished in less than one equilibrium stage.

Equations for Describing Gilliland's Graph

Many equations have been proposed to describe Gilliland's curve for multicomponent distillation. However, the difficulty with some of these equations has been in meeting the end conditions of X = 0, Y = 1 and X = 1, Y = 0. A review of the many equations proposed by these authors is as follows:

Proposed Equations:

1. Hengstebeck [42] (1961)

$$\log Y = A + B(\log X) + C(\log X)^2 + D(\log X)^3 + E(\log X)^4 \quad (7\text{-}118)$$

where $A = -1.3640187$
$B = -3.0920489$
$C = -3.407344729$
$D = -1.74673876$
$E = -0.33268897$

2. Liddle [43] (1968)

$$\text{For } 0.0 \le X \le 0.01,\ Y = 1.0 - 18.5715X \quad (7\text{-}119)$$

$$\text{For } 0.01 \le X \le 0.90,\ Y = 0.545827 - 0.591422X + 0.002743/X \quad (7\text{-}120)$$

$$\text{For } 0.90 \le X \le 1.0,\ Y = 0.16595 - 0.16595X \quad (7\text{-}121)$$

3. Van-Winkle and Todd [44] (1971)

$$\text{For } 0.0078 < X < 0.125,\ Y = 0.5039 - 0.5968X - 0.0908(\log X) \quad (7\text{-}122)$$

$$\text{For } 1.25 < X \text{ to } X = 1.0,\ Y = 0.6257 - 0.9868X + 0.516X^2 - 0.1738X^3 \quad (7\text{-}123)$$

4. Molokavov [45] (1972)

$0 \le (X, Y) \le 1.0$

$$Y = 1 - \exp\left[\left(\frac{1 + 54.4X}{11 + 117.2X}\right)\left(\frac{X - 1}{X^{0.5}}\right)\right] \quad (7\text{-}124)$$

5. Hohman and Lockhart [46] (1972)

$X = 0,\ Y = 0.65$

$X = 1.0,\ Y = 0.067$

$$Y = \frac{0.65 - 0.50X}{1.0 + 1.25X} \quad (7\text{-}125)$$

6. Eduljee [47] (1975)

$X = 0, Y = 1.0$

$X = 1.0, Y = 0$

$$Y = 0.75 - 0.75X^{0.5668} \tag{7-126}$$

7. Huan-Yang Chang [48] (1981)

For $X = 0, Y = 1.0$

$X = 1.0, Y = 0$

$$Y = 1 - \exp\left(1.49 + 0.315X - \frac{1.805}{X^{0.1}}\right) \tag{7-127}$$

8. Harg [49] (1985)

For $X = 0, Y = 1.0$

$X = 1.0, Y = 0$

$$Y = 1 - X^{1/3} \tag{7-128}$$

9. McCormick [50] (1988)

$X = 0, Y = 1.0$

$X = 1.0, Y = 0$

$Y = 1 - X^B$

where

$$B = 0.105(\log X) + 0.44 \tag{7-129}$$

From the equations listed, McCormick's gives a good agreement in the normal operating range of real towers. The reflux ratio, R, is calculated as a multiple of the minimum reflux ratio, R_{min}.

That is,

$$R = FACTOR.R_{min} \tag{7-130}$$

The multiplier "FACTOR" generally varies from 1.2 to about 1.5 for conventional columns, but because of economic situations, the range is now between 1.05 and 1.20.

Kirkbride's Feed Plate Location

After the minimum number of stages and the minimum reflux ratio have been determined, the number of theoretical stages is then calculated. The ratio of the number of plates above the feed stage (including the partial condenser) to the number below the feed stage (including the reboiler) can be obtained using Kirkbride's empirical equation [51]. The equation was developed on the basis that the ratio of rectifying trays to stripping trays depends on:

- The fraction of the heavy key component (in the feed) removed in the overhead.
- The fraction of the light key component removed in the bottoms.
- The concentration of the heavy key component in the overhead.
- The concentration of the light key component in the bottoms.

Kirkbride's feed plate equation is expressed as:

$$\log\left[\frac{m}{p}\right] = 0.206 \log\left\{\left(\frac{B}{D}\right)\left(\frac{x_{HK}}{x_{LK}}\right)_F \left[\frac{(x_{LK})_B}{(x_{HK})_D}\right]^2\right\} \qquad (7\text{-}131)$$

where B = molar flow bottoms product
D = molar flow top product
m = number of theoretical stages above the feed plate, including any partial condenser
p = number of theoretical stages below the feed plate, including the reboiler
$(x_{LK})_F$ = concentration of the light key in the feed
$(x_{HK})_F$ = concentration of the heavy key in the feed
$(x_{LK})_B$ = concentration of the light key in the bottoms product
$(x_{HK})_D$ = concentration of the heavy key in the top product

Nomenclature

A_I, B_I = correlation constants in Hengstebeck-Geddes equation
b = number of moles of a component in the bottoms
B = bottoms flow rate moles/hr
d = number of moles of a component in the distillate
D = distillate flow rate moles/hr
F = feed flow rate moles/hr
f = number of moles of a component in the feed

FACTOR = multiplier for the reflux ratio (that is, FACTOR R_{min})
K = equilibrium constant for a component in the feed
n = number of components
N = number of theoretical plates
N_{min} = minimum number of theoretical plates at total reflux
q = pseudo-ratio of liquid to vapor for the feed
R = reflux ratio
R_{min} = minimum reflux ratio
x = mole fraction of a component where x_B, x_D, x_F = mole fractions in the bottoms, distillate, and feed, respectively

Greek Letters

α = relative volatility with respect to the heavy key
θ = Underwood's constant
$\sum$ = summation
HK, LK = heavy and the light key components
i = individual component identifier

PROBLEMS AND SOLUTIONS

Problem 7-1

A multicomponent hydrocarbon gas mixture is composed as follows:

Component	Mol %	K
Methane (CH_4)	27.52	7.88
Ethane (C_2H_6)	16.34	2.77
Propane (C_3H_8)	29.18	1.18
Isobutane (iC_4H_{10})	5.37	0.61
Normal butane (nC_4H_{10})	17.18	0.48
Isopentane (iC_5H_{12})	1.72	0.264
Normal pentane(nC_5H_{12})	2.18	0.225
Hexane (C_6H_{14})	0.47	0.102
Heptane (C_7H_{16})	0.04	0.048

Operating temperature and pressure are 178°C and 400 psia. Determine the dew point temperature of the gas mixture.

Solution

The computer program PROG71 calculates the dew and bubble points of any multicomponent hydrocarbon mixture based on the user supplied K-values. The program will handle feed streams containing up to 15 components. The feed entries may be moles, mole fraction, or mole percent. The dew point ($\Sigma X = \Sigma Y/K$) should be 1.0 or very close to 1.0, depending on the tolerance the user will accept. If the sum printed is not equal to 1.0 (within the user tolerance), a message is printed instructing the user to assume a new temperature. The iteration is repeated using the K_i's corresponding to the new temperature chosen. The temperature supplied does not affect the computation, but is printed and stored as a reminder to the user of which temperature (and corresponding K-values) was used for the last iteration. Table 7-15 shows the input data and computer output instructing the user that the dew point temperature is increased.

At 200 psia, calculate the bubble point temperature of the following:

Component	Mol %	K @ 260°F	K @ 235°F	K @ 237°F
iC_4H_{10}	18.2	1.92	1.62	1.65
nC_4H_{10}	23.8	1.58	1.35	1.35
iC_5H_{12}	33.7	0.93	0.76	0.77
nC_5H_{12}	12.1	0.81	0.64	0.64
C_6H_{14}	12.2	0.42	0.315	0.32

Solution

The computer program PROG71 determines the bubble points of the hydrocarbon mixture. As with the dew point, the bubble point ($\Sigma Y = \Sigma KX$) is computed until the sum is 1.0 or very close to 1.0, depending on the tolerance the user will accept. If the sum printed is not equal to 1.0 (within tolerance), the iteration is repeated using the K_i's corresponding to the new temperature. Tables 7-16, 7-17, and 7-18 give both the data input and computer outputs for the bubble points of the hydrocarbon mixture at 260°F, 235°F and 237°F.

Problem 7-2

The composition of the feed to a natural gas liquefaction plant is shown in the feed stream data. The feed will be flashed at 600 psia and

Table 7-15
Input Data and Computer Output for Dew and Bubble Points Calculations

```
DATA71.DAT
------------
DEW
178
9
27.52  7.88
16.34  2.77
29.18  1.18
5.37   0.61
17.18  0.48
1.72   0.264
2.18   0.225
0.47   0.102
0.04   0.048
```

```
                   DEW AND BUBBLE POINTS CALCULATIONS
*****************************************************************************

     DEW     POINT CALCULATION

     TEMPERATURE oF:     178.00

     NUMBER OF COMPONENTS IN THE FEED STREAM: 9

     NUMBER OF COMPONENTS      FEED COMPOSITION (MOLE %)      K-VALUE
-----------------------------------------------------------------------------
             1                         27.5200                  7.8800
             2                         16.3400                  2.7700
             3                         29.1800                  1.1800
             4                          5.3700                   .6100
             5                         17.1800                   .4800
             6                          1.7200                   .2640
             7                          2.1800                   .2250
             8                           .4700                   .1020
             9                           .0400                   .0480
-----------------------------------------------------------------------------
     TOTAL COMPOSITION:               100.0000

     NUMBER OF COMPONENTS      MOLE FRACTION                X=Y/K
-----------------------------------------------------------------------------
            1                   .2752                        .0349
            2                   .1634                        .0590
            3                   .2918                        .2473
            4                   .0537                        .0880
            5                   .1718                        .3579
            6                   .0172                        .0652
            7                   .0218                        .0969
            8                   .0047                        .0461
            9                   .0004                        .0083
-----------------------------------------------------------------------------
     TOTAL DEW POINT:                                       1.0036

     RAISE THE DEW-POINT TEMPERATURE: oF
```

Table 7-16
Input Data and Computer Output for Dew and Bubble Points Calculations

```
DATA71.DAT
----------
BUBBLE
260
5
18.2  1.92
23.8  1.58
33.7  0.93
12.1  0.81
12.2  0.42


                      DEW AND BUBBLE POINTS CALCULATIONS
*****************************************************************************

     BUBBLE  POINT CALCULATION

     TEMPERATURE oF:     260.00

     NUMBER OF COMPONENTS IN THE FEED STREAM: 5

     NUMBER OF COMPONENTS      FEED COMPOSITION (MOLE %)       K-VALUE
-----------------------------------------------------------------------------
                1                     18.2000                    1.9200
                2                     23.8000                    1.5800
                3                     33.7000                     .9300
                4                     12.1000                     .8100
                5                     12.2000                     .4200
-----------------------------------------------------------------------------
     TOTAL COMPOSITION:               100.0000

     NUMBER OF COMPONENTS      MOLE FRACTION                  Y=KX
-----------------------------------------------------------------------------
               1               .1820                           .3494
               2               .2380                           .3760
               3               .3370                           .3134
               4               .1210                           .0980
               5               .1220                           .0512
-----------------------------------------------------------------------------
     TOTAL BUBBLE POINT:                                      1.1881

     LOWER THE BUBBLE POINT TEMPERATURE: oF
```

20°F. If the flow rate is 1,000 moles/h, calculate the flow rates of the liquid and vapor streams and their compositions.

Feed stream data:

Number	Component Name	Feed Mole Fraction	Equilibrium Constant, K
1	CO_2	0.0112	0.90
2	CH_4	0.8957	2.70
3	C_2H_6	0.0526	0.38
4	C_3H_8	0.0197	0.098
5	iC_4H_{10}	0.0068	0.038

(table continued on next page)

Table 7-16
(continued)

Number	Component Name	Feed Mole Fraction	Equilibrium Constant, K
6	nC_4H_{10}	0.0047	0.024
7	C_5H_{12}	0.0038	0.0075
8	C_6H_{14}	0.0031	0.00019
9	C_7H_{16} and heavier	0.0024	0.0007

Solution

The computer program PROG72 performs equilibrium flash calculations for an ideal multi-component mixture. The program listed determines the moles of each component in the liquid and vapor phases

Table 7-17
Input Data and Computer Output for Dew and Bubble Points Calculations

```
DATA71.DAT
----------
BUBBLE
235
5
18.2  1.62
23.8  1.35
33.7  0.76
12.1  0.64
12.2  0.315


                     DEW AND BUBBLE POINTS CALCULATIONS
***************************************************************************

     BUBBLE  POINT CALCULATION

     TEMPERATURE oF:     235.00

     NUMBER OF COMPONENTS IN THE FEED STREAM: 5

     NUMBER OF COMPONENTS      FEED COMPOSITION (MOLE %)      K-VALUE
---------------------------------------------------------------------------
                1                     18.2000                 1.6200
                2                     23.8000                 1.3500
                3                     33.7000                  .7600
                4                     12.1000                  .6400
                5                     12.2000                  .3150
---------------------------------------------------------------------------
     TOTAL COMPOSITION:              100.0000

     NUMBER OF COMPONENTS      MOLE FRACTION              Y=KX
---------------------------------------------------------------------------
                1              .1820                     .2948
                2              .2380                     .3213
                3              .3370                     .2561
                4              .1210                     .0774
                5              .1220                     .0384
---------------------------------------------------------------------------
     TOTAL BUBBLE POINT:                                 .9881

     RAISE THE BUBBLE POINT TEMPERATURE: oF
```

Table 7-18
Input Data and Computer Output for Dew and Bubble Points Calculations

```
DATA71.DAT
-----------
BUBBLE
235
5
18.2  1.65
23.8  1.35
33.7  0.77
12.1  0.64
12.2  0.32
```

```
                        DEW AND BUBBLE POINTS CALCULATIONS
****************************************************************************

    BUBBLE  POINT CALCULATION

    TEMPERATURE oF:     235.00

    NUMBER OF COMPONENTS IN THE FEED STREAM: 5

    NUMBER OF COMPONENTS      FEED COMPOSITION (MOLE %)      K-VALUE
-----------------------------------------------------------------------------
              1                     18.2000                    1.6500
              2                     23.8000                    1.3500
              3                     33.7000                     .7700
              4                     12.1000                     .6400
              5                     12.2000                     .3200
-----------------------------------------------------------------------------
    TOTAL COMPOSITION:             100.0000

    NUMBER OF COMPONENTS      MOLE FRACTION                  Y=KX
-----------------------------------------------------------------------------
              1               .1820                        .3003
              2               .2380                        .3213
              3               .3370                        .2595
              4               .1210                        .0774
              5               .1220                        .0390
-----------------------------------------------------------------------------
    TOTAL BUBBLE POINT:                                    .9976

    RAISE THE BUBBLE POINT TEMPERATURE: oF
```

including the feed fraction condensed or vaporized. In addition, all feed moles and K-values are printed. As an added feature, the program checks the feed composition at the conditions given. This determines whether the feed is all vapor or all liquid. These computations are performed before the flash calculations are started, and a message is printed if either condition exists. Table 7-19 gives the input data and the computer output of the multicomponent mixture.

Problem 7-3*

Size an absorber tower for a methy ethyl amine (MEA) system with the following conditions:

Table 7-19
Input Data and Computer Output for Multicomponent Equilibrium Flash Calculations

```
DATA72.DAT
-------------
20.0
600.0
9
11.2    0.90
895.7   2.70
52.6    0.38
19.7    0.098
6.8     0.038
4.7     0.024
3.8     0.0075
3.1     0.00019
2.4     0.0007


                      MULTICOMPONENT EQUILIBRIUM FLASH CALCULATIONS

 MULTICOMPONENT EQUILIBRIUM FLASH CALCULATION AT   20.0 DEG. F AND  600.0 psia
******************************************************************************

COMPONENT K-VALUE      FEED                 LIQUID                  VAPOR
NUMBER              Mols/h.  Mol. frac.  Mols/h.  Mol. frac.  Mols/h.  Mol. frac.
------------------------------------------------------------------------------
 1       .900     11.200       .011        .510       .012    10.690       .011
 2      2.700    895.700       .896      14.030       .341   881.670       .920
 3       .380     52.600       .053       5.343       .130    47.257       .049
 4       .098     19.700       .020       6.004       .146    13.696       .014
 5       .038      6.800       .007       3.608       .088     3.192       .003
 6       .024      4.700       .005       3.016       .073     1.684       .002
 7       .007      3.800       .004       3.235       .079      .565       .001
 8       .000      3.100       .003       3.086       .075      .014       .000
 9       .001      2.400       .002       2.362       .057      .038       .000
------------------------------------------------------------------------------
 TOTALS          1000.000      1.000      41.195      1.000   958.805      1.000
------------------------------------------------------------------------------
```

Vapor flow	40,000 lb/h.
Vapor density	0.295 lb/ft^3
Liquid flow	330,000 lb/h.
Liquid density	61.85 lb/ft^3
Foam factor	0.75
Residence Time	4.5s
Tray Spacing	24in.
Surface tension	57.6 dyne/cm.

The author developed computer program PROG73 for solving problem 7-3 in the text, using Nutter's *Float Valve Design Manual.* The developed program and calculation of the tray geometry are the responsibility of the author. The author expresses his gratitude to Nutter Engineering for the use of the photographs and the information from the Float Valve Design Manual.

Solution

The computer program PROG73 determines the parameters required for sizing a tower using valve trays. The program calculates the bubbling area, downcomer area, tower area, and diameter. The tower diameter may be rounded to an appropriate value and the area is recalculated. Once the tower diameter is set, the downcomer area ratio is determined and the downcomer height is computed from Tables 7-5 to 7-9. Table 7-20 shows the input data and computer output for tower sizing using valve trays. The computer output gives the tower area of 26.571 ft^2 and a diameter of 5.816 ft.

Tray Geometry

From the tower size (normally by increasing the diameter to the nearest 6-inch increment), the following procedure is used to calculate the downcomer dimensions.

Table 7-20
Input Data and Computer Output for Tower Design Using Valve Trays

```
DATA73.DAT
-----------------------------
40000.0   330000.0  61.85
0.295     0.75  4.5
24.0      57.6
```

```
                            TOWER DESIGN FOR VALVE TRAYS
*****************************************************************************
    VAPOR FLOW RATE, lb/hr.:                                      40000.0
    VAPOR VOLUMETRIC RATE, ft^3/sec.:                              37.665
    LIQUID FLOW RATE, lb/hr.:                                     330000.0
    LIQUID VOLUMETRIC RATE, ft^3/sec.:                              1.482
    LIQUID DENSITY, lb/ft^3.:                                      61.850
    VAPOR DENSITY, lb/ft^3.:                                         .295
    FOAM FACTOR:                                                     .750
    DOWNCOMER RESIDENCE TIME, sec.:                                 4.500
    TRAY SPACING, in.:                                              24.
    SURFACE TENSION, dyne/cm.:                                     57.60
    SURFACE TENSION/VAPOR DENSITY (X):                             195.254
    SAFETY FACTOR:                                                   .745
    DENSITY RADICAL:                                                 .069
    BUBBLING AREA, ft^2:                                           10.905
    DOWNCOMER AREA, ft^2:                                           4.446
    TOWER AREA, ft^2:                                              26.571
    TOWER DIAMETER, ft:                                             5.816
    DOWNCOMER AREA RATIO:                                           .2246
-----------------------------------------------------------------------------
```

The downcomer area ratio is:

$$R_{DCA} = \frac{A_{DC}}{(2A_{DC} + A_b)}$$

The calculated tower diameter is increased to 6.0 ft and the tower area becomes

$$A = \frac{\pi . d^2}{4}$$

$$= \frac{\pi \times 6^2}{4}$$

$$= 28.27 \text{ ft}^2$$

Using Tables 7-5 to 7-9 and R_{DCA} will allow a direct computation of chord height for the side downcomer. This is rounded up to the nearest 1/2-inch incremental dimension. Using this dimension, the corrected downcomer area is calculated from Tables 7-5 to 7-9. The computed output of the tower used by the downcomer area (R_{DCA}) is 0.2246. That is,

$$\frac{A_d}{A_t} = 0.2246$$

$\frac{H}{DIA}$	$\frac{L}{DIA}$	$\frac{A_d}{A_t}$
0.2760	0.8940	0.2246

The corresponding downcomer height-to-tower-diameter ratio is 0.2760.

The downcomer height is (0.2760) (6) (12)
= 19.87 in. + 1/2 in.
= 20.4 in.

$$\text{The new } \frac{H}{DIA} = \frac{20.4}{72}$$

$$= 0.2833$$

This gives a downcomer-area-to-tower-area ratio of 0.2329.

$\frac{H}{DIA}$	$\frac{L}{DIA}$	$\frac{A_d}{A_t}$
0.2830	0.9009	0.2326
Avg. 0.28325	Avg. 0.90115	Avg. 0.2329
0.2835	0.9014	0.2332

That is

$$\frac{A_d}{A_t} = 0.2329$$

The downcomer area, A_d, is (0.2329) (28.27)
= 6.584 ft^2

The weir length, L, is (0.90115 × 72)
= 64.88 in.
= 65 in.

The computed liquid flow rate is 1.482 ft^3/sec or 664.907 USgpm.

conversion: 1 ft^3/sec = 448.655 USgpm

$$\text{The liquid flow per inch of weir} = \frac{664.907}{65}$$

$$= 10.23 \text{ USgpm per inch of weir}$$

A single-pass tray is selected.

Problem 7-4

A packed tower with 1-inch Raschig rings are to be used to absorb ammonia from air by contacting the gas stream with water. The entering gas flow is 40 lb mol/h and contains 5.0% NH_3. Ninety percent of the NH_3 is to be removed from the air. The entering water flow rate is 3,200 lb/h. Absorption is to be carried out at 1 atm. abs. and 20°C. Estimate:

1. The diameter of the tower for a ΔP of 1.0 in. H_2O/ft. packing.
2. The vapor rate at 70% of flooding condition.

Physical properties:

$$\rho_G = (28.4)\left(\frac{1}{359}\right)\left(\frac{273}{293}\right)$$

$$= 0.0737 \text{ lb/ft}^3$$

$$\rho_L = 62.3 \text{ lb/ft}^3$$

$$\mu_L = 1 \text{cP}$$

$$F_p = 155$$

Solution

When calculating the tower diameter, conditions at the bottom of the tower should be used because this corresponds to the maximum flow rates. At the bottom of the column:

$$MW_{gas} = 0.05 \times 17 + 0.95 \times 29$$

$$= 28.4 \text{ lb/lb. mol.}$$

Molecular weight of ammonia $\left(MW_{NH_3} = 17 \frac{\text{lb}}{\text{lb. mol}}\right)$

NH_3 removed from the air $= (0.9)(0.05)(40)$

$$= \left(1.8 \frac{\text{lb. mol}}{\text{hr}}\right)\left(17 \frac{\text{lb}}{\text{lb. mol}}\right)$$

$$= 30.6 \text{ lb/hr}$$

Gas flow rate at the bottom $= \left(40 \frac{\text{lb. mol}}{\text{hr}}\right)\left(28.4 \frac{\text{lb}}{\text{lb. mol}}\right)$

$$= 1{,}136 \text{ lb/hr}$$

Liquid flow rate at the bottom = 3200 + 30.6

$$= 3230.6 \text{ lb/hr}$$

The computer program PROG74 calculates the diameter of a packed tower for pressure drops of 0.05, 0.10, 0.25, 0.50, 1.0 and 1.5 in H_2O/ft.

The simulation is based on the generalized pressure drop correlation of Sherwood *et al.* [20].

The curves have been fitted to a series of equations developed by Blackwell [13]. In addition, the program computes the vapor rate and vapor velocity at 70% of flooding condition. Table 7-21 illustrates the input data and computer output of the packed tower.

Problem 7-5

A column is to be designed to separate 1000 moles/hr of a binary mixture of benzene (C_6H_6) and toluene (C_7H_8). The feed will contain 40% benzene and 60% toluene. A distillate that is 99% benzene and a bottoms that is 1% benzene are desired at a reflux ratio of 3 to 1. For this mixture, the average value of relative volatility (α) is 2.50. Estimate the number of equilibrium stages at this reflux ratio and the optimum feed stage location.

Solution

The computer program PROG75 uses the analytical method of a quadratic equation to determine the number of stages in the rectifying and stripping sections of a distillation column. The program uses Smoker's equations involving two components to calculate the required number of stages. Table 7-22 gives the input data and computer output. The

Table 7-21
Input Data and Computer Output for Packed Tower Design

```
DATA74.DAT
-------------------------
3230.6  1136.0  0.0737
62.3    155.0   1.0    1.0
```

```
                        PACKED TOWER DESIGN
*****************************************************************************
    LIQUID FLOW RATE, lb/hr.:                                 3230.600
    GAS FLOW RATE, lb/hr.:                                    1136.000
    GAS DENSITY, lb/ft.^3:                                   .0737
    LIQUID DENSITY, lb/ft.^3:                              62.3000
    TOWER PACKING FACTOR:                                    155.0
    PRESSURE DROP, INCH-H2O:                                 1.000
    LIQUID VISCOSITY, cP:                                    1.000
    X CO-ORDINATE IN THE GENERALIZED PLOT:                   .0979
    Y CO-ORDINATE IN THE GENERALIZED PLOT:                   .0719
    CALCULATED VAPOR RATE, lb/s.ft^2:                        .2617
    X CO-ORDINATE AT FLOODING CONDITION:                     .0978
    Y CO-ORDINATE AT FLOODING CONDITION:                     .1335
    VAPOR RATE AT 70% FLOODING CONDITION, lb/s.ft^2:         .2496
    VAPOR VELOCITY AT 70% FLOODING CONDITION, ft./sec:        3.39
    TOWER AREA, ft^2:                                         1.21
    TOWER DIAMETER, inches:                                  14.87
    TOWER AREA AT 70% FLOODING CONDITION, ft^2:               1.67
    TOWER DIAMETER AT 70% FLOODING CONDITION, inches:        17.49
-----------------------------------------------------------------------------
```

Table 7-22
Input Data and Computer Output for Calculating Equilibrium Number of Stages Using Smoker's Equations

```
DATA75.DAT
---------------
2.5   2.5
0.40  0.99  0.01
3
```

```
              EQUILIBRIUM NUMBER OF STAGES BY SMOKER'S EQUATION
*****************************************************************************
    THE RELATIVE VOLATILITY OF COMPONENT 1.:                          2.500
    THE RELATIVE VOLATILITY OF COMPONENT 2.:                          2.500
    THE MOLE FRACTION OF THE FEED:                                    .4000
    THE MOLE FRACTION OF THE DISTILLATE:                              .9900
    THE MOLE FRACTION OF THE BOTTOMS:                                 .0100
    THE REFLUX RATIO:                                                  3.00
    THE NUMBER OF STAGES IN THE RECTIFYING SECTION:                  7.87
    THE NUMBER OF STAGES IN THE STRIPPING SECTION:                   7.76
    TOTAL NUMBER OF STAGES:                                          15.63
    FEED STAGE LOCATION:                                               7.8
-----------------------------------------------------------------------------
```

required number of stages between benzene and toluene mixture is 16. The optimum feed location is 8.

Problem 7-6

The feed to a butane-pentane splitter of the following composition is to be fractionated into a distillate product that contains 95% of the n-butane contained in the feed. The bottoms product contains 95% of the iso-pentane in the feed. The reflux ratio for the fractionation will be 1.3 R_{min}, and the column pressure will be 100 psia at the top plate. The reflux and feed are at their bubble point temperatures. The feed composition and equilibrium constant are:

Number	Component	x_F	K_i
1	iC_4H_{10}	0.06	2.15
2	nC_4H_{10} (LK)	0.17	1.70
3	iC_5H_{12} (HK)	0.32	0.835
4	nC_5H_{12}	0.45	0.70

Use the short-cut method to determine:

1. The recoveries of the components in the distillate and bottoms.
2. The minimum number of stages.
3. The minimum reflux ratio.
4. The actual number of theoretical plates.
5. The optimum location of the feed plate.

Solution

The computer program PROG76 gives the multicomponent distribution calculations based on a series of equations developed by Hengstebeck-Geddes [35,36], while the minimum tray calculations (at total reflux) use the equations developed by Fenske [37]. The number of theoretical equilibrium stages is determined using Gilliland's [38,39] empirical correlations. The program listed calculates the following: feed component recovery in both the distillate and bottoms products, the minimum number of stages, Underwood constant, minimum reflux ratio, actual reflux ratio, total number of theoretical plates, and the optimum location of the feed plate in a distillation column. The user has an option of entering the feed components (moles) and the equilibrium constants or the feed and the relative volatilities. Feed components must be entered in order of decreasing relative volatility, with the light key (LK) and heavy key (HK) components adjacent to each other. Table 7-23 shows the input data and computer output of the butane-pentane splitter.

Table 7-23
Input Data and Computer Output for Multicomponent System Fractionation

```
DATA76.DAT
-----------
EQUIL
4
0.06    2.15
0.17    1.70
0.32    0.835
0.45    0.70
0.95    0.95
3    1  1.3
```

```
                        MULTICOMPONENT SYSTEM FRACTIONATION
*****************************************************************************

COMPONENT       FEED     REL VOLATILITY   DISTILLATE             BOTTOMS
NUMBER          MOLES        ALPHA            %         MOLES        %       MOLES
-----------------------------------------------------------------------------
   1            .0600       2.5749        99.2532      .0596       .7468     .0004
   2            .1700       2.0359        95.0000      .1615      5.0000     .0085
   3            .3200       1.0000         5.0000      .0160     95.0000     .3040
   4            .4500        .8383         1.2067      .0054     98.7933     .4446
-----------------------------------------------------------------------------
  THE HEAVY KEY COMPONENT NUMBER:                               3
  PERCENTAGE RECOVERY OF THE LIGHT KEY COMPONENT
  IN THE DISTILLATE (%):                                        95.00
  PERCENTAGE RECOVERY OF THE HEAVY KEY COMPONENT
  IN THE BOTTOMS (%):                                           95.00
  MINIMUM NUMBER OF STAGES:                                       8.3
  TOTAL MOLES IN THE DISTILLATE:                                .2425
  TOTAL MOLES IN THE BOTTOMS:                                   .7575
  UNDERWOOD CONSTANT:                                          1.6213
  MINIMUM REFLUX RATIO:                                        2.8036
  ACTUAL REFLUX RATIO:                                         3.6447
  NUMBER OF THEORETICAL PLATES IN THE COLUMN:                    16.2
  THE POSITION OF THE FEED PLATE:                                 6.7
-----------------------------------------------------------------------------
```

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```
        PROGRAM PROG71

C       CALCULATION OF THE DEW POINT AND BUBBLE POINT OF GAS MIXTURE.
C       THIS PROGRAM WILL CALCULATE DEW POINT AND BUBBLE POINT BASED
C       ON THE SUPPLIED K-VALUES.
C       THE PROGRAM WILL COVER FEED STREAMS CONTAINING UP TO 15
C       COMPONENTS.
C
C       ***************************************************************
C       Ki = EQUILIBRIUM FLASH CONSTANT FOR EACH FEED STREAM
C       Mi = TOTAL MOLES OF COMPONENT i IN THE FEED STREAM
C       Ni = MOLE FRACTION OF COMPONENT i IN THE FEED STREAM
C       ***************************************************************

        CHARACTER*10 FEED
C
        COMMON/DATA/BP,DP,J,K,N
        REAL K(20), M(20), N(20), BP(20), DP(20)

        OPEN (UNIT = 3, FILE='DATA71.DAT', STATUS='OLD', ERR=18)
        OPEN (UNIT = 1, FILE='PRN')

C
C       READ EITHER THE DEW POINT OR BUBBLE POINT TEMPERATURE
C       READ THE TOTAL NUMBER OF COMPONENTS
C       READ THE MOLES OF EACH FEED COMPONENT
C       READ THE K-VALUE OF EACH COMPONENT
C
        READ (3, 10, ERR=19) FEED
 10     FORMAT (A6)

        READ (3,*,ERR=19) T
        READ (3,*,ERR=19) J
        READ (3,*,ERR=19)(M(I),K(I),I=1,J)

        WRITE (1, 100)
 100    FORMAT (///,20X,'DEW AND BUBBLE POINTS CALCULATIONS',/1H ,
     *         76(1H*))

        WRITE (1, 110) FEED
 110    FORMAT (/,6X, A6, 2X,'POINT CALCULATION')
        WRITE (1, 120) T
 120    FORMAT (/,6X,'TEMPERATURE oF:',F10.2)
        WRITE (1, 130) J
 130    FORMAT (/,6X,'NUMBER OF COMPONENTS IN THE FEED STREAM:',I2)
        WRITE (1, 140)
 140  FORMAT (/,6X,'NUMBER OF COMPONENTS',6X,'FEED COMPOSITION (MOLE %)',
     *          6X,'K-VALUE',/1H ,76(1H-))

        DO I = 1, J
        WRITE (1, 150) I,M(I),K(I)
 150    FORMAT (13X, I2, 24X, F8.4, 16X, F8.4)
        END DO

        GO TO 20
   18   WRITE (1, 160)
 160    FORMAT (6X,'DATA FILE DOES NOT EXIST')
        GO TO 999
```

```
   19   WRITE (1, 170)
  170   FORMAT (6X,'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

  20    SUM=0.0

        DO I = 1, J
        SUM=SUM+M(I)
        END DO

        WRITE (1, 180)
  180   FORMAT (1H ,76(1H-))

        WRITE (1, 190)SUM
  190   FORMAT (6X,'TOTAL COMPOSITION:', T40, F8.4)
C
C       CALCULATE THE MOLE FRACTION OF COMPONENT IN THE FEED STREAM
C
        DO I = 1, J
        N(I)=M(I)/SUM
        END DO

C
C       CHECK WHETHER THE FEED IS AT BUBBLE POINT OR DEW POINT.
C
        IF (FEED .EQ. 'DEW' .OR. FEED .EQ. 'dew') THEN
        GO TO 30
        ELSEIF (FEED .EQ. 'BUBBLE' .OR. FEED .EQ. 'bubble') THEN
        CALL BUBBLE
        GO TO 999
        ENDIF

  30    CALL DEW
        GO TO 999

        CLOSE (3,STATUS='KEEP')
        CLOSE (1)
  999   STOP
        END
C
C       ****************************************************************
C       THIS PROGRAM CALCULATES THE DEW POINT
C       ****************************************************************

        SUBROUTINE DEW
        COMMON/DATA/BP,DP,J,K,N
        REAL N(20), K(20), DP(20) , BP(20)

        DPT = 0.0
        DO I = 1, J
        DP(I)=N(I)/K(I)
        DPT=DPT+N(I)/K(I)
        END DO

        WRITE (1, 200)
  200   FORMAT (/,6X,'NUMBER OF COMPONENTS',6X,'MOLE FRACTION',16X,
     *          'X=Y/K',/1H ,76(1H-))

        DO I =1, J
```

```
        WRITE (1, 210)I, N(I), DP(I)
 210    FORMAT (12X, I2, 16X, F8.4, 20X, F8.4)
        END DO

        WRITE (1, 220)DPT
 220    FORMAT(1H ,76(1H-),/,6X,'TOTAL DEW POINT:', T59, F8.4)

        IF (DPT .GE. 1.0) THEN
        GO TO 10
        ELSE
        WRITE (1, 230)
 230    FORMAT(/,6X,'LOWER THE DEW-POINT TEMPERATURE: oF')
        ENDIF

        GO TO 20

 10     WRITE (1, 240)
 240    FORMAT(/,6X,'RAISE THE DEW-POINT TEMPERATURE: oF')

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

 20     WRITE (1, *) CHAR(12)

        RETURN
        END
C
C
C       ****************************************************************
C       THIS PROGRAM CALCULATES THE BUBBLE-POINT
C       ****************************************************************
C
        SUBROUTINE BUBBLE
        COMMON/DATA/BP,DP,J,K,N
        REAL N(20), K(20), DP(20), BP(20)

        BPT=0.0

        DO I = 1, J
        BP(I) =N(I)*K(I)
        BPT=BPT+N(I)*K(I)
        END DO

        WRITE (1, 250)
 250    FORMAT (/,6X, 'NUMBER OF COMPONENTS', 6X, 'MOLE FRACTION',16X,
     *          'Y=KX',/1H ,76(1H-))

        DO I =1 ,J
        WRITE (1, 260) I, N(I), BP(I)
 260    FORMAT (12X, I2, 16X, F8.4, 20X, F8.4)
        END DO

        WRITE (1, 270)BPT
 270    FORMAT(1H ,76(1H-),/,6X,'TOTAL BUBBLE POINT:', T59, F8.4)

        IF (BPT .GE. 1.0) THEN
        GO TO 30
        ELSE

        WRITE (1, 280)
 280    FORMAT(/,6X,'RAISE THE BUBBLE POINT TEMPERATURE: oF')
```

```
        ENDIF
        GO TO 35

   30   WRITE (1, 290)
  290   FORMAT(/,6X,'LOWER THE BUBBLE POINT TEMPERATURE: oF')

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

  35    WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
      PROGRAM PROG72

C     EQUILIBRIUM FLASH CALCULATIONS
C     THE PROGRAM USES THE ITERATIVE CONVERGENCE METHOD SUGGESTED BY
C     I.H. OLIVER AND LATER MODIFIED BY S.T. KOSTECKE TO CALCULATE
C     FLASH VAPORIZATION CONTAINING UP TO 15 COMPONENTS OF
C     MULTICOMPONENT MIXTURES OF OIL, GAS AND CHEMICAL PROCESSES.
C     THIS PROGRAM FURTHER CHECKS THE FEED COMPOSITION AT THE
C     CONDITIONS GIVEN TO DETERMINE WHETHER THE FEED IS ALL VAPOR
C     OR ALL LIQUID.  THIS PROGRAM IS BASED ON THE WELL-KNOWN AND
C     WIDELY USED VAPORIZATION EQUILIBRIUM RELATIONSHIPS THAT
C     APPEAR IN HANDBOOKS BY THE NATURAL GAS PROCESSORS SUPPILIERS
C     ASSOCIATIONS AND IN OTHER LITERATURE.
C     ***************************************************************
C
C     Mi  = TOTAL MOLES OF COMPONENT i IN THE FEED STREAM
C     Ki  = EQUILIBRIUM FLASH CONSTANT FOR EACH COMPONENT i
C           IN THE FEED STREAM
C     R   = L/V RATIO
C     R1  = NEW L/V RATIO FOR EACH ITERATIVE CALCULATION
C     L   = TOTAL MOLES OF LIQUID AT EQUILIBRIUM CONDITIONS
C     V   = TOTAL MOLES OF VAPOR AT EQUILIBRIUM CONDITIONS
C     Ni  = MOLES FRACTION OF COMPONENT i IN THE FEED STREAM
C     Li  = TOTAL MOLES OF COMPONENT i IN THE LIQUID PHASE
C     Vi  = TOTAL MOLES OF COMPONENT i IN THE VAPOR PHASE
C     X   = MOLE FRACTION OF FEED IN THE LIQUID PHASE AT EQUILIBRIUM
C     Y   = MOLE FRACTION OF FEED IN THE VAPOR PHASE AT EQUILIBRIUM
C     E,F = CONSTANTS USED BY KOSTECKS
C     ****************************************************************
C

      DIMENSION C(15), V(15), X1(15), Y1(15)
      REAL K(15), L1, L(15), M(15), N(15)


      COMMON/DATA1/ NUM, T, P, M, K
      COMMON/DATA2/ ADD1, ADD2, ADD3

      OPEN (UNIT = 3, FILE='DATA72.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT = 1, FILE='PRN')

C     READ FLASH TEMPERATURE, oF                            = T
C     READ FLASH PRESSURE, psia                             = P
C     READ NUMBER OF COMPONENTS                             = NUM
C     READ FEED AND EQUILIBRIUM CONSTANT OF EACH COMPONENT = M, K

      READ (3, *, ERR=19) T
      READ (3, *, ERR=19) P
      READ (3, *, ERR=19) NUM

      DO I = 1, NUM
      READ (3, *, ERR=19) M(I), K(I)
      END DO

      GO TO 10

 18   WRITE (*, 100)
 100  FORMAT (5X, 'DATA FILE DOES NOT EXIST')
      GO TO 999
```

```
 19     WRITE (*, 110)
 110    FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999


 10     WRITE(1, 120)
 120    FORMAT(//,20X,'MULTICOMPONENT EQUILIBRIUM FLASH CALCULATIONS')


        SUM=0.0

        DO I = 1, NUM
        SUM = SUM + M(I)
        END DO

C       CALCULATE MOLE FRACTION OF COMPONENT IN THE FEED STREAM


        DO I = 1, NUM
             N(I)=M(I)/SUM
        END DO

        TOTAL=0.0

        DO I = 1, NUM
             TOTAL = TOTAL + N(I)
        END DO

C       CHECK WHETHER THE FEED IS ALL LIQUID OR VAPOR

        SUM1=0.0

        DO I1 = 1, NUM
        SUM1 = SUM1 + N(I1)*K(I1)
        END DO

        IF ( SUM1 .GT. 1.0) THEN
        GO TO 45
        ELSE
             GO TO 900
        ENDIF

 45      SUM2 = 0.0

        DO I2 = 1, NUM
            SUM2 = SUM2+N(I2)/K(I2)
        END DO

        IF(SUM2 .GT. 1.0) THEN
             GO TO 60
        ELSE
        GO TO 1000
        ENDIF

C       GUESS R=L/V


 60     R=1.0
 65     SUM3=0.0
```

```
        DO I3 = 1, NUM
        C(I3)=(M(I3)*(K(I3)-1.0)*(R+1.0))/(K(I3)+R)
        END DO

C       CALCULATE E AND F CONSTANTS USED BY KOSTECKE.

        E = 0.0
        F = 0.0

        DO I4 = 1, NUM
        E = E+C(I4)
        F = F+(C(I4)**2/M(I4))
        END DO


C       CALCULATE R1, THE NEW L/V RATIO

        R1=ABS((F*R-E*(R+1.0))/(F+E*(R+1.0)))
        IF ( ABS(E) .LT. 0.001) THEN
        GO TO 90
        ELSE
             R=R1
        GO TO 65
        ENDIF

 90     L1 = 0.0
        V1 = 0.0

        DO I5 = 1, NUM
        L(I5) = (M(I5)*R1)/(K(I5)+R1)
        V(I5) = M(I5)-L(I5)
        L1 = L1 + L(I5)
        V1 = V1 + V(I5)
        END DO

        R2=L1/V1


C       CALCULATE X: MOLE FRACTION OF FEED IN THE LIQUID PHASE
C       AT EQUILIBRIUM, AND Y: MOLE FRACTION OF FEED IN THE VAPOR
C       PHASE AT EQUILIBRIUM.
C
        VAL1=0.0
        VAL2=0.0
        VAL3=0.0

        DO I6 = 1, NUM
        VAL1 = VAL1+L(I6)
        VAL2 = VAL2+M(I6)
        VAL3 = VAL3+V(I6)
        END DO


C       CALCULATE THE MOLE FRACTIONS IN THE LIQUID AND VAPOR PHASES.
C
        DO I = 1, NUM
        X1(I) =L(I)/VAL1
        Y1(I) =V(I)/VAL3
        END DO
```

```
C       CALCULATE THE TOTAL MOLE FRACTIONS OF THE FEED, LIQUID AND
C       VAPOR PHASES
C
        ADD1 = 0.0
        ADD2 = 0.0
        ADD3 = 0.0

        DO I = 1, NUM
        ADD1 = ADD1+X1(I)
        ADD2 = ADD2+N(I)
        ADD3 = ADD3+Y1(I)
        END DO
C
C       PRINT THE RESULTS ON THE SCREEN
C
        CALL OUTPUT(N, L, X1, V, Y1, VAL1, VAL2, VAL3)

C       PRINT THE RESULTS ONTO THE PRINTER

        CALL PAPER (N, L, X1, V, Y1, VAL1, VAL2, VAL3)

        GO TO 999

 900    WRITE(*,300)
 300    FORMAT(3X,'THE FEED COMPOSITION IS ALL LIQUID')
        GO TO 999


 1000   WRITE(*,400)
 400    FORMAT(3X,'THE FEED COMPOSITION IS ALL VAPOR')

        CLOSE (UNIT=3, STATUS='KEEP')
        CLOSE (UNIT=1)

 999    STOP
        END

C
C       ****************************************************************
C       THIS PROGRAM OUTPUTS THE RESULTS ON THE SCREEN
C       *****************************************************************
C
C
        SUBROUTINE OUTPUT (N, L, X1, V, Y1, VAL1, VAL2, VAL3)
        DIMENSION X1(15), Y1(15), V(15)
        REAL K(15), M(15), N(15), L(15)

        COMMON/DATA1/ NUM, T, P, M, K
        COMMON/DATA2/ ADD1, ADD2, ADD3

        WRITE(*, 130)
 130    FORMAT(2X,'MULTICOMPONENT EQUILIBRIUM FLASH CALCULATION AT '\)

        WRITE(*, 140) T, P
 140    FORMAT(F6.1,1X,'DEG. F',1X,'AND',1X,F6.1,1X,'PSIA')

        WRITE(*, 150)
 150    FORMAT(79(1H*))
```

```
      WRITE(*, 160)
 160  FORMAT(/,1X,'COMPONENT',1X,'K-VALUE',6X,'FEED',16X,'LIQUID ',\)

      WRITE(*, 170)
 170  FORMAT(15X,'VAPOR')

      WRITE(*, 180)
 180  FORMAT(1X,'NUMBER',12X,'Mols/h.',2X,'Mol. frac.',2X,'Mols/h.',\)

      WRITE(*, 190)
 190  FORMAT(2X,'Mol.frac.',2X,'Mols/h.',2X,'Mol.frac.')

      WRITE(*, 200)
 200  FORMAT(78(1H-))

      DO I = 1, NUM
      WRITE(*, 210) I, K(I), M(I), N(I), L(I), X1(I), V(I)
 210  FORMAT(1X,I2,5X,F5.3,2X,F9.3,2X,F8.3,3X,F9.3,2X,F8.3,2X,F9.3\)

      WRITE(*, 220) Y1(I)
 220  FORMAT(2X,F8.3)
      END DO

      WRITE(*, 230)
 230  FORMAT(78(1H-))

      WRITE(*, 240) VAL2, ADD2, VAL1, ADD1
 240  FORMAT(2X,'TOTALS',7X,F9.3,5X,F5.3,3X,F9.3,5X,F5.3,\)

      WRITE(*, 250) VAL3, ADD3
 250  FORMAT(2X,F9.3,5X,F5.3)

      WRITE(*, 260)
 260  FORMAT (78(1H-))
      RETURN
      END

C
C     ******************************************************************
C     THIS PROGRAM PRINTS THE RESULTS ONTO THE PRINTER
C     ******************************************************************

      SUBROUTINE PAPER (N, L, X1, V, Y1, VAL1, VAL2, VAL3)

      DIMENSION V(15), X1(15), Y1(15)
      REAL K(15), L(15), M(15), N(15)

      COMMON/DATA1/NUM, T, P, M, K
      COMMON/DATA2/ADD1, ADD2, ADD3

      WRITE (1, 270)
 270 FORMAT (/,2X,'MULTICOMPONENT EQUILIBRIUM FLASH CALCULATION AT ',\)

      WRITE (1, 280) T, P
 280  FORMAT (F6.1, 1X, 'DEG. F', 1X, 'AND', 1X, F6.1, 1X, 'psia')

      WRITE (1, 290)
 290  FORMAT (80(1H*))
```

```
        WRITE (1, 300)
 300  FORMAT (/, 1X,'COMPONENT', 1X,'K-VALUE',6X,'FEED',16X,'LIQUID ',\)

        WRITE (1, 310)
 310    FORMAT (15X, 'VAPOR')

        WRITE (1, 320)
 320  FORMAT (1X, 'NUMBER',12X,'Mols/h.',2X,'Mol. frac.',2X,'Mols/h.',\)

        WRITE (1, 330)
 330    FORMAT (2X,'Mol. frac.', 2X, 'Mols/h.', 2X,'Mol. frac.')

        WRITE (1, 340)
 340    FORMAT (80(1H-))

        DO I = 1, NUM

        WRITE (1, 350) I, K(I), M(I), N(I), L(I), X1(I), V(I)
 350    FORMAT (1X,I2,5X,F5.3,2X,F9.3,2X,F8.3,3X,F9.3,2X,F8.3,2X,F9.3,\)

        WRITE (1, 360) Y1(I)
 360    FORMAT (2X,F8.3)

        END DO

        WRITE (1, 370)
 370    FORMAT (80(1H-))

        WRITE (1, 380) VAL2, ADD2, VAL1, ADD1
 380    FORMAT (2X,'TOTALS', 7X, F9.3, 5X, F5.3, 3X, F9.3, 5X, F5.3,\)

        WRITE (1, 390) VAL3, ADD3
 390    FORMAT (2X, F9.3, 5X, F5.3)

        WRITE (1, 400)
 400    FORMAT (80(1H-))

C       FORM FEED THE PRINTING PAPER ON TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
        PROGRAM PROG73

C       TOWER SIZING FOR VALVE TRAYS.
C       THE PROGRAM EMPLOYS THE NUTTER METHOD FOR CALCULATING
C       TOWER DIAMETER WHERE VALVE-TYPE TRAYS ARE USED.
C       TOWER SIZING GRAPHS AND CURVES IN NUTTER'S FLOAT VALVE
C       DESIGN HAVE BEEN FITTED TO A SERIES OF EQUATIONS AND ARE
C       USED IN THIS PROGRAM.
C       ***************************************************************
C       RD      =   DENSITY RADICAL
C       DENV    =   VAPOR DENSITY, lb/ft.^3
C       DENL    =   LIQUID DENSITY, lb/ft.^3
C       SURT    =   SURFACE TENSION, dyne/cm.
C       V       =   VELOCITY AT ZERO LIQUID LOAD, ft./sec.
C       FT      =   TRAY SPACING FACTOR
C       WV      =   VAPOR FLOW RATE, lb/hr.
C       VCFS    =   VOLUMETRIC VAPOR FLOW RATE, ft.^3/sec.
C       WL      =   LIQUID FLOW RATE, lb/hr.
C       LCFS    =   VOLUMETRIC LIQUID FLOW RATE, ft.^3/sec.
C       AB      =   BUBBLING AREA, ft.^2.
C       FF      =   FOAM FACTOR
C       ADC     =   DOWNCOMER AREA, ft.^2.
C       REST    =   DOWNCOMER RESIDENCE TIME, sec.
C       TS      =   TRAY SPACING, inch.
C       TSF     =   SAFETY FACTOR
C       AT      =   TOWER AREA, ft^2
C       D       =   TOWER DIAMETER, ft.
C       ***************************************************************
C
C
        REAL K, M, LCFS
        COMMON PI

        COMMON/MULT1/ X, SF, RD, V, VRD
        COMMON/MULT2/ AB, ADC, AT, DIA, RDCA
        COMMON/MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
        COMMON/MULT4/ LCFS, VCFS

        OPEN (UNIT=3,FILE='DATA73.DAT',STATUS='OLD',ERR=18)
        OPEN (UNIT=1,FILE='PRN')

C       READ THE VAPOR FLOW RATE, WV: lb/hr.
C       READ THE LIQUID FOW RATE, WL: lb/hr.
C       READ THE LIQUID DENSITY, DENL: lb/ft^3.
C       READ THE VAPOR DENSITY, DENL: lb/ft^3.
C       READ THE FOAM FACTOR, FF:
C       READ THE DOWNCOMER RESIDENCE TIME, REST: sec.
C       READ THE TRAY SPACING, TS:
C       READ THE SURFACE TENSTION, SURT: dyne/cm.


        READ(3, *, ERR=19) WV, WL, DENL
        READ(3, *, ERR=19) DENV, FF, REST
        READ(3, *, ERR=19) TS, SURT

        GO TO 20
```

```
 18     WRITE (*, 21)
 21     FORMAT(3X,'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 22)
 22     FORMAT(3X,'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

C       CONSTANTS FOR VELOCITY AT ZERO LIQUID LOAD, ft/sec.
C       (W.W. BLACKWELL, Chemical Process Design On A Programmable
C       Calculator, Mc. Graw-Hill, 1984).


 20     PI = 3.1415927
        A = 0.22982
        B = 0.44605
        C = 0.03452
        D = 0.00415
        E = 0.00017
        K = 0.91146
        M = -0.03821


C       CALCULATE THE RATIO OF SURFACE TENSION TO THE VAPOR DENSITY, X

        X=SURT/DENV

C       CALCULATE THE SAFETY FACTOR.

        SF=K*(X)**M

C       CALCULATE THE DENSITY RADICAL.

        RD=SQRT(DENV/(DENL-DENV))
C
C       V IS VALID FOR 0.1 < X < 3000.

C       CALCULATE THE VELOCITY AT ZERO LIQUID LOAD, ft/sec.

        VAL1=A+B*ALOG(X)-C*(ALOG(X))**2+D*(ALOG(X))**3-E*(ALOG(X))**4
        V=EXP(VAL1)
        VRD=V*RD

        IF (VRD .GE. 0.5) THEN
        GO TO 23
        ELSE
        ENDIF
        GO TO 24

 23     VRD = 0.5

C       CHECK THE TRAY SPACING, TS.


 24     IF (TS .EQ. 12.0 ) THEN

        GO TO 33

        ELSEIF (TS .EQ. 18.0) THEN
```

```
       GO TO 44
       ELSEIF (TS .EQ. 24.0) THEN
       GO TO 55
       ELSEIF (TS .EQ. 30.0) THEN
       GO TO 66
       ELSEIF (TS .EQ. 36.0) THEN
       GO TO 77
       ENDIF

 33    CALL PROG1
C      PRINT THE RESULTS ON THE SCREEN
       CALL OUTPUT
C      PRINT THE RESULTS ONTO A PRINTER.
       CALL PAPER
       GO TO 999
 44    CALL PROG2
C      PRINT THE RESULTS ON THE SCREEN
       CALL OUTPUT
C      PRINT THE RESULTS ONTO A PRINTER
       CALL PAPER
       GO TO 999

 55    CALL PROG3
C      PRINT THE RESULTS ON THE SCREEN
       CALL OUTPUT
C      PRINT THE RESULTS ONTO A PRINTER
       CALL PAPER
       GO TO 999
 66    CALL PROG4
C      PRINT THE RESULTS ON THE SCREEN
       CALL OUTPUT
```

```
C       PRINT THE RESULTS ONTO A PRINTER.

        CALL PAPER

        GO TO 999

 77     CALL PROG5

C       PRINT THE RESULTS ON THE SCREEN.

        CALL OUTPUT

C       PRINT THE RESULTS ONTO A PRINTER.

        CALL PAPER

        CLOSE (3, STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END
C
C       ***************************************************************
C       TOWER SIZING FOR VALVE TRAYS USING A 12 INCH TRAY SPACING.
C       ***************************************************************

        SUBROUTINE PROG1

        REAL LCFS
        COMMON PI

        COMMON/MULT1/ X, SF, RD, V, VRD
        COMMON/MULT2/ AB, ADC, AT, DIA, RDCA
        COMMON/MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
        COMMON/MULT4/ LCFS, VCFS

        G = 0.77174
        H = -0.02964

C       CALCULATE THE TRAY SPACING FACTOR, TSF

        TSF = G+H*ALOG(X)

C       CALCULATE THE VAPOR VOLUMETRIC RATE, VCFS

        VCFS = WV/(DENV*3600.0)

C       CALCULATE THE LIQUID VOLUMETRIC RATE, LCFS

        LCFS = WL/(DENL*3600.0)

        IF (VRD .GT. 0.5) THEN
        VRD = 0.5
        ELSE
        ENDIF

C       CALCULATE THE BUBBLING AREA, AB

        AB = (VCFS*RD+LCFS)/(TSF*VRD*FF)
```

```
      ADC = (REST*LCFS*12.0)/(FF*TS)

C     CALCULATE THE TOWER AREA, AT

      AT = (2.0*ADC+AB)/SF

C     CALCULATE THE TOWER DIAMETER, DIA.

      DIA = SQRT((4.0*AT)/PI)

C
C     CALCULATE THE DOWNCOMER AREA RATIO, RDCA
C
      RDCA = ADC/(2.*ADC + AB)

      RETURN
      END

C     ***************************************************************
C     TOWER SIZING FOR VALVE TRAYS USING AN 18 INCH TRAY SPACING.
C     ***************************************************************

      SUBROUTINE PROG2

      REAL LCFS

      COMMON PI
      COMMON/MULT1/ X, SF, RD, V, VRD
      COMMON/MULT2/ AB, ADC, AT, DIA, RDCA
      COMMON/MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
      COMMON/MULT4/ LCFS, VCFS

      G = 0.93655
      H = -0.02310

C     CALCULATE THE TRAY SPACING FACTOR, TSF

      TSF = G+H*ALOG(X)

C     CALCULATE THE VAPOR VOLUMETRIC RATE, VCFS

      VCFS = WV/(DENV*3600.0)

C     CALCULATE THE LIQUID VOLUMETRIC RATE, LCFS

      LCFS = WL/(DENL*3600.0)

      IF ( VRD .GT. 0.5) THEN
      VRD = 0.5
      ELSE
      ENDIF

C     CALCULATE THE BUBBLING AREA, AB.

      AB = (VCFS*RD+LCFS)/(TSF*VRD*FF)

C     CALCULATE THE DOWNCOMER AREA, ADC

      ADC = (REST*LCFS*12.0)/(FF*TS)
```

```
      ADC = (REST*LCFS*12.0)/(FF*TS)

C     CALCULATE THE TOWER AREA, AT.

      AT = (2.0*ADC+AB)/SF

C     CALCULATE THE TOWER DIAMETER, DIA.

      DIA = SQRT((4.0*AT)/PI)

C     CALCULATE THE DOWNCOMER AREA RATIO, RDCA

      RDCA = ADC/(2.0*ADC+AB)

      RETURN
      END

C     ****************************************************************
C     TOWER SIZING FOR VALVE TRAYS USING A 24 INCH TRAY SPACING.
C     ****************************************************************

      SUBROUTINE PROG3

      REAL LCFS

      COMMON PI
      COMMON/MULT1/ X, SF, RD, V, VRD
      COMMON/MULT2/ AB, ADC, AT, DIA, RDCA
      COMMON/MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
      COMMON/MULT4/ LCFS, VCFS

C     CALCULATE THE TRAY SPACING FACTOR, TSF
C     FOR ALL VALUES OF X, TSF=1.0

      TSF = 1.0


C     CALCULATE THE VAPOR VOLUMETRIC RATE, VCFS

      VCFS = WV/(DENV*3600.0)

C     CALCULATE THE LIQUID VOLUMETRIC RATE, LCFS

      LCFS = WL/(DENL*3600.0)

      IF ( VRD .GT. 0.5) THEN
      VRD = 0.5
      ELSE
      ENDIF

C     CALCULATE THE BUBBLING AREA, AB

      AB = (VCFS*RD+LCFS)/(TSF*VRD*FF)

C     CALCULATE THE DOWNCOMER AREA, ADC

      ADC = (REST*LCFS*12.0)/(FF*TS)

C     CALCULATE THE TOWER AREA, AT.
```

```
      AT = (2.0*ADC+AB)/SF

C     CALCULATE THE TOWER DIAMETER, DIA.

      DIA = SQRT((4.0*AT)/PI)

C     CALCULATE THE DOWNCOMER AREA RATIO, RDCA

      RDCA = ADC/((2.0*ADC)+AB)

      RETURN
      END
C
C     ***************************************************************
C     TOWER SIZING FOR VALVE TRAYS USING A 30 INCH TRAY SPACING.
C     ***************************************************************

      SUBROUTINE PROG4

      REAL LCFS
      COMMON PI

      COMMON/MULT1/ X, SF, RD, V, VRD
      COMMON/MULT2/ AB, ADC, AT, DIA, RDCA
      COMMON/MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
      COMMON/MULT4/ LCFS, VCFS

      G = 0.98067
      H = 0.03220

C     CALCULATE THE TRAY SPACING FACTOR, TSF

      TSF = G + H*ALOG(X)

      IF ( X .LT. 1.85 ) THEN
      TSF = 1.0
      ELSE
      ENDIF

C     CALCULATE THE VAPOR VOLUMETRIC RATE, VCFS

      VCFS = WV/(DENV*3600.0)

C     CALCULATE THE LIQUID VOLUMETRIC RATE, LCFS

      LCFS = WL/(DENL*3600.0)

      IF ( VRD .GT. 0.5) THEN
      VRD = 0.5
      ELSE
      ENDIF

C     CALCULATE THE BUBBLING AREA, AB

      AB = (VCFS*RD+LCFS)/(TSF*VRD*FF)

C     CALCULATE THE DOWNCOMER AREA, ADC.

      ADC =(REST*LCFS*12.0)/(FF*TS)
```

```
C       CALCULATE THE TOWER AREA, AT

        AT = (2.0*ADC+ AB)/SF

C       CALCULATE THE TOWER DIAMETER, DIA.

        DIA = SQRT((4.0*AT)/PI)

C       CALCULATE THE DOWNCOMER AREA RATIO, RDCA

        RDCA = ADC/((2.0*ADC)+AB)

        RETURN
        END

C       ****************************************************************
C       TOWER SIZING FOR VALVE TRAYS USING A 36 INCH TRAY SPACING.
C       ****************************************************************

        SUBROUTINE PROG5

        REAL LCFS
        COMMON PI

        COMMON/MULT1/ X, SF, RD, V, VRD
        COMMON/MULT2/ AB, ADC, AT, DIA, RDCA
        COMMON/MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
        COMMON/MULT4/ LCFS, VCFS

        G = 0.96583
        H = 0.06162

C       CALCULATE THE TRAY SPACING FACTOR, TSF.

        TSF = G+H*ALOG(X)

        IF (X .LT. 1.85) THEN
        TSF = 1.0
        ELSE
        ENDIF

C       CALCULATE THE VAPOR VOLUMETRIC RATE, VCFS

        VCFS = WV/(DENV*3600.0)

C       CALCULATE THE LIQUID VOLUMETRIC RATE, LCFS.

        LCFS = WL/(DENL*3600.0)

        IF (VRD .GT. 0.5) THEN
        VRD = 0.5
        ELSE
        ENDIF

C       CALCULATE THE BUBBLING AREA, AB.

        AB = (VCFS*RD+LCFS)/(TSF*VRD*FF)

C       CALCULATE THE DOWNCOMER AREA, ADC
```

```
          ADC = (REST*LCFS*12.0)/(FF*TS)

C         CALCULATE THE TOWER AREA, AT.

          AT = (2.0*ADC+AB)/SF

C         CALCULATE THE TOWER DIAMETER, DIA.

          DIA = SQRT((4.0*AT)/PI)

C         CALCULATE THE DOWNCOMER AREA RATIO, RDCA

          RDCA = ADC/((2.0*ADC)+AB)

          RETURN
          END

C         ***************************************************************
C         THIS PROGRAM PRINTS THE RESULTS ONTO THE SCREEN

          SUBROUTINE OUTPUT

          REAL LCFS
          COMMON/MULT1/ X, SF, RD, V, VRD
          COMMON/MULT2/ AB, ADC, AT, DIA, RDCA
          COMMON/MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
          COMMON/MULT4/ LCFS, VCFS

          WRITE (*, 100)
 100      FORMAT (//, 25X, 'TOWER DESIGN FOR VALVE TRAYS',/,78(1H*))

          WRITE (*, 110) WV, VCFS, WL, LCFS, DENL
 110      FORMAT (5X,'VAPOR FLOW RATE, lb/hr.:', T60, F10.1,/,
     *            5X,'VAPOR VOLUMETRIC RATE, ft^3/sec.:', T60, F10.3,/,
     *            5X,'LIQUID FLOW RATE, lb/hr.:', T60, F10.1,/,
     *            5X,'LIQUID VOLUMETRIC RATE, ft^3/sec.:', T60, F10.3,/,
     *            5X,'LIQUID DENSITY, lb/ft^3.:', T60, F10.3)

          WRITE (*, 120) DENV, FF, REST
 120      FORMAT (5X,'VAPOR DENSITY, lb/ft^3.:', T60, F10.3,/,
     *            5X,'FOAM FACTOR:', T60, F10.3,/,
     *            5X,'DOWNCOMER RESIDENCE TIME, sec.:', T60, F10.3)

          WRITE (*, 130) TS, SURT
 130      FORMAT (5X,'TRAY SPACING, in.:', T60, F8.0,/,
     *            5X,'SURFACE TENSION, dyne/cm.:', T60, F8.2)

          WRITE (*, 140) X, SF, RD
 140      FORMAT (5X,'SURFACE TENSION/VAPOR DENSITY (X):', T60, F10.3,/,
     *            5X,'SAFETY FACTOR:', T60, F10.3,/,
     *            5X,'DENSITY RADICAL:', T60, F10.3)


          WRITE (*, 150) AB, ADC, AT
 150      FORMAT (5X,'BUBBLING AREA, ft^2:', T60, F10.3,/,
     *            5X,'DOWNCOMER AREA, ft^2:', T60, F10.3,/,
     *            5X,'TOWER AREA, ft^2:', T60, F10.3)

          WRITE (*, 160) DIA, RDCA
 160      FORMAT (5X,'TOWER DIAMETER, ft:', T60, F10.3,/,
```

```
     *          5X,'DOWNCOMER AREA RATIO:', T60, F10.4)

        WRITE (*, 170)
 170    FORMAT (78(1H-))

        RETURN
        END

C
C       ***************************************************************
C       THIS PROGRAM PRINTS THE RESULTS ON THE PRINTER.
C       ***************************************************************
C
        SUBROUTINE PAPER

        REAL LCFS
        COMMON /MULT1/ X, SF, RD, V, VRD
        COMMON/ MULT2/ AB, ADC, AT, DIA, RDCA
        COMMON/ MULT3/ WV, WL, DENL, DENV, FF, REST, TS, SURT
        COMMON/ MULT4/ LCFS, VCFS

        WRITE (1, 180)
 180    FORMAT (///, 25X, 'TOWER DESIGN FOR VALVE TRAYS',/,78(1H*))

        WRITE (1, 190) WV, VCFS, WL, LCFS, DENL
 190    FORMAT (5X,'VAPOR FLOW RATE, lb/hr.:', T60, F10.1,/,
     *          5X,'VAPOR VOLUMETRIC RATE, ft^3/sec.:', T60, F10.3,/,
     *          5X,'LIQUID FLOW RATE, lb/hr.:', T60, F10.1,/,
     *          5X,'LIQUID VOLUMETRIC RATE, ft^3/sec.:',T60,F10.3,/,
     *          5X,'LIQUID DENSITY, lb/ft^3.:', T60, F10.3)

        WRITE (1, 200) DENV, FF, REST
 200    FORMAT (5X,'VAPOR DENSITY, lb/ft^3.:', T60, F10.3,/,
     *          5X,'FOAM FACTOR:', T60, F10.3,/,
     *          5X,'DOWNCOMER RESIDENCE TIME, sec.:', T60, F10.3)

        WRITE (1, 210) TS, SURT
 210    FORMAT (5X,'TRAY SPACING, in.:', T60, F8.0,/,
     *          5X,'SURFACE TENSION, dyne/cm.:', T60, F8.2)

        WRITE (1, 220) X, SF, RD
 220    FORMAT (5X,'SURFACE TENSION/VAPOR DENSITY (X):', T60, F10.3,/,
     *          5X,'SAFETY FACTOR:', T60, F10.3,/,
     *          5X,'DENSITY RADICAL:', T60, F10.3)

        WRITE (1, 230) AB, ADC, AT
 230    FORMAT (5X,'BUBBLING AREA, ft^2:', T60, F10.3,/,
     *          5X,'DOWNCOMER AREA, ft^2:', T60, F10.3,/,
     *          5X,'TOWER AREA, ft^2:', T60, F10.3)

        WRITE (1, 240) DIA, RDCA
 240    FORMAT (5X,'TOWER DIAMETER, ft:', T60, F10.3,/,
     *          5X,'DOWNCOMER AREA RATIO:', T60, F10.4)

        WRITE (1, 250)
 250    FORMAT (78(1H-))

C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
        PROGRAM PROG74

C       PACKED-TOWER SIZING
C       THE TOWER SIZING METHOD IS BASED ON THE GENERALIZED PRESSURE
C       DROP CORRELATION OF SHERWOOD, SHIPLEY AND HOLLOWAY AND
C       REPLOTTED IN FIGURE GR-109 R-5 BY NORTON CO.  THIS CORRELATION
C       IS A PLOT OF X .VS. Y FOR PRESSURE DROP CURVES RANGING FROM
C       0.5 TO 1.5 INCH OF WATER.  FROM THESE CURVES THE TOWER DIAMETER
C       CAN BE EVALUATED.
C       ***************************************************************
C
C       L       =   LIQUID RATE, lb/h
C       G       =   VAPOR RATE, lb/h
C       DG      =   VAPOR DENSITY, lb/ft^3
C       DL      =   LIQUID DENSITY, lb/ft^3
C       X       =   X CO-ORDINATE IN GR-109 R-5 PLOT
C       Y       =   Y CO-ORDINATE IN GR-109 R-5 PLOT
C       G1      =   VAPOR RATE, lb/s.ft^2
C       PF      =   PACKING FACTOR FOR PACKING USED
C       LVIS    =   LIQUID VISCOSITY, cP
C       GC      =   GRAVITATIONAL CONSTANT = 32.2 ft/s^2
C       AREA    =   TOWER AREA, ft^2
C       DIA     =   TOWER DIAMTER, ft
C       DELP    =   PRESSURE DROP inch H2O/ft.
C       PI      =   CONSTANT = 3.1415927
C       ***************************************************************


        COMMON/TOWER1/ GC, PI
        COMMON/TOWER2/ X, Y, X1, Y1
        COMMON/TOWER3/ AREA, DIA
        COMMON/TOWER4/ G1, G2, VG
        COMMON/TOWER5/ AREAF, DIAF
        REAL L, LVIS

        OPEN (UNIT = 3, FILE='DATA74.DAT', STATUS='OLD', ERR=18)
        OPEN (UNIT = 1, FILE='PRN')



C       READ LIQUID FLOW RATE, lb/hr.           =   L
C       READ GAS FLOW RATE, lb/hr.              =   G
C       READ GAS DENSITY, lb/ft^3.              =   DG
C       READ LIQUID DENSITY, lb/ft^3.           =   DL
C       READ TOWER PACKING FACTOR               =   PF
C       READ PRESSURE DROP, inch-H2O/ft.        =   DELP
C       READ LIQUID VISCOSITY, cP.              =   LVIS

        READ (3, *, ERR =19) L, G, DG
        READ (3, *, ERR =19) DL, PF, DELP, LVIS

        GO TO 10

 18     WRITE (*, 100)
 100    FORMAT (5X, 'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 110)
```

```
 110    FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999


 10     PI = 3.1415927
        GC = 32.2

C       WHERE 0.01 < X < 2.0
        SUM1=DG/(DL-DG)
        X = L/G*SQRT(SUM1)


        IF (DELP .EQ. 0.05) THEN
        GO TO 30

        ELSEIF(DELP .EQ. 0.10) THEN
        GO TO 35

        ELSEIF(DELP .EQ. 0.25) THEN
        GO TO 40

        ELSEIF(DELP .EQ. 0.50) THEN
        GO TO 45

        ELSEIF(DELP .EQ. 1.0) THEN
        GO TO 50

        ELSEIF(DELP .EQ. 1.5) THEN
        GO TO 55

        ENDIF

   30   CALL PROG1 (L, G, DG, DL, PF, LVIS)

C       PRINT THE RESULTS ON THE SCREEN

        CALL OUTPUT (L, G, DG, DL, PF, DELP, LVIS)

C       PRINT THE RESULTS ONTO A PRINTER

        CALL PAPER (L, G, DG, DL, PF, DELP, LVIS)

        GO TO 999

   35   CALL PROG2 (L, G, DG, DL, PF, LVIS)

C       PRINT THE RESULTS ON THE SCREEN

        CALL OUTPUT (L, G, DG, DL, PF, DELP, LVIS)

C       PRINT THE RESULTS ONTO A PRINTER

        CALL PAPER (L, G, DG, DL, PF, DELP, LVIS)
        GO TO 999

   40   CALL PROG3 (L, G, DG, DL, PF, LVIS)

C       PRINT THE RESULTS ON THE SCREEN
```

```
      CALL OUTPUT (L, G, DG, DL, PF, DELP, LVIS)
C     PRINT THE RESULTS ONTO A PRINTER
      CALL PAPER (L, G, DG, DL, PF, DELP, LVIS)
      GO TO 999
   45 CALL PROG4 (L, G, DG, DL, PF, LVIS)
C     PRINT THE RESULTS ON THE SCREEN
      CALL OUTPUT (L, G, DG, DL, PF, DELP, LVIS)
C     PRINT THE RESULTS ONTO A PRINTER
      CALL PAPER (L, G, DG, DL, PF, DELP, LVIS)
      GO TO 999
   50 CALL PROG5 (L, G, DG, DL, PF, LVIS)

C     PRINT THE RESULTS ON THE SCREEN
      CALL OUTPUT (L, G, DG, DL, PF, DELP, LVIS)
C     PRINT THE RESULTS ONTO A PRINTER
      CALL PAPER (L, G, DG, DL, PF, DELP, LVIS)
      GO TO 999
   55 CALL PROG6 (L, G, DG, DL, PF, LVIS)
C     PRINT THE RESULTS ON THE SCREEN
      CALL OUTPUT (L, G, DG, DL, PF, DELP, LVIS)
C     PRINT THE RESULTS ONTO A PRINTER
      CALL PAPER (L, G, DG, DL, PF, DELP, LVIS)
      GO TO 999

      CLOSE (UNIT = 3, STATUS='KEEP')
      CLOSE (UNIT = 1)
  999 STOP
      END
C
C
C     ***************************************************************
C     PACKED-TOWER SIZING WITH A PRESSURE DROP OF 0.05 inch H2O/ft
C     ***************************************************************

      SUBROUTINE PROG1 (L, G, DG, DL, PF, LVIS)
      REAL L,LVIS

      COMMON/TOWER1/ GC, PI
      COMMON/TOWER2/ X, Y, X1, Y1
      COMMON/TOWER3/ AREA, DIA
      COMMON/TOWER4/ G1, G2, VG
```

```
        COMMON/TOWER5/ AREAF, DIAF

C       CONSTANTS FOR DELP=0.05

        C0 = -6.30253
        C1 = -0.60809
        C2 = -0.11932
        C3 = -0.00685
        C4 = 0.000320

C       WHERE 0.001  < Y < 0.15

        SUM1 = ALOG(X)
        SUM2 = (ALOG(X))**2
        SUM3 = (ALOG(X))**3
        SUM4 = (ALOG(X))**4
        SUMT = C0+(C1*SUM1)+(C2*SUM2)+(C3*SUM3)+(C4*SUM4)

        Y1 = EXP(SUMT)

C       CALCULATE VAPOR RATE lb/s.ft^2

        VAL1 = Y1*DG*(DL-DG)*GC
        VAL2 = PF*(LVIS)**0.1
        RATIO = VAL1/VAL2
        G1 = (RATIO)**0.5

C       CALCULATE TOWER AREA AND TOWER DIAMETER

        AREA = G/(3600.*G1)
        DIA = 12.0*((4.0*AREA)/PI)**0.5

C       CALCULATE Y  CO-ORDINATE IN GR-109 R-5 PLOT

        VAL3 = (G1**2)*PF*(LVIS)**0.1
        VAL4 = DG*(DL-DG)*GC
        Y = VAL3/VAL4

C       CALCULATE THE PACKED TOWER FLOODING CONDITIONS

        CALL FLOOD (L, G, DG, DL, PF, LVIS)

        RETURN
        END

C       ****************************************************************
C       PACKED-TOWER SIZING WITH A PRESSURE DROP OF 0.10 inch H2O/ft
C       ****************************************************************

        SUBROUTINE PROG2 (L, G, DG, DL, PF, LVIS)

        REAL L,LVIS
        COMMON/TOWER1/ GC, PI
        COMMON/TOWER2/ X, Y, X1, Y1
        COMMON/TOWER3/ AREA, DIA
        COMMON/TOWER4/ G1, G2, VG
        COMMON/TOWER5/ AREAF, DIAF

C       CONSTANTS FOR DELP=0.1
```

```
      C0 = -5.50093
      C1 = -0.78508
      C2 = -0.13496
      C3 =  0.00134
      C4 =  0.00174

C     WHERE 0.001 < Y < 0.15

      SUM1 = ALOG(X)
      SUM2 = (ALOG(X))**2
      SUM3 = (ALOG(X))**3
      SUM4 = (ALOG(X))**4
      SUMT = C0+(C1*SUM1)+(C2*SUM2)+(C3*SUM3)+(C4*SUM4)
      Y1 = EXP(SUMT)

C     CALCULATE VAPOR RATE, lb/s.ft^2

      VAL1 = Y1*DG*(DL-DG)*GC
      VAL2 = PF*(LVIS)**0.1
      RATIO = VAL1/VAL2
      G1 = (RATIO)**0.5

C     CALCULATE TOWER AREA AND TOWER DIAMETER

      AREA = G/(3600.*G1)
      DIA = 12.0*((4.0*AREA)/PI)**0.5

C     CALCULATE Y  CO-ORDINATE IN GR-109 R-5 PLOT

      VAL3 = (G1**2)*PF*(LVIS)**0.1
      VAL4 = DG*(DL-DG)*GC
      Y = VAL3/VAL4


C     CALCULATE THE PACKED TOWER FLOODING CONDITIONS.

      CALL FLOOD (L, G, DG, DL, PF, LVIS)

      RETURN
      END

C     ***************************************************************
C     PACKED-TOWER SIZING WITH A PRESSURE DROP OF 0.25 inch H2O/ft
C     ***************************************************************

      SUBROUTINE PROG3 (L, G, DG, DL, PF, LVIS)

      REAL L, LVIS
      COMMON/TOWER1/ GC, PI
      COMMON/TOWER2/ X, Y, X1, Y1
      COMMON/TOWER3/ AREA, DIA
      COMMON/TOWER4/ G1, G2, VG
      COMMON/TOWER5/ AREAF, DIAF

C     CONSTANTS FOR DELP=0.25

      C0 = -5.00319
      C1 = -0.95299
      C2 = -0.13930
      C3 =  0.01264
```

```
      C4 =  0.00334

C     WHERE 0.001 < Y < 0.15

      SUM1 = ALOG(X)
      SUM2 = (ALOG(X))**2
      SUM3 = (ALOG(X))**3
      SUM4 = (ALOG(X))**4
      SUMT = C0+(C1*SUM1)+(C2*SUM2)+(C3*SUM3)+(C4*SUM4)
      Y1 = EXP(SUMT)

C     CALCULATE VAPOR RATE, lb/s.ft^2

      VAL1 = Y1*DG*(DL-DG)*GC
      VAL2 = PF*(LVIS)**0.1
      RATIO = VAL1/VAL2
      G1 = SQRT(RATIO)

C     CALCULATE TOWER AREA AND TOWER DIAMETER

      AREA = G/(3600.0*G1)
      DIA = 12.0*SQRT((4.0*AREA)/PI)

C     CALCULATE Y  CO-ORDINATE IN GR-109 R-5 PLOT

      VAL3 = (G1**2)*PF*(LVIS)**0.1
      VAL4 = DG*(DL-DG)*GC
      Y = VAL3/VAL4

C     CALCULATE THE PACKED TOWER FLOODING CONDITONS.

      CALL FLOOD (L, G, DG, DL, PF, LVIS)
      RETURN
      END

C     ****************************************************************
C     PACKED TOWER SIZING WITH A PRESSURE DROP OF 0.5 inch H2O/ft
C     ****************************************************************

      SUBROUTINE PROG4 (L, G, DG, DL, PF, LVIS)

      REAL L,LVIS
      COMMON/TOWER1/ GC, PI
      COMMON/TOWER2/ X, Y, X1, Y1
      COMMON/TOWER3/ AREA, DIA
      COMMON/TOWER4/ G1, G2, VG
      COMMON/TOWER5/ AREAF, DIAF

C     CONSTANTS FOR DELP=0.5

      C0 = -4.39918
      C1 = -0.99404
      C2 = -0.16983
      C3 =  0.00873
      C4 =  0.00343

C     WHERE 0.001 < Y < 0.15

      SUM1 = ALOG(X)
      SUM2 = (ALOG(X))**2
```

```
        SUM3 = (ALOG(X))**3
        SUM4 = (ALOG(X))**4
        SUMT = C0+(C1*SUM1)+(C2*SUM2)+(C3*SUM3)+(C4*SUM4)
        Y1 = EXP(SUMT)

C       CALCULATE VAPOR RATE, lb/s.ft^2

        VAL1 = Y1*DG*(DL-DG)*GC
        VAL2 = PF*(LVIS)**0.1
        RATIO = VAL1/VAL2
        G1 = (RATIO)**0.5

C       CALCULATE TOWER AREA AND TOWER DIAMETER

        AREA = G/(3600.*G1)
        DIA = 12.0*((4.0*AREA)/PI)**0.5

C       CALCULATE Y  CO-ORDINATE IN GR-109 R-5 PLOT

        VAL3 = (G1**2)*PF*(LVIS)**0.1
        VAL4 = DG*(DL-DG)*GC
        Y = VAL3/VAL4

C       CALCULATE THE PACKED TOWER FLOODING CONDITIONS.

        CALL FLOOD (L, G, DG, DL, PF, LVIS)
        RETURN
        END

C       ***************************************************************
C       PACKED-TOWER SIZING WITH A PRESSURE DROP OF 1 inch H2O/ft.
C       ***************************************************************

        SUBROUTINE PROG5 (L, G, DG, DL, PF, LVIS)

        REAL L,LVIS

        COMMON/TOWER1/ GC, PI
        COMMON/TOWER2/ X, Y, X1, Y1
        COMMON/TOWER3/ AREA, DIA
        COMMON/TOWER4/ G1, G2, VG
        COMMON/TOWER5/ AREAF, DIAF

C       CONSTANTS FOR DELP=1.0

        C0 = -4.09505
        C1 = -1.00120
        C2 = -0.15871
        C3 =  0.00797
        C4 =  0.00318

C       WHERE 0.001 < Y < 0.15

        SUM1 = ALOG(X)
        SUM2 = (ALOG(X))**2
        SUM3 = (ALOG(X))**3
        SUM4 = (ALOG(X))**4
        SUMT = C0+(C1*SUM1)+(C2*SUM2)+(C3*SUM3)+(C4*SUM4)
        Y1 = EXP(SUMT)
```

```
C       CALCULATE VAPOR RATE, lb/s.ft^2

        VAL1 = Y1*DG*(DL-DG)*GC
        VAL2 = PF*(LVIS)**0.1
        RATIO = VAL1/VAL2
        G1 = (RATIO)**0.5

C       CALCULATE TOWER AREA AND TOWER DIAMETER

        AREA = G/(3600.*G1)
        DIA = 12.0*((4.0*AREA)/PI)**0.5

C       CALCULATE Y  CO-ORDINATE IN GR-109 R-5 PLOT

        VAL3 = (G1**2)*PF*(LVIS)**0.1
        VAL4 = DG*(DL-DG)*GC
        Y = VAL3/VAL4

C       CALCULATE THE PACKED TOWER FLOODING CONDITIONS.


        CALL FLOOD (L, G, DG, DL, PF, LVIS)
        RETURN
        END

C       ****************************************************************
C       PACKED-TOWER SIZING WITH A PRESSURE DROP OF 1.5 inch H2O/ft.
C       ****************************************************************

        SUBROUTINE PROG6 (L, G, DG, DL, PF, LVIS)

        REAL L, LVIS
        COMMON/TOWER1/ GC, PI
        COMMON/TOWER2/ X, Y, X1, Y1
        COMMON/TOWER3/ AREA, DIA
        COMMON/TOWER4/ G1, G2, VG
        COMMON/TOWER5/ AREAF, DIAF

C       CONSTANTS FOR DELP=1.5

        C0 = -4.02555
        C1 = -0.98945
        C2 = -0.08291
        C3 = -0.03237
        C4 =  0.00532

C       WHERE 0.001 < Y < 0.15

        SUM1 = ALOG(X)
        SUM2 = (ALOG(X))**2
        SUM3 = (ALOG(X))**3
        SUM4 = (ALOG(X))**4
        SUMT = C0+(C1*SUM1)+(C2*SUM2)+(C3*SUM3)+(C4*SUM4)
        Y1 = EXP(SUMT)

C       CALCULATE VAPOR RATE lb/s.ft^2

        VAL1 = Y1*DG*(DL-DG)*GC
        VAL2 = PF*(LVIS)**0.1
        RATIO = VAL1/VAL2
```

```
        G1 = (RATIO)**0.5

C       CALCULATE TOWER AREA AND TOWER DIAMETER

        AREA = G/(3600.*G1)
        DIA = 12.0*((4.0*AREA)/PI)**0.5

C       CALCULATE Y CO-ORDINATE IN GR-109 R-5 PLOT

        VAL3 = (G1**2)*PF*(LVIS)**0.1
        VAL4 = DG*(DL-DG)*GC
        Y = VAL3/VAL4

C       CALCULATE THE PACKED TOWER FLOODING CONDITIONS.

        CALL FLOOD (L, G, DG, DL, PF, LVIS)
        RETURN
        END

C       ***************************************************************
C       THIS PROGRAM CALCULATES THE VAPOR RATE AT FLOODING CONDITION
C       ***************************************************************

        SUBROUTINE FLOOD (L, G, DG, DL, PF, LVIS)

        REAL L,LVIS
        COMMON/TOWER1/ GC, PI
        COMMON/TOWER2/ X, Y, X1, Y1
        COMMON/TOWER3/ AREA, DIA
        COMMON/TOWER4/ G1, G2, VG
        COMMON/TOWER5/ AREAF, DIAF
C
        X1 = (L/G)*SQRT(DG/DL)
        TI = 62.4/DL
        Y1=10.0**(-1.6678-(1.085*ALOG10(X1))-(0.29655*(ALOG10(X1))**2))
        VAL1 = Y1*DL*DG*GC
        VAL2 = PF*TI*(LVIS)**2
        RATIO = VAL1/VAL2
        G2 = SQRT(RATIO)

C       CALCULATE VAPOR RATE AT 70% OF FLOODING CONDITION

        G2 = 0.7*G2

C       CALCULATE VAPOR VELOCITY AT 70% FLOODING CONDITION

        VG=G2/DG

C       CALCULATE THE TOWER AREA AT 70% FLOODING CONDITION.

C       SINCE THE FLOODING CORRELATION IS NOT PERFECT, HENCE
C       TO HAVE A 95% CONFIDENCE, USE A SAFETY FACTOR OF 1.32
C       FOR THE CALCULATED CROSS-SECTIONAL AREA (Bolles and Fair,
C       Chem. Eng., 89 (14), 109 (July 12, 1982).

        AREAF = 1.32*(G/(3600.0*G2))

C       CALCULATE THE TOWER DIAMETER AT 70% FLOODING CONDITION

        DIAF = SQRT((4.0*AREAF)/PI)
```

```
C       DIAMETER IN inches:

        DIAF = 12.0*DIAF

        RETURN
        END

C       ******************************************************************
C       THIS PROGRAM OUTPUTS THE RESULTS ON THE SCREEN
C       ******************************************************************

        SUBROUTINE OUTPUT (L, G, DG, DL, PF, DELP, LVIS)

        REAL L,LVIS
        COMMON/TOWER2/ X, Y, X1, Y1
        COMMON/TOWER3/ AREA, DIA
        COMMON/TOWER4/ G1, G2, VG
        COMMON/TOWER5/ AREAF, DIAF

        WRITE (*, 120)
 120    FORMAT(20X,'PACKED TOWER DESIGN')

        WRITE (*, 130)
 130    FORMAT(78(1H*))

        WRITE (*, 140) L
 140    FORMAT(5X,'LIQUID FLOW RATE, lb/hr.:', T60, F12.3)

        WRITE (*, 150) G
 150    FORMAT(5X,'GAS FLOW RATE, lb/hr.:', T60, F12.3)

        WRITE (*, 160) DG
 160    FORMAT(5X,'GAS DENSITY, lb/ft^3:', T60, F8.4)

        WRITE (*, 170) DL
 170    FORMAT(5X,'LIQUID DENSITY, lb/ft^3:', T60, F8.4)

        WRITE (*, 180) PF
 180    FORMAT(5X,'TOWER PACKING FACTOR:', T60, F8.1)

        WRITE (*, 190) DELP
 190    FORMAT(5X,'PRESSURE DROP, inch H2O/ft:', T60, F8.3)

        WRITE (*, 200) LVIS
 200    FORMAT(5X,'LIQUID VISCOSITY, cP:', T60, F8.3)

        WRITE (*, 210) X
 210    FORMAT(5X,'X CO-ORDINATE IN THE GENERALIZED PLOT:', T60, F8.4)

        WRITE (*, 220) Y
 220    FORMAT(5X,'Y CO-ORDINATE IN THE GENERALIZED PLOT:', T60, F8.4)

        WRITE (*, 230) G1
 230    FORMAT(5X,'CALCULATED VAPOR RATE, lb/s.ft^2:', T60, F8.4)

        WRITE (*, 240) X1
 240    FORMAT(5X,'X CO-ORDINATE AT FLOODING CONDITION:', T60, F8.4)

        WRITE (*, 250) Y1
```

```
 250    FORMAT(5X,'Y CO-ORDINATE AT FLOODING CONDITION:', T60, F8.4)

        WRITE (*, 260) G2
 260    FORMAT(5X,'VAPOR RATE AT 70% FLOODING CONDITION, lb/s.ft^2:',\,
     *         T60, F8.4)

        WRITE (*, 270) VG
 270    FORMAT(5X,'VAPOR VELOCITY AT 70% FLOODING CONDITION, ft./s.:',\,
     *         T60, F8.2)

        WRITE (*, 280) AREA
 280    FORMAT(5X,'TOWER AREA, ft^2:' T60, F8.2)

        WRITE (*, 290) DIA
 290    FORMAT(5X,'TOWER DIAMETER, inches:', T60, F8.2)

        WRITE (*, 300) AREAF
 300    FORMAT(5X,'TOWER AREA AT 70% FLOODING CONDITION, ft^2:',T60,F8.2)

        WRITE (*, 310) DIAF
 310   FORMAT(5X,'TOWER DIAMETER AT 70% FLOODING CONDITION, inches:',\,
     *       T60, F8.2)

        WRITE (*, 320)
 320    FORMAT (78(1H-))
        RETURN
        END
C
C       ****************************************************************
C       THIS PROGRAM PRINTS THE RESULTS ONTO A PRINTER
C       ****************************************************************

        SUBROUTINE PAPER (L, G, DG, DL, PF, DELP, LVIS)

        REAL L, LVIS

        COMMON/TOWER2/ X, Y, X1, Y1
        COMMON/TOWER3/ AREA, DIA
        COMMON/TOWER4/ G1, G2, VG
        COMMON/TOWER5/ AREAF, DIAF

        WRITE (1, 330)
 330    FORMAT (///,25X,'PACKED TOWER DESIGN')

        WRITE (1, 340)
 340    FORMAT (78(1H*))

        WRITE (1, 350) L
 350    FORMAT (5X,'LIQUID FLOW RATE, lb/hr.:', T60, F12.3)

        WRITE (1, 360) G
 360    FORMAT (5X,'GAS FLOW RATE, lb/hr.:', T60, F12.3)

        WRITE (1, 370) DG
 370    FORMAT (5X,'GAS DENSITY, lb/ft.^3:', T60, F8.4)

        WRITE (1, 380) DL
 380    FORMAT (5X,'LIQUID DENSITY, lb/ft.^3:', T60, F8.4)

        WRITE (1, 390) PF
```

```
 390     FORMAT (5X,'TOWER PACKING FACTOR:', T60, F8.1)

         WRITE (1, 400) DELP
 400     FORMAT (5X,'PRESSURE DROP, INCH-H2O:', T60, F8.3)

         WRITE (1, 410) LVIS
 410     FORMAT (5X,'LIQUID VISCOSITY, cP:', T60, F8.3)

         WRITE (1, 420) X
 420     FORMAT (5X,'X CO-ORDINATE IN THE GENERALIZED PLOT:', T60, F8.4)

         WRITE (1, 430) Y
 430     FORMAT (5X,'Y CO-ORDINATE IN THE GENERALIZED PLOT:', T60, F8.4)

         WRITE (1, 440) G1
 440     FORMAT (5X,'CALCULATED VAPOR RATE, lb/s.ft^2:', T60, F8.4)

         WRITE (1, 450) X1
 450     FORMAT (5X,'X CO-ORDINATE AT FLOODING CONDITION:', T60, F8.4)

         WRITE (1, 460) Y1
 460     FORMAT (5X,'Y CO-ORDINATE AT FLOODING CONDITION:', T60, F8.4)

         WRITE (1, 470) G2
 470     FORMAT (5X,'VAPOR RATE AT 70% FLOODING CONDITION, lb/s.ft^2:',\,
     *           T60, F8.4)

         WRITE (1, 480) VG
 480     FORMAT (5X,'VAPOR VELOCITY AT 70% FLOODING CONDITION, ft./sec:',\,
     *           T60, F8.2)

         WRITE (1, 490) AREA
 490     FORMAT (5X,'TOWER AREA, ft^2:', T60, F8.2)

         WRITE (1, 500) DIA
 500     FORMAT (5X,'TOWER DIAMETER, inches:', T60, F8.2)

         WRITE (1, 510) AREAF
 510     FORMAT (5X,'TOWER AREA AT 70% FLOODING CONDITION, ft^2:',\,
     *           T60,F8.2)

         WRITE (1, 520) DIAF
 520  FORMAT (5X,'TOWER DIAMETER AT 70% FLOODING CONDITION, inches:',\,
     *        T60, F8.2)

         WRITE (1, 530)
 530     FORMAT (78(1H-))

C        FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

         WRITE (1, *) CHAR(12)
         RETURN
         END
```

```
        PROGRAM PROG75

C       NUMBER OF STAGES AT LOW CONCENTRATIONS.
C       THIS PROGRAM CALCULATES THE NUMBER OF EQUILIBRIUM STAGES
C       USING THE SMOKER EQUATIONS.
C       IN THE LOW-CONCENTRATION REGION THE EQUILIBRIUM RELATION FOLLOWS
C       HENRY'S LAW AND Y=KX, AND THIS RELATIONSHIP IS USED TO PLOT THE
C       EQUILIBRIUM LINE IF DATA ARE NOT AVAILABLE.  THE EQUATIONS
C       DEVELOPED BY SMOKER WILL HANDLE THESE OPERATIONS ANALYTICALLY.
C
C       ******************************************************************
C       A1      =   AVERAGE RELATIVE VOLATILITY OF THE RECTIFYING SECTION
C       A2      =   AVERAGE RELATIVE VOLATILITY OF THE STRIPPING SECTION
C       R       =   REFLUX RATIO
C       XF      =   MOLE FRACTION OF THE FEED
C       XD      =   MOLE FRACTION OF THE TOP PRODUCT
C       XB      =   MOLE FRACTION OF THE BOTTOMS PRODUCT
C       N1      =   NUMBER OF STAGES IN THE RECTIFYING SECTION
C       N2      =   NUMBER OF STAGES IN THE STRIPPING SECTION
C       TOTAL   =   THE TOTAL NUMBER OF STAGES.
C       POST    =   THE OPTIMUM FEED STAGE LOCATION.
C       *******************************************************************
C
C
        REAL K,K1,K2,N1,N2

        COMMON/MASS/K1,K2


        OPEN (UNIT=3, FILE='DATA75.DAT', STATUS='OLD', ERR=18)
        OPEN (UNIT=1, FILE='PRN')

C       READ THE RELATIVE VOLATILITIES OF THE TWO COMPONENTS A1, A2.
C       READ THE MOLE FRACTION OF THE FEED, XF.
C       READ THE MOLE FRACTION OF THE DISTILLATE, XD.
C       READ THE MOLE FRACTION OF THE BOTTOMS, XB.
C       READ THE REFLUX RATIO, R.


        READ (3, *, ERR=19) A1, A2
        READ (3, *, ERR=19) XF, XD, XB
        READ (3, *, ERR=19) R

        GO TO 5

 18     WRITE (*, 23)
 23     FORMAT (5X,'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 29)
 29     FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

 5      WRITE (1, 100)
 100  FORMAT(//,15X,49HEQUILIBRIUM NUMBER OF STAGES BY SMOKER'S EQUATION,
     *  /1H ,78(1H*))

        WRITE (1, 110) A1, A2
 110    FORMAT(5X,'THE RELATIVE VOLATILITY OF COMPONENT 1.:', T60,
     *           F10.3,/,5X,'THE RELATIVE VOLATILITY OF COMPONENT 2.:',
```

```
     *           T60,F10.3)

        WRITE (1, 120) XF, XD, XB, R
 120    FORMAT(5X,'THE MOLE FRACTION OF THE FEED:', T60, F10.4,/,
     *         5X,'THE MOLE FRACTION OF THE DISTILLATE:', T60, F10.4,/,
     *         5X,'THE MOLE FRACTION OF THE BOTTOMS:', T60, F10.4,/,
     *         5X,'THE REFLUX RATIO:', T60, F10.2)

        GO TO 10

C       CALCULATE THE NUMBER OF STAGES IN THE RECTIFYING SECTION

 10     S1=R/(R+1.0)
        B1=XD/(R+1.0)


C       CALCULATE  K, THE VALUE OF THE X-ORDINATE AT THE POINT WHERE
C       THE EXTENDED OPERATING LINE INTERSECT THE VAPOUR-LIQUID
C       EQUILIBRIUM CURVE FROM THE QUADRATIC EQUATION AX^2+BX+C=0

C       CALCULATE THE CO-EFFICIENTS OF THE QUADRATIC EQUATION IN
C       THE RECTIFYING SECTION

        A = S1*(A1-1.0)
        B = S1+B1*(A1-1.0)-A1
        C = B1

C       SOLVE THE QUADRATIC EQUATION

        CALL PROG1 (A, B, C, K)

C       CALCULATE THE NUMBER OF STAGES IN THE RECTIFYING SECTION, N1


        C1 = 1.0+(A1-1.0)*K
        X1 = XD-K
        X2 = XF-K
        BETA1 = (S1*C1*(A1-1.0))/(A1-(S1*(C1**2)))
        VAL1 = (X1*(1.0-(BETA1*X2)))/(X2*(1.0-(BETA1*X1)))
        VAL2 = A1/(S1*(C1**2))

C       CALCULATE THE NUMBER OF STAGES IN THE RECTIFYING SECTION.

        N1=ALOG(VAL1)/ALOG(VAL2)

        WRITE (1, 130) N1
 130    FORMAT(5X,'THE NUMBER OF STAGES IN THE RECTIFYING SECTION:',
     *         T60, F8.2)


C       CALCULATE THE NUMBER OF STAGES IN THE STRIPPING SECTION, N2


        S2 = ((R*XF)+XD-(R+1.0)*XB)/((R+1.0)*(XF-XB))
        B2 = ((XF-XD)*XB)/((R+1.0)*(XF-XB))

C       CALCULATE THE CO-EFFICIENTS OF THE QUADRATIC EQUATION AX^2+BX+C=0
C       IN THE STRIPPING SECTION
```

```
        A = S2*(A2-1.0)
        B = (S2+B2*(A2-1.0)-A2)
        C = B2

C       CALCULATE THE NUMBER OF STAGES IN THE RECTIFYING SECTION.

        CALL PROG1 (A, B, C, K)

        X3 = XF-K
        X4 = XB-K
        C2 = 1.0+(A2-1.0)*K
        BETA2 = (S2*C2*(A2-1.0))/(A2-(S2*(C2**2)))
        VAL3 = (X3*(1.0-(BETA2*X4)))/(X4*(1.0-(BETA2*X3)))
        VAL4 = A2/(S2*(C2**2))

        N2 = ALOG(VAL3)/ALOG(VAL4)

        WRITE (1, 140) N2
 140    FORMAT(5X,'THE NUMBER OF STAGES IN THE STRIPPING SECTION:',
     *       T60, F8.2)

        TOTAL = N1+N2

        WRITE (1, 150) TOTAL
 150    FORMAT(5X,'TOTAL NUMBER OF STAGES:', T60, F8.2)


C       THE FEED LOCATION IS THAT FROM THE STRIPPING SECTION TO
C       THE BOTTOM OF THE COLUMN.

        POST = N2

        WRITE (1, 160) POST
 160    FORMAT (5X,'FEED STAGE LOCATION:', T60, F8.1)

        WRITE (1, 170)
 170    FORMAT (78(1H-))

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE (3,STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END
C
C       ****************************************************************
C       THIS PROGRAM SOLVES THE QUADRATIC EQUATION AX^2+BX+C=0 IN THE
C       RECTIFYING AND STRIPPING SECTIONS
C       ****************************************************************

        SUBROUTINE PROG1 (A, B, C, K)

        REAL K,K1,K2
        COMMON/MASS/K1,K2

        D = (B**2-4.0*A*C)
```

```
      IF ( D .LT. 0.0) THEN
      GO TO 10
      ELSE
      K1= (-B+SQRT(D))/(2.0*A)
      K2= (-B-SQRT(D))/(2.0*A)
      ENDIF

      IF (K1 .LT. 0.0 .OR. K1 .GT. 1.0) THEN
      GO TO 20
      ELSE
      K = K1
      GO TO 30
      ENDIF

20    IF (K2 .LT. 0.0 .OR. K2 .GT. 1.0) THEN
      GO TO 40
      ELSE
      K=K2
      GO TO 30
      ENDIF

40    WRITE (*, 190)
190   FORMAT(6X,'ROOTS ARE OUT OF LIMITS CHECK PROBLEM SPECIFICATION')
      GO TO 30
10    WRITE (*, 200)
200   FORMAT(6X,'IMAGINARY ROOTS, CHECK PROBLEM SPECIFICATION')
30    RETURN
      END
```

```
        PROGRAM PROG76
C       RAPID ESTIMATES OF MULTICOMPONENT DISTILLATION AND
C       MINIMUM TRAYS IN DISTILLATION COLUMNS
C       THIS PROGRAM WILL CALCULATE THE FEED COMPONENT RECOVERY
C       IN BOTH THE COLUMN DISTILLATE AND BOTTOMS PRODUCTS AND
C       ESTIMATE THE MINIMUM NUMBER OF STAGES NEEDED TO PERFORM
C       THE GIVEN SEPARATION.
C       FEED STREAMS CONTAINING UP TO 12 COMPONENTS CAN BE HANDLED
C       BY THIS PROGRAM.
C
C       THE FOLLOWING ASSUMPTIONS FOR THIS PROGRAM ARE:
C
C       1.  THERE IS ONLY ONE FEED STREAM WITH 12 OR FEWER COMPONENTS.
C       2.  THERE IS ONLY ONE HEAVY KEY COMPONENT.
C       3.  FEED COMPONENTS ARE ARRANGED IN ORDER OF DECREASING
C           RELATIVE VOLATILITY, WITH THE LIGHT KEY (LK) AND HEAVY KEY
C           (HK) COMPONENTS SHOWN ADJACENT TO EACH OTHER.
C       4.  THE FEED ENTERS THE COLUMN AT THE OPTIMAL STAGE.
C       5.  THE COLUMN PRODUCES TWO PRODUCTS (DISTILLATE AND BOTTOMS)
C           WITH OVERHEAD CONDENSER AND BOTTOM REBOILER.
C       *****************************************************************
C       ALPHAi   =  RELATIVE VOLATILITY OF COMPONENT i
C       Ki       =  EQUILIBRIUM CONSTANT FOR COMPONENT i IN THE FEED STREAM
C       KHK      =  EQUILIBRIUM CONSTANT FOR HEAVY KEY COMPONENT
C                   IN THE FEED STREAM
C       Di       =  COMPONENT i IN DISTILLATE, MOL
C       Bi       =  COMPONENT i IN BOTTOMS, MOL
C       BHK      =  HEAVY KEY COMPONENT IN BOTTOMS, MOL
C       FHK      =  HEAVY KEY COMPONENT IN THE FEED, MOL
C       DLK      =  LIGHT KEY COMPONENT IN DISTILLATE, MOL
C       FLK      =  LIGHT KEY COMPONENT IN THE FEED, MOL
C       ALPHA(LK)=  RELATIVE VOLATILITY OF LIGHT KEY COMPONENT
C       Fi       =  COMPONENT i IN THE FEED
C       NUM1     =  MINIMUM TRAYS AT TOTAL REFLUX
C       DHK      =  HEAVY KEY COMPONENT IN DISTILLATE, MOL
C       BLK      =  LIGHT KEY COMPONENT IN BOTTOMS, MOL
C       A,B      =  CORRELATION CONSTANTS
C       Q        =  FEED THERMAL CONDITION (RATIO OF LIQUID TO VAPOR
C                   FOR THE FEED)
C       RECLK    =  THE PERCENTAGE RECOVERY OF THE LIGHT KEY COMPONENT
C       RECHK    =  THE PERCENTAGE RECOVERY OF THE HEAVY KEY COMPONENT
C       FACTOR   =  FACTOR FOR THE REFLUX RATIO (i.e. FACTOR*MREF)
C       FEED     =  THE POSITION OF THE FEED PLATE
C       CHOICE   =  DETERMINE WHETHER FEED IS EQUILIBRIUM CONSTANT OR
C                   RELATIVE VOLATILITY.
C       ************************************************************
C
        CHARACTER*5 CHOICE

        DIMENSION ALPHA(20), B(20), D(20), F(20), PERD(20), PERB(20)
        DIMENSION XF(20), XB(20), XD(20)
        REAL K(20), MB(20), MD(20), NUM1, MREF

        COMMON/DATA1/NUM, F, K, RECLK, RECHK, K1, Q, FACTOR
        COMMON/DATA2/THETA, FEED

        OPEN (UNIT = 3, FILE='DATA76.DAT', STATUS='OLD', ERR=18)
        OPEN (UNIT =1, FILE='PRN')
```

```
C
C        READ THE CHOICE OF PARAMETER e.g. RELATIVE VOLATILITY (REL) OR
C        EQUILIBRIUM CONSTANT (EQUIL).
C        READ THE TOTAL NUMBER OF COMPONENTS, NUM
C        READ THE FEED AND RELATIVE VOLATILITY OR EQUILIBRIUM CONSTANT, F,K
C        READ THE RECOVERIES OF LIGHT AND HEAVY KEYS, RECLK, RECHK.
C        READ THE POSITION OF THE HEAVY KEY COMPONENT, K1.
C        READ THE THERMAL FEED CONDITION, Q
C        READ THE FACTOR FOR THE REFLUX RATIO, FACTOR.

         READ (3, 5, ERR=19) CHOICE

 5       FORMAT (A)

         IF (CHOICE .EQ. 'REL' .OR. CHOICE .EQ. 'rel') THEN

C        READ THE TOTAL NUMBER OF COMPONENTS

         READ (3, *, ERR=19) NUM

C        READ THE FEED AND THE RELATIVE VOLATILITY OF EACH COMPONENT.


         DO I = 1, NUM
         READ (3, *, ERR=19) F(I), K(I)
         END DO

         ELSEIF (CHOICE .EQ. 'EQUIL' .OR. CHOICE .EQ. 'equil') THEN


C        READ THE TOTAL NUMBER OF COMPONENTS.

         READ (3, *, ERR=19) NUM

C        READ THE FEED AND THE EQUILIBRIUM CONSTANT OF EACH COMPONENT.

         DO I = 1, NUM
         READ (3, *, ERR=19) F(I), K(I)
         END DO
         ENDIF

C        READ THE RECOVERIES OF THE LIGHT AND HEAVY COMPONENTS.


         READ (3, *, ERR=19) RECLK, RECHK

C        READ THE POSITION OF THE HEAVY KEY COMPONENT.
C        READ THE THERMAL CONDITION OF THE FEED.
C        READ THE FACTOR FOR THE REFLUX RATIO.


         READ (3, *, ERR=19) K1, Q, FACTOR

         GO TO 10

 18      WRITE (*, 22)
 22      FORMAT (5X, 'DATA FILE DOES NOT EXIST')
         GO TO 999
```

```
 19     WRITE (*, 23)
 23     FORMAT (5X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999


C       ARRANGE THE FEEDS AND EQUILIBRIUM CONSTANT/RELATIVE
C       VOLATILITY IN THE ORDER OF DECREASING VALUE



 10     CALL SORT (K, F, NUM)


C       CHECK WHETHER EQUILIBRIUM CONSTANTS OR RELATIVE VOLATILITY
C       IS CHOSEN WITH THE FEED COMPONENTS

        IF ( CHOICE .EQ. 'EQUIL' .OR. CHOICE .EQ. 'equil') THEN
             GO TO 15
        ELSEIF (CHOICE .EQ. 'REL' .OR. CHOICE .EQ. 'rel') THEN

        DO I = 1, NUM
              ALPHA(I)=K(I)
        END DO
        ENDIF
              GO TO 25

C       CALCULATE THE RELATIVE VOLATILITIES OF THE COMPONENTS
C       EQUILIBRIUM VALUES OF THE LIGHT KEY AND HEAVY KEY COMPONENTS ARE:

 15     DO I = 1, NUM
        ALPHA(I)=K(I)/K(K1)
        END DO

C       CALCULATE THE CORRELATION CONSTANTS: A1,B1


 25     A1=ALOG10((1.0-RECHK)/RECHK)
        VAL1=(RECLK/(1.0-RECLK))*(RECHK/(1.0-RECHK))
        B1=ALOG10(VAL1)/ALOG10(ALPHA(K1-1))

C       CALCULATE THE COMPONENT MOLES IN THE DISTILLATE

        DO I = 1, NUM
        D(I)=((10**A1)*(ALPHA(I)**B1))/(1.0+((10**A1)*(ALPHA(I)**B1)))
        PERD(I)=D(I)*100.0
        MD(I)=D(I)*F(I)
        END DO

C       CALCULATE THE RECOVERY OF THE LIGHT KEY COMPONENT IN THE
C       DISTILLATE

        K2=K1-1
        D(K2)=F(K2)*RECLK

C       CALCULATE THE TOTAL MOLES IN THE DISTILLATE

        SUM1=0.0

        DO I = 1, NUM
```

```
          SUM1=SUM1+MD(I)
        END DO

C       CALCULATE THE PERCENTAGE RECOVERY IN THE BOTTOMS PRODUCT

        DO I = 1, NUM
          B(I)=1.0/(1.0+((10**A1)*(ALPHA(I)**B1)))
          PERB(I)=B(I)*100.0
          MB(I)=B(I)*F(I)
        END DO

C       CALCULATE THE RECOVERY OF THE HEAVY KEY COMPONENT IN THE BOTTOMS

        B(K1)=F(K1)*RECHK

C       CALCULATE THE TOTAL PRODUCT IN THE BOTTOMS

        SUM2=0.0

        DO I = 1, NUM
          SUM2=SUM2+MB(I)
        END DO

C       CALCULATE THE MINIMUM NUMBER OF TRAYS IN THE COLUMN

        VAL2=(MD(K1-1)/(MD(K1))*(MB(K1)/MB(K1-1)))
        AMIN=ALOG(VAL2)/(ALOG(ALPHA(K1-1)))
        RECLK=RECLK*100.0
        RECHK=RECHK*100.0


C       CALCULATE THE MOLE FRACTIONS IN THE FEED,DISTILLATE AND BOTTOMS


        SUMB=0.0
        SUMD=0.0
        SUMF=0.0

        DO J = 1, NUM
         SUMB=SUMB+MB(J)
         SUMD=SUMD+MD(J)
         SUMF=SUMF+F(J)

        END DO

        DO I = 1, NUM
         XB(I)=MB(I)/SUMB
         XD(I)=MD(I)/SUMD
         XF(I)=F(I)/SUMF

        END DO


        CALL UNDERW (NUM, Q, XF, XD, THETA, MREF, ALPHA, K1)

C       USE McCORMICK'S EQUATION TO DETERMINE GILLILAND'S GRAPHICAL
C       CORRELATION AND HENCE THE EQUILIBRIUM NUMBER OF STAGES.
```

```
        REF=FACTOR*MREF
        X=(REF-MREF)/(REF+1.0)
        C=0.105*ALOG10(X)+0.44
        Y=1.0-(X**C)
        NUM1=(Y+AMIN)/(1.0-Y)


C       USE KIRKBRIDE'S EMPIRICAL EQUATION TO ESTIMATE THE POSITION
C       OF THE FEED PLATE.

        Z1=(XF(K1)/XF(K1-1)*(SUM2/SUM1)*(XB(K1-1)/XD(K1))**2)
        C1=0.206*ALOG10(Z1)
        Z2=10**C1
        FEED=(Z2*NUM1)/(1.0+Z2)
C
        CALL OUTPUT(NUM,F,ALPHA,PERD,MD,PERB,MB,K1,RECLK,RECHK,AMIN,
     *  SUM1,SUM2,MREF,REF,NUM1)


        CLOSE (3, STATUS='KEEP')
        CLOSE (1)

 999    STOP
        END


C       ****************************************************************
C       THIS PROGRAM CALCULATES THE FEED COMPONENTS IN ORDER
C       OF DECREASING RELATIVE VOLATILITY.
C       ****************************************************************

        SUBROUTINE SORT (X, Y, N)

        DIMENSION X(20), Y(20)
            N1=N-1
        DO 10 I=1,N1
            I1=I+1
        DO 20 J=I1,N
            IF(X(I) .GE. X(J)) THEN
        GO TO 20
        ELSE
        HOLD=X(I)
        X(I)=X(J)
        X(J)=HOLD
            HOLD=Y(I)
            Y(I)=Y(J)
            Y(J)=HOLD

            ENDIF
 20     CONTINUE
 10     CONTINUE

        RETURN
        END

C       ****************************************************************
C       THIS PROGRAM CALCULATES THE UNDERWOOD CONSTANT THETA, USING THE
C       BINARY SEARCH METHOD AND THE MINIMUM REFLUX RATIO
C       (i.e. AT AN INFINITE NUMBER OF PLATES)
C       ****************************************************************
```

```
        SUBROUTINE UNDERW (N, Q, XF, XD, THETA, MREF, ALPHA, K1)
        DIMENSION ALPHA(20), XF(20), XD(20)
        REAL MREF,LHS
        THETA1=ALPHA(K1)
        THETA2=ALPHA(K1-1)

        DO 10 I=1,20
        THETA=0.5*(THETA1+THETA2)
        LHS=Q-1.0

        DO J = 1, N
        LHS=LHS+((ALPHA(J)*XF(J))/(ALPHA(J)-THETA))
        END DO

        IF (LHS .LT. 0.0) THEN
        THETA1=THETA
        GO TO 10
        ELSEIF (LHS .GT. 0.0) THEN
        THETA2=THETA
        GO TO 10
        ELSEIF (LHS .EQ. 0.0) THEN
        GO TO 50
        ENDIF

 10     CONTINUE
 50     MREF=-1.0

        DO K = 1, N
        MREF=MREF+((ALPHA(K)*XD(K))/(ALPHA(K)-THETA))
        END DO

        RETURN
        END
C     ****************************************************************
C
C     THIS PROGRAM OUTPUTS THE RESULTS ON THE SCREEN
C     ****************************************************************

      SUBROUTINE OUTPUT(NUM,F,ALPHA,PERD,MD,PERB,MB,K1,RECLK,RECHK,AMIN,
     *SUM1,SUM2,MREF,REF,NUM1)

        DIMENSION F(20), ALPHA(20), PERD(20), PERB(20)
        REAL MD(20), MB(20), NUM1, MREF
        COMMON/DATA2/THETA, FEED

        WRITE (*, 100)
 100    FORMAT(25X,'MULTICOMPONENT SYSTEM FRACTIONATION')

        WRITE (*, 110)
 110    FORMAT(80(1H*))

        WRITE (*, 120)
 120    FORMAT(/,1X,'COMPONENT',7X,'FEED',5X,'REL VOLATILITY',3X,
     *  'DISTILATTE ',8X,'BOTTOMS ')

        WRITE (*, 130)
 130    FORMAT(1X,'NUMBER',9X,'MOLES',7X,'ALPHA',10X,'%',8X,'MOLES',8X,
     *'%',6X,'MOLES')
```

```
        WRITE (*, 140)
 140    FORMAT (80(1H-))

        DO 10 I=1,NUM

        WRITE (*, 150) I,F(I),ALPHA(I),PERD(I),MD(I),PERB(I),MB(I)
 150    FORMAT(3X,I2,7X,F9.4,3X,F9.4,3X,F9.4,2X,F9.4,3X,F9.4,2X,F9.4)
 10     CONTINUE

        WRITE (*, 160)
 160    FORMAT (80(1H-))

        WRITE (*, 170) K1
 170    FORMAT(3X,'THE HEAVY KEY COMPONENT NUMBER IS:',T60,I2)

        WRITE (*, 180) RECLK
 180    FORMAT(3X,'PERCENTAGE RECOVERY OF THE LIGHT KEY COMPONENT',/,
     *  3X,'IN THE DISTILLATE IS (%):',T60,F7.2)

        WRITE (*, 190) RECHK
 190    FORMAT(3X,'PERCENTAGE RECOVERY OF THE HEAVY KEY COMPONENT',/,
     *  3X,'IN THE BOTTOMS IS (%):',T60,F7.2)

        WRITE (*, 200) AMIN
 200    FORMAT(3X,'MINIMUM NUMBER OF STAGES IS:',T60,F9.1)

        WRITE (*, 210) SUM1, SUM2
 210    FORMAT(3X,'TOTAL MOLES IN THE DISTILLATE IS:',T60,F9.4,/,
     *  3X,'TOTAL MOLES IN THE BOTTOMS IS:',T60,F9.4)

        WRITE (*, 220) THETA
 220    FORMAT(3X,'UNDERWOOD CONSTANT:',T60,F9.4)

        WRITE (*, 230) MREF
 230    FORMAT(3X,'MINIMUM REFLUX RATIO:',T60,F9.4)

        WRITE (*, 240) REF
 240    FORMAT(3X,'ACTUAL REFLUX RATIO:',T60,F9.4)

        WRITE (*, 250) NUM1
 250    FORMAT(3X,'NUMBER OF THEORETICAL PLATES IN THE COLUMN:',T60,F9.1)

        WRITE (*, 260) FEED
 260    FORMAT(3X,'THE POSITION OF THE FEED PLATE IS:',T60,F4.1)

        WRITE (*, 270)
 270    FORMAT (1H ,80(1H-))

        OPEN (UNIT=1, FILE='LPT1')

        CALL PAPER (NUM,F,ALPHA,PERD,MD,PERB,MB,K1,RECLK,RECHK,AMIN,
     *          SUM1,SUM2,MREF,REF,NUM1)

        CLOSE (1)
        RETURN
        END

C       ************************************************************
C       THIS PROGRAM PRINTS THE RESULTS ONTO A PRINTER
```

```
C         **********************************************************
          SUBROUTINE PAPER(NUM,F,ALPHA,PERD,MD,PERB,MB,K1,RECLK,RECHK,
     *    AMIN,SUM1,SUM2,MREF,REF,NUM1)

          DIMENSION F(20), ALPHA(20), PERD(20), PERB(20)
          REAL MD(20), MB(20), MREF, NUM1

          COMMON/DATA2/THETA, FEED

          WRITE (1, 280)
 280      FORMAT (///,25X,'MULTICOMPONENT SYSTEM FRACTIONATION',/,1H ,
     *            80(1H*))

          WRITE (1, 290)
 290      FORMAT (/, 1X,'COMPONENT',7X,'FEED',5X,'REL VOLATILITY', 3X,
     *    'DISTILLATE ', 8X, 'BOTTOMS ')

          WRITE (1, 300)
 300      FORMAT (1X,'NUMBER',9X,'MOLES',7X,'ALPHA',10X,'%',8X,'MOLES',8X,
     *    '%',6X,'MOLES')

          WRITE (1, 310)
 310      FORMAT (80(1H-))

          DO 10 I = 1 ,NUM

          WRITE (1, 320) I, F(I), ALPHA(I), PERD(I), MD(I), PERB(I), MB(I)
 320      FORMAT (3X,I2,7X,F9.4,3X,F9.4,3X,F9.4,2X,F9.4,3X,F9.4,2X,F9.4)

 10       CONTINUE

          WRITE (1, 330)
 330      FORMAT (80(1H-))

          WRITE (1, 340) K1
 340      FORMAT (3X,'THE HEAVY KEY COMPONENT NUMBER:', T60, I2)

          WRITE (1, 350) RECLK
 350      FORMAT (3X,'PERCENTAGE RECOVERY OF THE LIGHT KEY COMPONENT',/,
     *            3X,'IN THE DISTILLATE (%):', T60, F7.2)

          WRITE (1, 360) RECHK
 360      FORMAT (3X,'PERCENTAGE RECOVERY OF THE HEAVY KEY COMPONENT',/,
     *            3X,'IN THE BOTTOMS (%):', T60, F7.2)

          WRITE (1, 370) AMIN
 370      FORMAT (3X,'MINIMUM NUMBER OF STAGES:', T60, F9.1)

          WRITE (1, 380) SUM1, SUM2
 380      FORMAT (3X,'TOTAL MOLES IN THE DISTILLATE:', T60, F9.4,/,
     *            3X,'TOTAL MOLES IN THE BOTTOMS:', T60, F9.4)

          WRITE (1, 390) THETA
 390      FORMAT (3X,'UNDERWOOD CONSTANT:', T60, F9.4)

          WRITE (1, 400) MREF
 400      FORMAT (3X,'MINIMUM REFLUX RATIO:', T60, F9.4)

          WRITE (1, 410) REF
```

```
 410     FORMAT (3X,'ACTUAL REFLUX RATIO:', T60, F9.4)

         WRITE (1, 420) NUM1
 420     FORMAT (3X,'NUMBER OF THEORETICAL PLATES IN THE COLUMN:', T60,
     *           F9.1)

         WRITE (1, 430) FEED
 430     FORMAT (3X,'THE POSITION OF THE FEED PLATE:', T60, F9.1)

         WRITE (1, 440)
 440     FORMAT (80(1H-))

C        FORM FEED THE PRINTING PAPER TO THE TOP OF NEXT PAGE.

         WRITE (1, *) CHAR(12)
         RETURN

         END
```

CHAPTER 8

Heat Transfer

INTRODUCTION

The increasing cost of energy in recent years has resulted in increased attention to conservation and efficient energy management. Other types of technology, for example, pinch technology, have been employed in the energy integration of process plants and of heat exchangers in particular. This has often resulted in an improved performance of the plants at reduced operational costs. Various types of forced convective heat transfer equipment are used in the chemical process industries. These range from the simple shell and tube exchangers, double pipe, finned tube and tubular air cooled exchangers to the plate types, spiral and compact heat exchangers. Table 8-1 lists the major types of heat exchanger [1].

BASIC THEORY

Heat is transferred from points of high temperature to points of lower temperature by direct contact of particles of matter or the emission and absorption of radiant energy. The three classifications of heat transfer are:

Conduction. The transfer of heat from one body to another by physical contact. The rate of heat flow by conduction is proportional to the area available for the heat transfer and the temperature gradient in the direction of the heat flow path. The rate of heat flow in a given direction can be expressed as:

$$\frac{dQ}{d\theta} = -kA\frac{dT}{dx} \tag{8-1}$$

Table 8-1
Summary of Types of Heat Exchangers

Type	Major Characteristics	Application
Shell and tube	Bundle of tubes encased in a cylindrical shell.	Always the first type exchanger to consider.
Air cooled heat exchanger	Rectangular tube bundles mounted on frame, with air used as the cooling medium	Economic where cost of cooling water is high.
Double pipe	Pipe within a pipe; inner pipe may be finned or plain.	For small units.
Extended surface	Externally finned tube.	Services where the outside tube resistance is appreciably greater than the inside resistance. Also used in debottlenecking existing units.
Brazed plate fin	Series of plates separated by corrugated fins.	Cryogenic services: all fluids must be clean.
Spiral wound	Spirally wound tube coils within a shell	Cryogenic services: fluids must be clean.
Scrapped surface	Pipe within a pipe, with rotating blades scraping the inside walls of the inner pipe.	Crystallization cooling applications.
Bayonet tube	Tube element consists of an outer and inner tube.	Useful for high temperature difference between shell and tube fluids.
Falling film coolers	Vertical units using a thin film of water in tubes.	Special cooling applications.
Barometric condenser	Direct contact of water and vapor.	Where mutual solubilities of water and process fluid permit.
Cascade coolers	Cooling water flows over series of tubes.	Special cooling applications for very corrosive process fluids.
Impervious graphite	Constructed of graphite for corrosion protection.	Used in very highly corrosive heat exchange services.

Source: Cheremisinoff [1]

where Q = amount of heat transferred in time θ hr, Btu
k = the thermal conductivity, or proportionality constant, Btu/(hr)(ft^2)(°F/ft)
A = area of heat transfer perpendicular to direction of heat flow, ft^2
T = temperature, °F
x = length of conduction path in direction of heat flow, ft

Convection. The transfer of heat by the mixing or movements of fluids or fluids with a solid. Mixing may occur as a result of density difference alone, as in natural convection. Alternatively, mechanically induced agitation may produce forced convection, as in turbulent flow in a heat exchanger tube, or to the heat transfer fluid in the jacket of an agitated vessel. The rate of heat transfer is:

$$\frac{dQ}{d\theta} = hA\Delta t \tag{8-2}$$

where h = the heat transfer coefficient or the proportionality constant, which is a function of the type of agitation, the degree of turbulence, and the nature of the fluid. For the steady state condition, Equation 8-2 becomes

$$q = hA\Delta t \tag{8-3}$$

Radiation. The transfer of heat by the absorption of radiant energy, transformed into heat in surrounding bodies. The rate at which radiant heat energy is emitted from a source is:

$$\frac{dQ}{d\theta} = \sigma\varepsilon AT^4 \tag{8-4}$$

where σ = Stefan-Boltzmann constant
= 0.1713×10^{-8} Btu/hrft^2(°R$)^4$
ε = emissivity of surface
A = exposed surface area of heat transfer, ft^2
T = absolute temperature, °R

The most common applications of heat transfer are a combination of one or more of these classifications. Also in many processes where a phase change occurs, that is, condensation, boiling, and evaporation, other physical phenomena play an important role in limiting the achievable heat transfer rate. However, only the most common, forced convective heat transfer, is considered here as well as an illustration of conductive heat transfer.

The procedures for the design of heat exchangers vary with the type of problem, but are often repetitive and tedious. An increasing number of software packages have been developed, for example, Heat Transfer and Fluid Flow Services (HTFS) and Heat Transfer Research Inc. (HTRI). These programs are available to the member companies. Two procedures are used in the design of heat exchangers. They are the rating method and the optimization design method.

The Rating Method

In the rating method, the designer assumes the form of an exchanger and then develops computations to determine whether the exchanger could handle the process requirements under known conditions. If the exchanger does not satisfy the requirements, a different exchanger is assumed, and the calculations repeated until a satisfactory design is obtained. For an example, for any given set of process requirements, the designer could assume an exchanger constructed of specific materials and having a known tube size, number of tubes, tube spacing, and passes, a shell size, baffling and number of passes (other more detailed assumptions such as removable bundle and floating head arrangements and end constructions). In addition, there are six process variables:

- inlet temperature of hot stream
- outlet temperature of hot stream
- inlet temperature of cold stream
- outlet temperature of hot stream
- flow rate of hot stream
- flow rate of cold stream

The designer will proceed by checking whether the energy balance calculations between the fluids are consistent. If there is a large deviation (for example 10%), the hot fluid duty is used for the design calculations. Further calculations could be the required heat transfer area, lengths, pressure drops on either side (ΔP), and an overall heat transfer coefficient. Repeated trials may be required to achieve an accurate overall heat transfer coefficient. If the results of the final design show that (allowing for any accumulations of scale during service between cleaning) the assumed exchanger is of reasonable dimensions, of a low cost, and will create acceptable pressure drops, the equipment is considered adequate for the duty.

Optimization Design Method

This approach is based upon optimum economic conditions. By choosing various conditions, the designer can arrive at a final design giving the least total cost for fixed charges and operation. Any increase in the fluid velocity on either side may result in a larger heat transfer coefficient, and consequently require a smaller heat transfer area and exchanger cost for a given rate of heat transfer. However, increased fluid velocity will result in a greater pressure drop and pumping costs. The optimum economic design occurs at the conditions where the total cost is at a minimum. This method minimizes the sum of the variable annual costs for the exchanger and its operation.

In general, the design of a heat exchanger involves the following steps:

1. Determine the flow rates and the rate of heat transfer required for given conditions.
2. Decide on the type of heat exchanger (e.g., 1:1, 1:2 type, or 2:4 type) to be used. Assume permissible scale factors and show the basic equipment specifications.
3. Calculate the fluid velocities of the film coefficients and the overall heat transfer coefficient.
4. Calculate the mean temperature difference driving force.
5. Determine the required area of heat transfer and the exchanger dimensions.
6. Evaluate the results to see that all dimensions, costs, ΔPs, and other design parameters are satisfactory.
7. If the results in Step 6 show that the exchanger is not satisfactory, the specifications given in Step 2 are inadequate. Choose new specifications and repeat Steps 3 through 7 until a satisfactory design is achieved.

This chapter presents rating calculations for the shell and tube heat exchanger, procedures for the design of double pipe or longitudinal finned tube heat exchanger, air cooler, heat tracer requirements for pipelines, and heat transfer in batch reactors.

LMTD IN SHELL AND TUBE HEAT EXCHANGERS

In a shell and tube heat exchanger, the rate of heat transfer from the hot to the cold fluid is directly proportional to the temperature difference between the two fluids. For the rating of heat exchangers, it is important to determine the mean temperature difference based on the hot and cold fluids' inlet and outlet temperatures. The heat transfer process is generally more efficient where there is countercurrent flow compared to co-current flow. The relative direction of the fluids affects the value of the log mean temperature difference (LMTD). A further advantage of approaching countercurrent flow, except where one fluid is isothermal (that is, constant temperature) is that in co-current flow, the hot fluid cannot be cooled below the cold fluid outlet temperature, so the ability to recover heat is limited. There are a few cases where co-current flow is preferred. For example, when cooling a viscous fluid, a higher heat transfer coefficient may be obtained by a rapid initial reduction in viscosity. Co-current may also be favorable if the temperature of the warmer fluid could otherwise be reduced to its freezing point.

In the majority of industrial operations, higher velocities, shorter tubes, and a more economical exchanger can be achieved with a multipass flow design as shown in Figure 8-1. The flow pattern is however part countercurrent and part co-current. Therefore, the mean temperature difference lies between the countercurrent and co-current log mean temperature differences (LMTD). The mean temperature differences for the

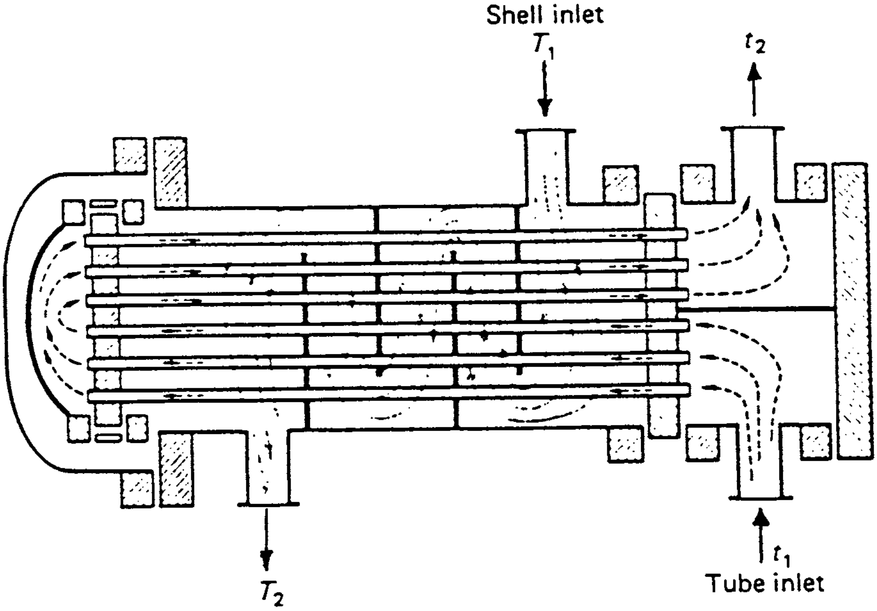


Figure 8-1. Flow patterns in a multipass exchanger (1:2 floating head as shown).

various types of crossflow exchanger are also less than for countercurrent flow designs, but greater than for co-current flow. In addition, the relationships between terminal temperatures and mean temperature difference restrict the performance of each type of exchanger. A correction factor, F, is defined to convert the LMTD to the corrected mean temperature difference (CMTD). For true countercurrent flow, F = 1, and as more co-current flow is introduced, the factor is reduced and the efficiency of the exchanger drops. A low value of F requires a large surface requirement for a given heat load. Performance can be enhanced by using several shells in series or by increasing the number of passes in the same shell. The lower limit of practical efficiency is in the range F = 0.75 to 0.8. The lowest F value is for one shell when rating shell and tube exchangers in series. This value is raised as the number of shells increases, and the flow more nearly resembles countercurrent flow. For the design of shell and tube exchangers, the minimum number of shells that will raise the F value above the chosen minimum of 0.75 to 0.8 is calculated.

Here, a computer program is written by setting the minimum correction factor to 0.75. The program automatically increases the number of shells until the value of F exceeds 0.75 or some other preset value.

Bowman *et al.* [2] simplified the calculations required to determine the mean temperature difference in a shell and tube exchanger. Figure 8-2 shows some of the major types of the shell and tube heat exchanger construction, and Figures 8-3 to 8-6 illustrate correction factor plots for various shell and tube exchangers. The equations given by Bowman *et al.* [2] are used to determine the corrected LMTD.

Heat Exchanger Design

The thermal rating of heat exchanger equipment requires the computation of the LMTD between the shell and tube fluids' temperatures. This is defined by

$$\text{LMTD} = \frac{\Delta t_1 - \Delta t_2}{\ln\left(\dfrac{\Delta t_1}{\Delta t_2}\right)} \tag{8-5}$$

where for countercurrent flow

Δt_1 = the larger terminal temperature difference, $T_1 - t_2$

(text continued on page 602)

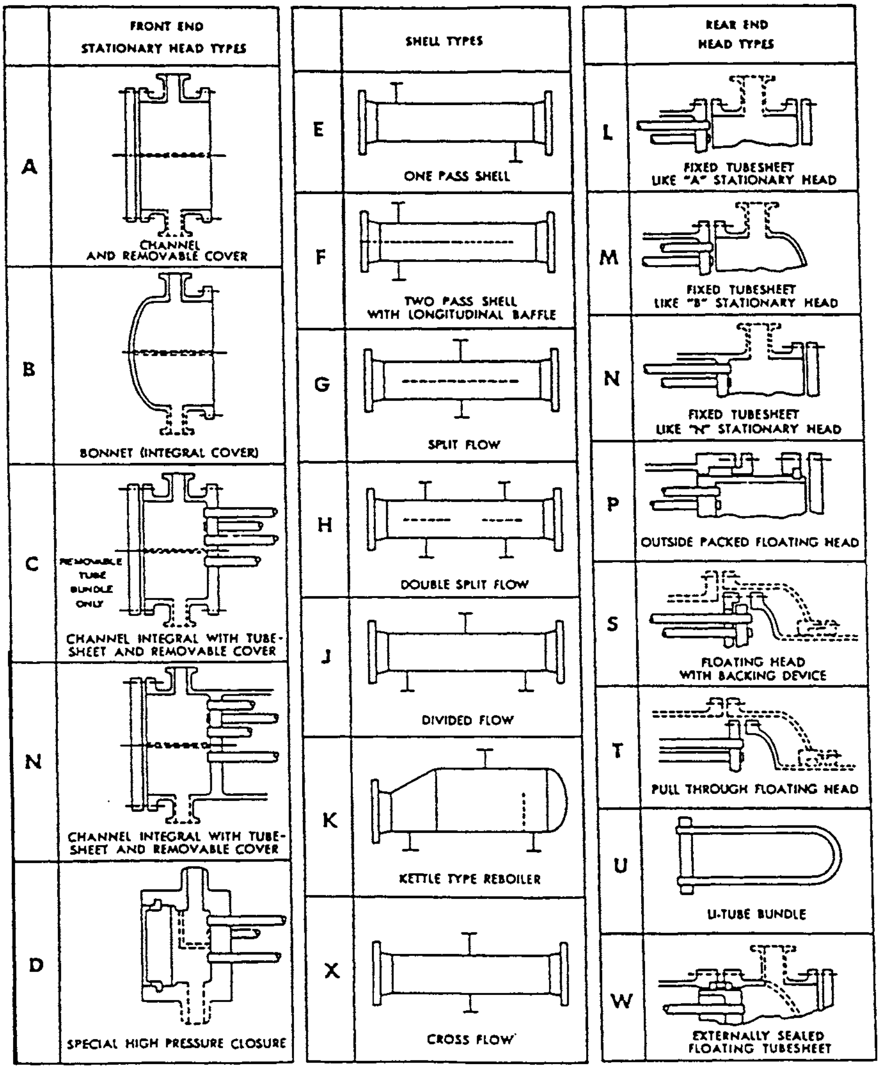
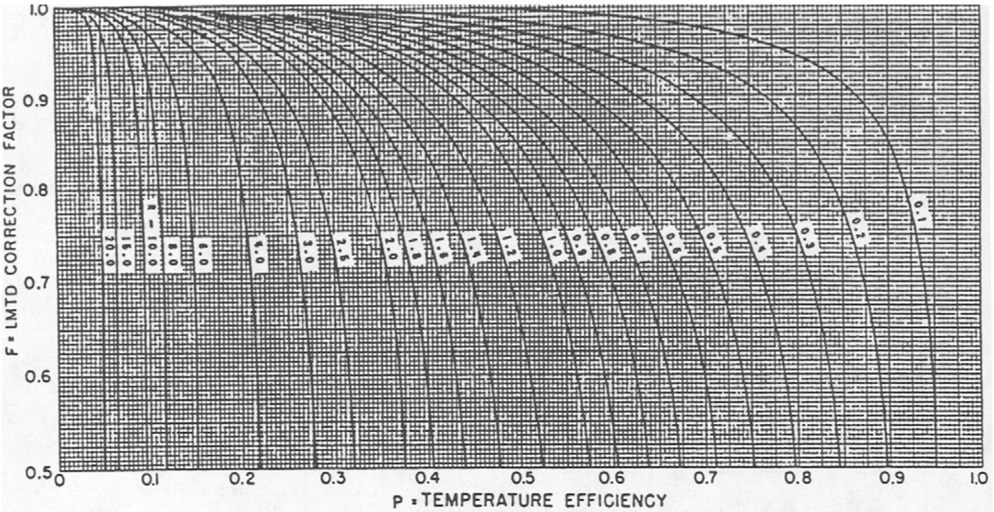
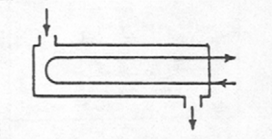


Figure 8-2. Tubular Exchanger Manufacturers Association (TEMA) classification and terminology for heat exchangers. TEMA heat exchanger head types.

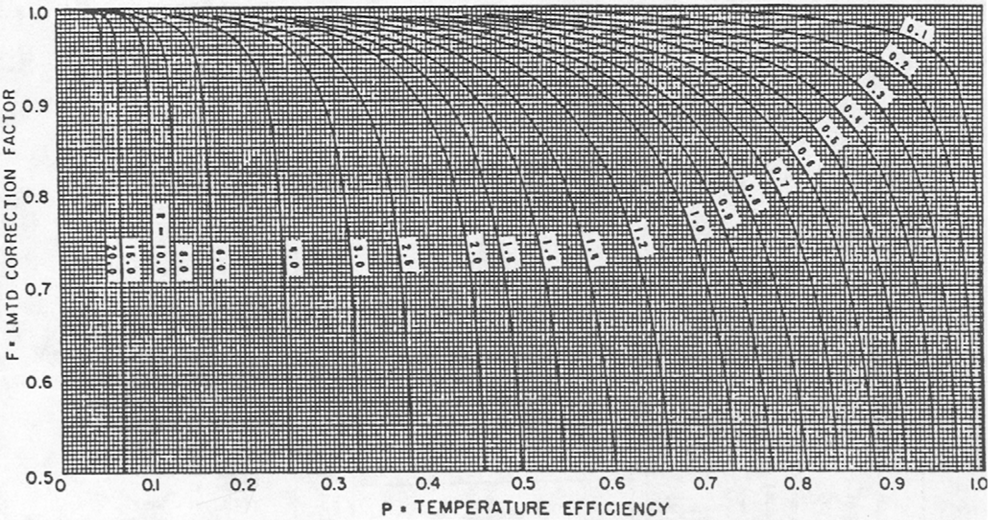


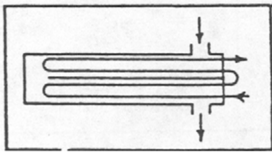


LMTD CORRECTION FACTOR

1 SHELL PASS EVEN NUMBER OF TUBE PASSES

$P = \frac{t_2 - t_1}{T_1 - t_1}$ $R = \frac{T_1 - T_2}{t_2 - t_1}$



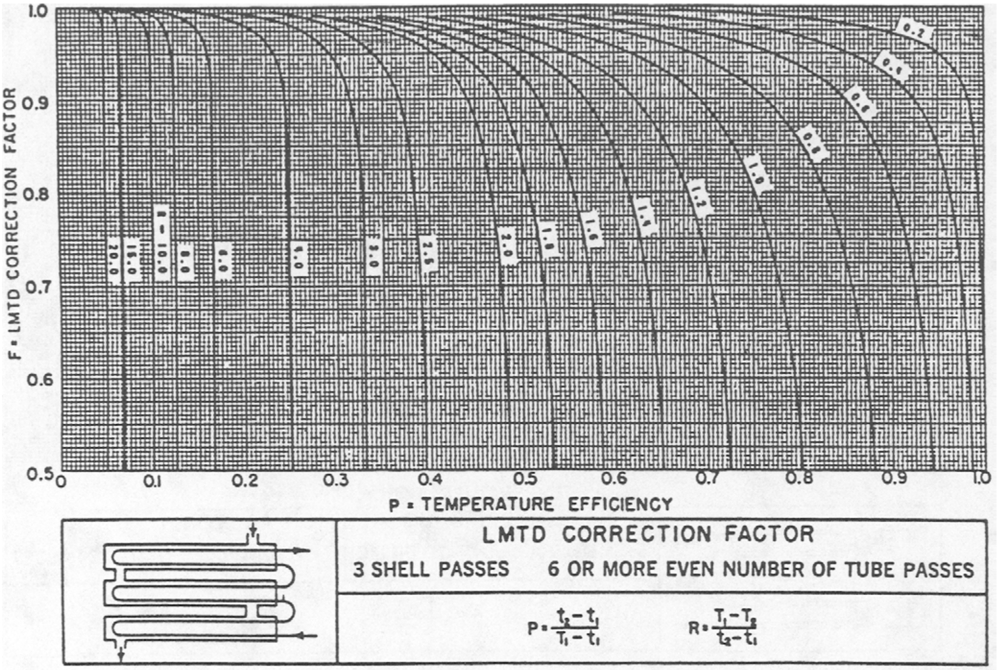


LMTD CORRECTION FACTOR

2 SHELL PASSES 4 OR MULTIPLE OF 4 TUBE PASSES

$P = \frac{t_2 - t_1}{T_1 - t_1}$ $R = \frac{T_1 - T_2}{t_2 - t_1}$

Figure 8-3. LMTD correction factor © 1978 Tubular Exchanger Manufacturers Association.



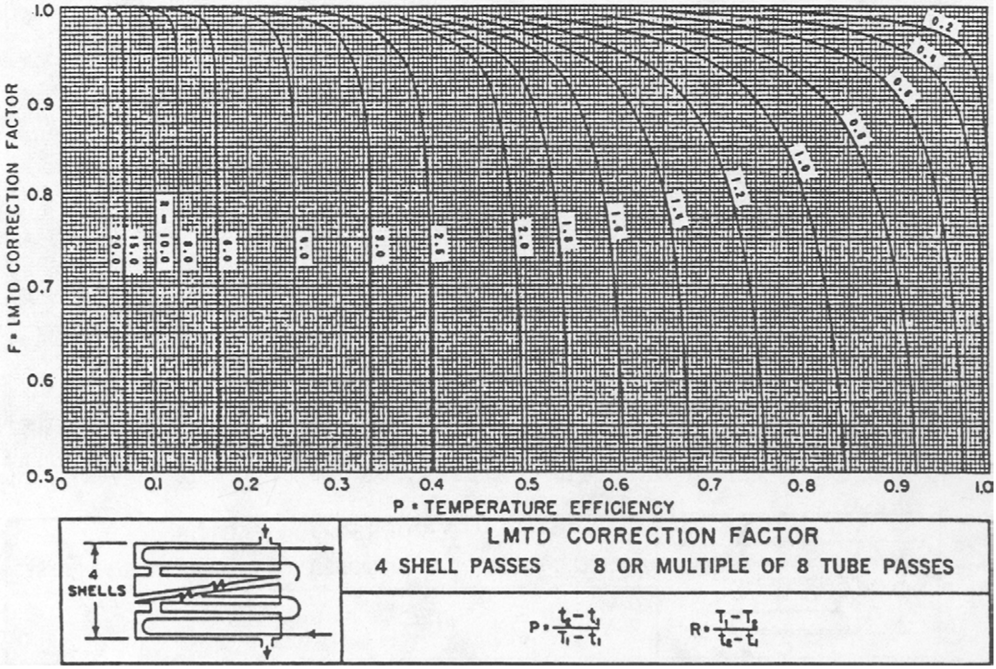
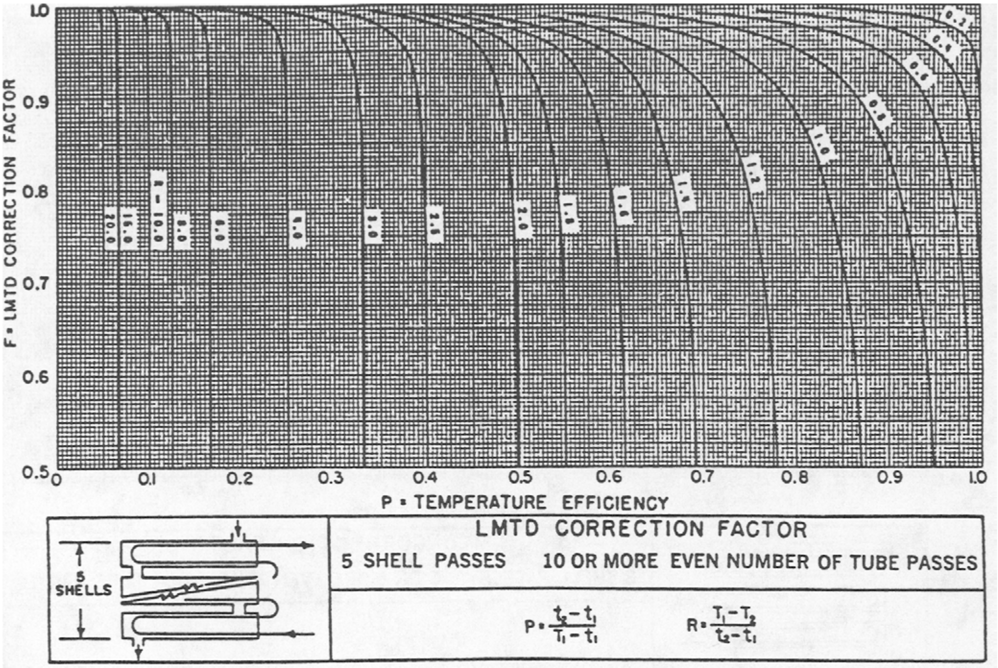


Figure 8-4. LMTD correction factor.



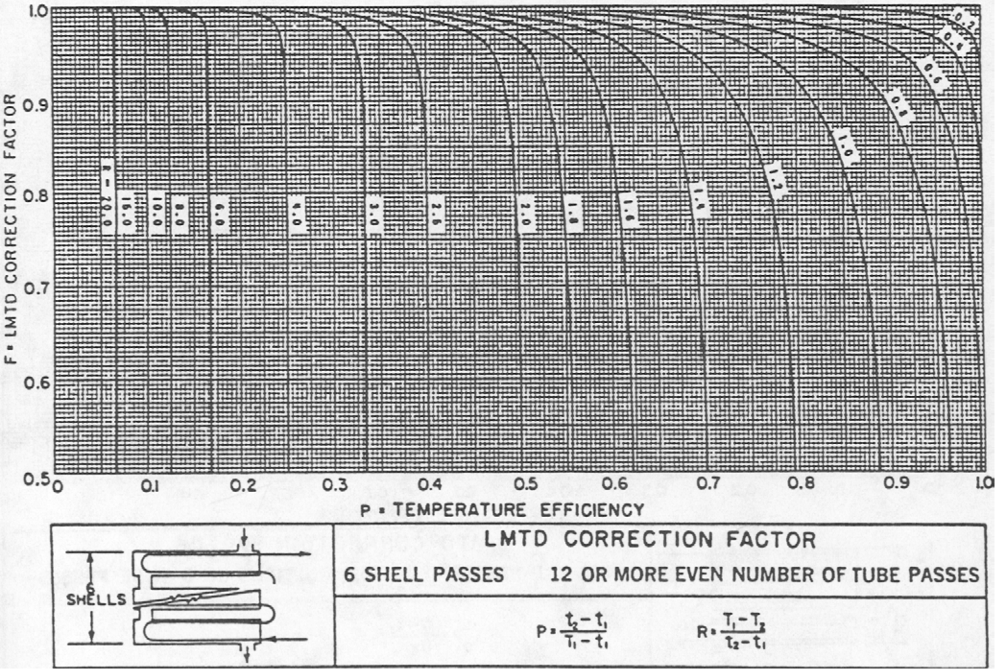
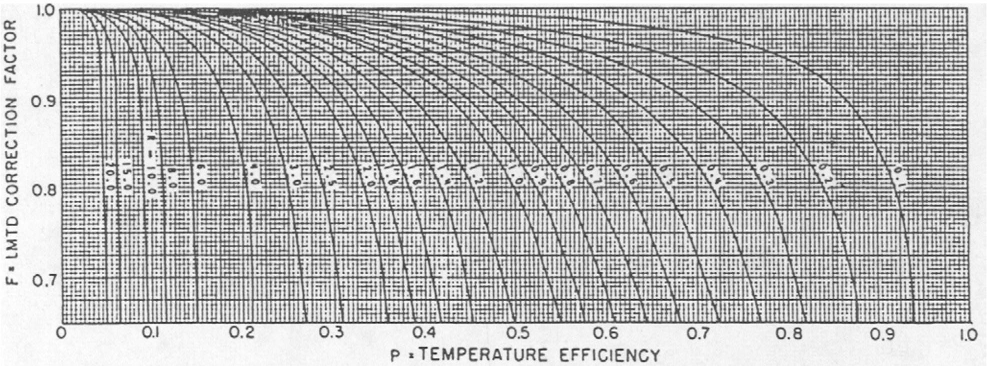
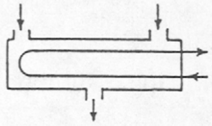


Figure 8-5. LMTD correction factor.

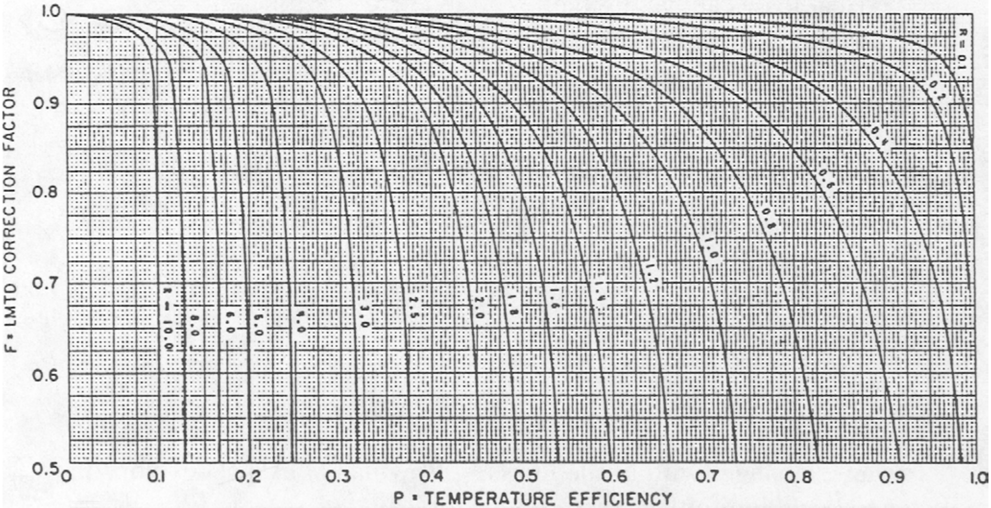


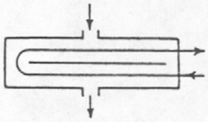


LMTD CORRECTION FACTOR

1 DIVIDED FLOW SHELL PASS — EVEN NUMBER OF TUBE PASSES

$P = \frac{t_2 - t_1}{T_1 - t_1}$ $R = \frac{T_1 - T_2}{t_2 - t_1}$





LMTD CORRECTION FACTOR

SPLIT FLOW SHELL — 2 TUBE PASSES

$P = \frac{t_2 - t_1}{T_1 - t_1}$ $R = \frac{T_1 - T_2}{t_2 - t_1}$

Figure 8-6. LMTD correction factor.

(text continued from page 596)

and

Δt_2 = the smaller terminal temperature difference, $T_2 - t_1$

For co-current flow

$\Delta t_1 = T_1 - t_1$

and

$\Delta t_2 = T_2 - t_2$

The equations used to calculate F are based on the following assumptions:

- The overall heat transfer coefficient, U, is constant through the heat exchanger.
- The rate of flow of each fluid is constant.
- The specific heat of each fluid is constant.
- There is no condensation of vapor or boiling of liquid in that part of the exchanger considered.
- Heat losses are negligible.
- There is equal heat transfer surface in each pass.
- The temperature of the shell side fluid in any shell side pass is uniform over any cross section.

Figure 8-7 shows typical temperature profiles of two fluids in true countercurrent flow through a 1-1 exchanger.

$$P = \frac{t_2 - t_1}{T_1 - t_1} \tag{8-6}$$

$$R = \frac{T_1 - T_2}{t_2 - t_1} \tag{8-7}$$

For an exchanger with N shell passes, Bowman *et al.* [2] developed a general solution for the correction factor,

$$F = \frac{\left(\dfrac{\sqrt{R^2+1}}{R-1}\right)\ln\left\{\dfrac{(1-P_x)}{(1-RP_x)}\right\}}{\ln\left\{\dfrac{(2/P_x)-1-R+\sqrt{R^2+1}}{(2/P_x)-1-R-\sqrt{R^2+1}}\right\}} \tag{8-8}$$

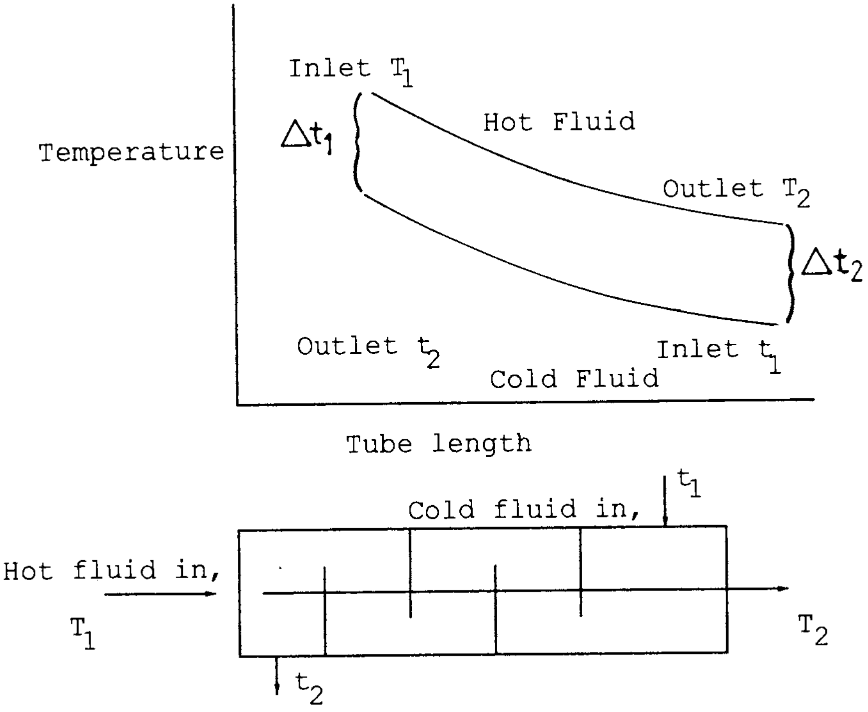


Figure 8-7. Counter-current flow in a 1-1 exchanger.

where

$$P_x = \frac{1 - \left[\frac{RP - 1}{P - 1}\right]^{1/N}}{R - \left[\frac{RP - 1}{P - 1}\right]^{1/N}} \qquad (8\text{-}9)$$

N is the total number of shell passes, that is, the product of shell passes per shell and the number of units in series. Solving for N by repetitive trial and error with a minimum desired F, the minimum required number of shell passes can be determined.

If R = 1, Equation 8-9 becomes indeterminate, which reduces to

$$P_x = \frac{P}{(N - NP + P)} \qquad (8\text{-}10)$$

Equation 8-8 then becomes

$$F = \frac{\dfrac{P_x\sqrt{R^2+1}}{1-P_x}}{\ln\left\{\dfrac{(2/P_x)-1-R+\sqrt{R^2+1}}{(2/P_x)-1-R-\sqrt{R^2+1}}\right\}} \qquad (8\text{-}11)$$

The corrected mean temperature difference (CMTD) becomes

$$\text{CMTD} = (\text{F})(\text{LMTD}) \qquad (8\text{-}12)$$

Nomenclature

F = correction factor
LMTD = log mean temperature difference,°F
N = number of series exchanger shells required
T_1 = hot fluid inlet temperature, °F
T_2 = hot fluid outlet temperature, °F
t_1 = cold fluid inlet temperature, °F
t_2 = cold fluid outlet temperature, °F

Shell and Tube Heat Exchanger Design

The various designs of heat exchangers are well illustrated in standard texts and in the literature [3,4,5,6,7,8,9]. Recently, Pooley *et al.* [10] developed algorithms for both shell and tube exchangers and compact exchangers. Their algorithms rely on the allowable pressure drops of both of the streams being contacted.

The rating of an exchanger involves using the equations to calculate the suitability of an existing exchanger for given process conditions. The following steps are used for rating a shell and tube exchanger where there is no phase of change. The process conditions required are

Hot fluid: $T_1, T_2, W, C, s, \mu, k, R_d, \Delta P$

Cold fluid: $t_1, t_2, w, c, s, \mu, k, R_d, \Delta P$

The data required are

SHELL SIDE	*TUBE SIDE*
ID	Number and length
Baffle space	ID, OD, BWG, and pitch
passes	passes

From the process conditions, the heat load, Q, is

(1) $Q = WC(T_1 - T_2) = wc(t_2 - t_1)$ (8-13)

(2) The true temperature difference, Δt (assuming a number of tube passes) is:

$$\text{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left\{\dfrac{T_1 - t_2}{T_2 - t_1}\right\}} \tag{8-14}$$

Approach factor, F_c, is determined from

$$P = \frac{t_2 - t_1}{T_1 - t_1} \tag{8-6}$$

$$R = \frac{T_1 - T_2}{t_2 - t_1} \tag{8-7}$$

and Figures 8-3 to 8-6. Alternatively, F_c can be calculated from Equation 8-8 and Equation 8-11.

(3) $\Delta t = (\text{LMTD})(F_c)$ (8-15)

Tube Side

(4) Flow area a_t, ft^2:

$$a_t = \frac{(\text{no. of tubes})(\text{flow area/tube})}{\text{no. of pases}}$$

$$= \frac{N_t . a_t'}{144n}, \quad ft^2 \tag{8-16}$$

(5) Mass velocity, G_t, is

$$G_t = \frac{w}{a_t}, \quad \left(\frac{lb}{ft^2 . hr}\right) \tag{8-17}$$

(6) Reynolds number, Re_t, is

$$Re_t = \frac{(ID/12). G_t}{\mu} \tag{8-18}$$

where

$$\mu = 2.42 \times cP\left(\frac{lb}{ft.hr.}\right)$$

(7) Prandtl number, Pr_t, is

$$Pr_t = \frac{c\mu}{k} \tag{8-19}$$

(8) The heat transfer coefficient, h_i, for viscous flow ($Re_t < 2100$) as given by Sieder and Tate's correlation [11]:

$$\frac{h_i . ID}{k} = 1.86\left(\frac{ID.G}{\mu}\right)^{1/3}\left(\frac{c\mu}{k}\right)^{1/3}\left(\frac{ID}{L}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{8-20}$$

where Nu = Nusselt number = h_i.ID/k
ID = inside tube diameter, ft

Equation 8-20 can be expressed as:

$$\frac{h_i . ID}{k} = 1.86\, Re_t^{0.33}\, Pr_t^{0.33}\left(\frac{ID}{L}\right)^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{8-21}$$

For turbulent flow ($Re_t > 10{,}000$), h_i, can be expressed as:

$$\frac{h_i . ID}{k} = C\left(\frac{ID.G_t}{\mu}\right)^{0.8}\left(\frac{c\mu}{k}\right)^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{8-22}$$

where C = 0.021 for gases
C = 0.023 for non-viscous liquids
C = 0.027 for viscous liquids

For applications in turbulent flow, the viscosity ratio can be omitted, and Equation 8-22 reduces to:

$$h_i = C.k\left(\frac{12}{ID}\right)Re_t^{0.8}\,Pr_t^{0.33} \tag{8-23}$$

for

$0.7 < Pr_t < 17{,}000$

Figure 8-8 shows the heat transfer coefficient of fluids inside tubes. The heat transfer coefficient based on the outside of the tube, h_{io}, is:

$$h_{io} = h_i\left(\frac{ID}{OD}\right) \tag{8-24}$$

(9) Recently, Hedrick [12] developed a new correlation for the heat transfer coefficient in the transition region between laminar and turbulent flow. The equations for determining the inside film coefficient and based on the outside tube diameter, h_{io}, are:

$$h_{io} = \left(\frac{16.1}{OD}\right)\left[B_i k\left(\frac{c\mu}{k}\right)^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}\right] \tag{8-25}$$

where

$$B_i = (-3.08 + 3.075X + 0.32567X^2 - 0.02185X^3)$$

$$\times\left(\frac{10.\,ID}{L}\right)^{\left[1-(X/10)^{0.256}\right]}$$

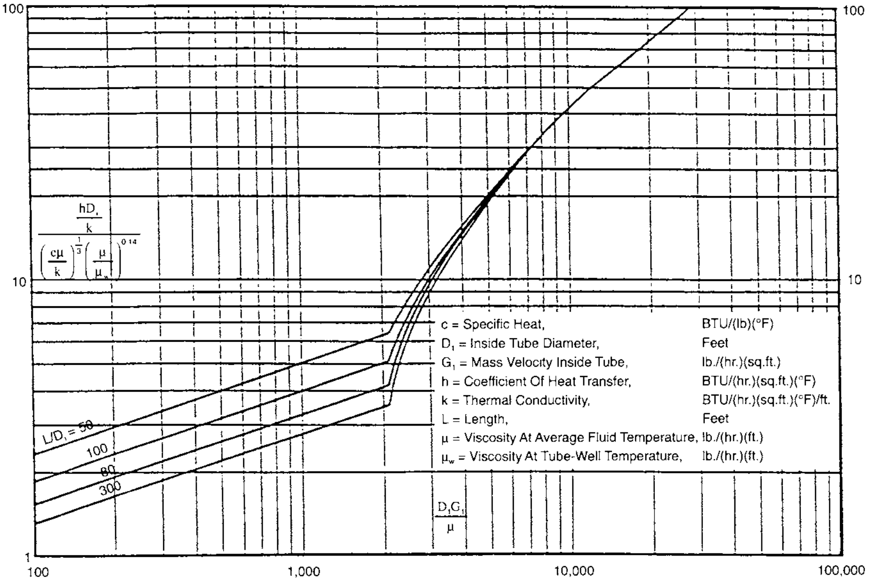


Figure 8-8. Coefficient of heat transfer fluids inside tubes.

and

$$X = \frac{Re_t}{1,000}$$

Simplified Equations

For common gases, Equation 8-23 can be simplified to give the approximate equation,

$$h_i = \frac{0.014 C_p G_t^{0.8}}{(ID/12)^{0.2}} \tag{8-26}$$

Similarly for water at ordinary temperature and pressure,

$$h_i = \frac{150(1 + 0.011 t_b) V_t^{0.8}}{ID^{0.2}} \tag{8-27}$$

where C_p = heat capacity of fluid, Btu/lb°F
ID = tube inside diameter, inch
G_t = mass velocity inside tube, lb/ft²hr
t_b = average (i.e., bulk) temperature of water, °F
$v_t^{0.8}$ = velocity of water, ft/sec

Total Pressure Drop, ΔPT

(10) From Re_t, determine the friction factor from Figure 8-9. Using the regression method in chapter one of the text, for $Re_t \leq 1000$, the friction factor correlation in Figure 8-9 can be approximated by

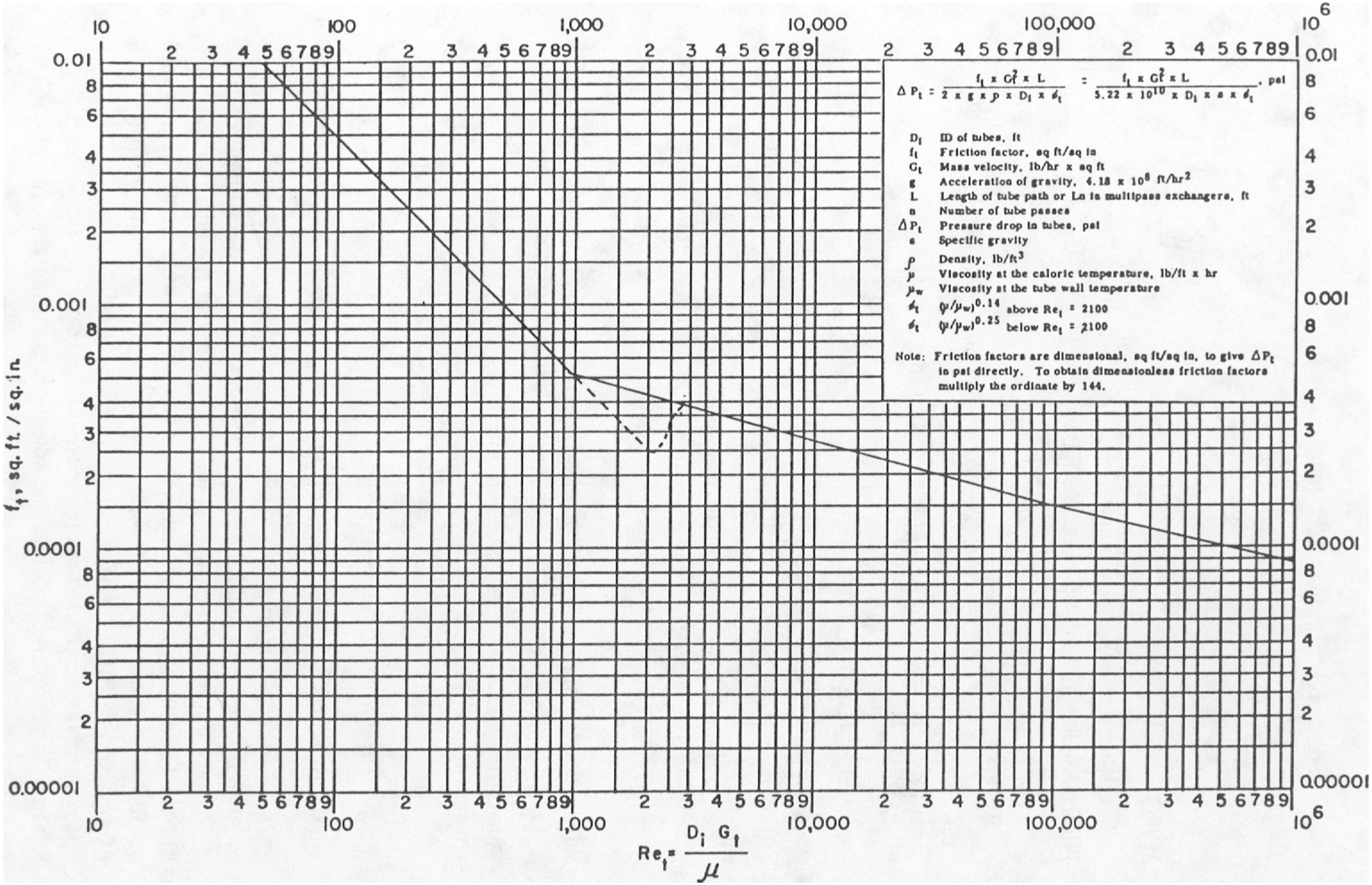
$$f_t = \frac{0.45}{Re_t^{0.9853}} \tag{8-28}$$

similarly, If $Re_t > 1000$, the friction factor is approximated by

$$f_t = \frac{0.0028}{Re_t^{0.2514}} \tag{8-29}$$

(11) The fluid velocity, V_t, is:

$$V_t = \frac{G_t}{3600.\rho} \tag{8-30}$$



$$\Delta P_t = \frac{f_t \times G_t^2 \times L}{2 \times g \times \rho \times D_t \times \phi_t} = \frac{f_t \times G_t^2 \times L}{5.22 \times 10^{10} \times D_t \times s \times \phi_t}, \text{ psi}$$

D_t	ID of tubes, ft
f_t	Friction factor, sq ft/sq in
G_t	Mass velocity, lb/hr x sq ft
g	Acceleration of gravity, 4.18×10^8 ft/hr^2
L	Length of tube path or Ln in multipass exchangers, ft
n	Number of tube passes
ΔP_t	Pressure drop in tubes, psi
s	Specific gravity
ρ	Density, lb/ft^3
μ	Viscosity at the caloric temperature, lb/ft x hr
μ_w	Viscosity at the tube wall temperature
ϕ_t	$(\mu/\mu_w)^{0.14}$ above $Re_t = 2100$
ϕ_t	$(\mu/\mu_w)^{0.25}$ below $Re_t = 2100$

Note: Friction factors are dimensional, sq ft/sq in, to give ΔP_t in psi directly. To obtain dimensionless friction factors multiply the ordinate by 144.

Figure 8-9. Tube side friction factors.

(12) Tube pressure drop, ΔP_t, psi

$$\Delta P_t = \frac{f_t . G_t^2 . L . n}{2g\rho(ID/12)} \tag{8-31}$$

where $G_t = lb/ft^2.s$
g = acceleration due to gravity, 32.17 ft/sec^2

Alternatively, ΔP_t can be expressed as:

$$\Delta P_t = \frac{f_t . G_t^2 . L . n}{5.22 \times 10^{10} . (ID/12) . s . \phi_t} \tag{8-32}$$

where $G_t = lb/ft^2hr$ and $\phi_t = \mu/\mu_w \approx 1$
s = specific gravity
L = length of tube, ft
n = number of tube passes

(13) The pressure drop of return losses, psi using Frank's [13] correlation is:

$$\Delta P_r = \frac{K . n . \rho . V_t^2}{2g(144)} \tag{8-33}$$

where K is the number of velocity heads loss per tube pass, where K = 2.5

(14) The pressure loss in both nozzles can be estimated from

$$\Delta P_n = 1.5\rho\left(\frac{V_n^2}{2g}\right)\left(\frac{1}{144}\right) \tag{8-34}$$

(15) Total pressure drop ΔP_T, psi

$$\Delta P_T = \Delta P_t + \Delta P_r + \Delta P_n \tag{8-35}$$

If ΔP_t is unacceptable, it is necessary to assume a new pass arrangement and repeat the calculations. The heat transfer coefficient of the shell and tube heat exchanger is only acceptable if the design is within limits of the allowable pressure drop for the streams being heated or cooled. The selection of the optimum allowable pressure drop for an exchanger is a function of the overall process design.

Pressure drop calculations for more complex geometries of shell and tube exchangers, and for plate and spiral plate exchangers, are given by

Sandler and Luckiewicz [14]. The acceptable range of pressure drops in a heat exchanger depends on the system operating pressure. Table 8-2 shows typical pressure drop ranges.

For high pressure drop design, fluid velocity may be the more limiting criterion, but a liquid velocity exceeding 15 ft/s can result in erosion-corrosion in an exchanger.

Shell Side

(1) Equivalent diameter, D_e, is calculated as follows:

$$\text{Square pitch: } D_e = \frac{4 \times \text{free area}}{\text{wetted perimeter}}$$

$$D_e = \frac{4(P_T^2 - \pi.OD^2/4)}{\pi.OD}, \quad \text{inch} \qquad (8\text{-}36)$$

Triangular pitch:

$$D_e = \left(\frac{1.72P_T^2 - 0.5.\pi.OD^2}{0.5.\pi.OD}\right) \qquad (8\text{-}37)$$

Clearance, C, between tubes is:

$$C = P_T - OD \qquad (8\text{-}38)$$

Tube Arrangement

Tubes can be arranged in triangular, square, or rotated square pitch. Triangular tube layouts give better shell side heat transfer coefficients and provide more surface area for a given shell diameter. Alternatively, square pitch or rotated square pitch layouts are used when mechanical

Table 8-2
Acceptable Pressure Drop Range for Shell and Tube Heat Exchanger

SYSTEM PRESSURE	PRESSURE DROP RANGE
Vacuum	5–10% of absolute system pressure.
1–10 psig	0.5–5 psi.
>10 psig	5 psi – 50% of system pressure.

cleaning of the outside of the tube is required. Widely spaced triangular patterns also allow for better cleaning. Both types of square pitches result in less shell-side turbulence and give low pressure drops, but lower heat transfer coefficients than triangular pitch.

Tables 8-3 to 8-10 show estimated tube counts for different square or triangular pitch arrangements. Figure 8-10 shows the tube layouts.

(2) Flow area a_s (assuming a plausible baffle spacing for the pressure drop allowed), is:

Table 8-3
Tube Count for $^{3}/_{8}$-in. OD Tubes on $^{13}/_{16}$-in. Δ Pitch

Tube Count for $^{3}/_{8}$ in. OD Tubes on $^{13}/_{16}$-in. △ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	22	20	16		19	18	12		19	14	12					
6.065	37	30	28		31	26	24		31	26	16					
7.981	68	66	60		61	52	48		56	52	44					
10.02	110	106	96		104	98	84		96	90	76					
12.00	170	164	148		151	142	128		151	138	128					
13.25	212	196	188		178	168	156		187	184	160					
15.25	283	270	252		241	232	220		258	242	224					
17.25	364	348	332		316	298	292		336	326	304					
19.25	454	440	420		396	388	352		421	412	392					
21.25	562	554	524		490	484	456		526	502	480					
23.25	668	646	612		588	570	548		608	598	556					
25.00																
27.00	922	902	868		812	808	764		868	836	804					
29.00																
31.00	1230	1212	1172		1106	1092	1040		1152	1124	1088					
33.00																
35.00	1590	1560	1516		1438	1430	1336		1496	1468	1424					

Tube Count for $^{5}/_{8}$ in. OD Tubes on $^{7}/_{8}$ in. △ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	22	18	16		19	14	12		14	14	12					
6.065	31	30	24		26	26	16		22	20	16					
7.981	61	52	48		55	48	44		51	48	40					
10.02	96	94	80		88	82	76		85	76	72					
12.00	151	138	132		130	124	112		130	120	112					
13.25	187	176	168		151	148	132		163	152	144					
15.25	241	232	224		206	196	184		216	214	196					
17.25	313	302	292		270	266	252		288	282	264					
19.25	396	384	352		336	334	312		358	350	340					
21.25	482	472	456		418	416	396		450	436	416					
23.25	568	554	536		506	492	472		526	506	484					
25.00																
27.00	792	780	752		704	700	660		724	720	696					
29.00																
31.00	1062	1030	1008		946	930	896		994	978	948					
33.00																
35.00	1356	1346	1304		1234	1220	1180		1288	1252	1220					

Courtesy of Tubular Exchanger Manufacturers Association (TEMA).

$$a_s = \frac{ID.C.B}{144.P_T}, \quad ft^2 \tag{8-39}$$

(3) Mass velocity, G_s is:

$$G_s = \frac{W}{a_s}, \quad \left(\frac{lb}{ft^2.hr}\right) \tag{8-40}$$

Table 8-4
Tube Count for 5/8-in. OD Tubes on 7/8-in. □ Pitch

Tube Count for 5/8-in. OD Tubes on 7/8-in. □ Pitch

Shell	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U		
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube		
	No. of Passes				No. of Passes				No. of Passes				No. of Passes		
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6
5.047	21	16	16		13	12	12		12	12	12				
6.065	26	26	24		22	22	16		21	16	16				
7.981	52	52	52		45	44	44		45	38	32				
10.02	89	82	80		76	76	68		74	70	68				
12.00	128	124	120		109	104	92		109	92	88				
13.25	158	158	148		137	128	120		138	136	128				
15.25	213	208	208		177	176	164		188	184	176				
17.25	277	266	264		241	236	220		246	244	240				
19.25	344	332	336		293	284	284		316	308	304				
21.25	420	404	400		366	364	360		394	388	384				
23.25	502	476	488		436	432	432		456	448	444				
25.00															
27.00	694	668	664		612	608	608		640	636	624				
29.00															
31.00	922	910	908		828	812	812		862	848	840				
33.00															
35.00	1181	1166	1160		1070	1064	1048		1122	1112	1100				

Tube Count for 3/4-in. OD Tubes on 15/16-in. △ Pitch

Shell	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	19	14	12		14	14	8		10	10	4		6	4		
6.065	27	26	20	18	22	18	16		19	18	12		14	8		
7.981	55	48	40	38	42	40	36	32	42	40	32	30	32	24		
10.02	85	76	72	68	74	72	60	54	73	66	60	54	56	52		
12.00	126	118	104	98	109	106	96	86	109	106	92	86	92	80		
13.25	151	148	140	134	130	124	112	108	140	138	124	108	114	104		
15.25	206	196	180	176	174	168	156	152	187	184	168	152	83	74		
17.25	268	266	240	230	241	222	216	210	253	242	224	210	220	204		
19.25	340	330	320	302	288	282	264	260	320	294	280	260	290	268		
21.25	416	408	392	384	384	368	344	338	400	380	352	338	360	340		
23.25	499	480	460	456	469	449	430	418	454	436	416	410	220	210		
25.00	576	558	530	516	544	529	500	490	514	498	471	465	506	488		
27.00	675	661	632	596	643	616	600	575	607	587	560	558	614	580		
29.00	790	773	736	720	744	732	704	695	707	690	663	657	720	684		
31.00	896	875	858		859	835	812	800	816	797	769	760	830	804		
33.00	1018	1011	976		973	959	926	900	931	910	876	870	944	916		
35.00	1166	1137	1098		1118	1093	1054	1010	1062	1039	998	993	1076	940		
37.00	1307	1277	1242		1253	1224	1184	1150	1200	1177	1135	1124	1218	1184		
39.00	1464	1425	1386		1392	1359	1318	1286	1341	1318	1282	1264	1366	1324		
42.00	1688	1669	1618		1616	1602	1552	1482	1558	1554	1502	1482	1600	1552		
45.00	1943	1912	1878		1870	1833	1800	1770	1875	1834	1736	1708	1854	1800		
48.00	2229	2189	2134		2145	2107	2060	2025	2132	2100	1998	1964	2122	2064		
51.00	2513	2489	2432		2411	2395	2344	2305	2431	2392	2286	2250	2410	2356		
54.00	2823	2792	2752		2737	2683	2642	2612	2730	2684	2574	2536	2732	2668		
60.00	3527	3477	3414		3400	3359	3294	3220	3395	3346	3228	3196	3398	3336		

Courtesy of TEMA.

(4) Shell velocity, V_s, ft/s is:

$$V_s = \frac{W}{3600.\, a_s \cdot \rho_s} \qquad (8\text{-}41)$$

(5) Reynolds number, Re_s, is:

$$Re_s = \frac{D_e \cdot G_s}{\mu} \qquad (8\text{-}42)$$

Table 8-5
Tube Count for 3/4-in. OD Tubes on 1-in. Δ Pitch

Tube Count for 3/4-in. OD Tubes on 1-in. Δ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell ID in.	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	14	14	12		10	10	8		10	10	4		6	4		
6.065	22	20	16	22	19	18	16		19	14	12		10	8		
7.981	42	40	36	40	38	36	32	28	37	32	28	26	28	24		
10.02	73	72	64	64	64	62	60	58	61	60	48	46	56	44		
12.00	109	86	80	98	96	94	84	78	96	94	80	78	86	72		
13.25	139	134	124	122	121	110	100	98	121	118	104	98	106	96		
15.25	187	180	168	164	151	146	140	138	163	164	144	140	148	136		
17.25	241	232	220	212	208	196	188	160	216	214	196	158	200	184		
19.25	296	290	280	270	258	242	232	230	276	270	260	235	254	240		
21.25	372	354	344	330	320	316	296	298	338	338	324	300	314	300		
23.25	434	420	404	404	380	372	364	335	396	396	376	339	388	368		
25.00	507	489	476	482	475	466	452	430	460	440	420	414	452	432		
27.00	604	594	568	582	530	526	508	495	558	554	536	494	538	524		
29.00	689	679	660	672	653	642	620	610	624	605	589	581	632	612		
31.00	808	804	772		724	696	688	669	756	744	716	669	732	708		
33.00	906	891	860		859	848	818	805	818	797	783	771	838	808		
35.00	1030	1026	1000		946	922	904	880	980	978	944	880	950	916		
37.00	1152	1134	1090		1106	1081	1054	996	1047	1039	1001	996	1074	1040		
39.00	1273	1259	1222		1218	1208	1174	1125	1172	1164	1130	1125	1200	1164		
42.00	1485	1461	1434		1426	1399	1376	1306	1367	1350	1322	1306	1406	1364		
45.00	1721	1693	1650		1652	1620	1586		1635	1608	1536	1504	1632	1584		
48.00	1968	1941	1902		1894	1861	1820		1887	1842	1768	1740	1870	1832		
51.00	2221	2187	2134		2142	2101	2060		2143	2104	2019	1992	2122	2076		
54.00	2502	2465	2414		2417	2379	2326		2399	2366	2270	2244	2396	2340		
60.00	3099	3069	3010		2990	2957	2906		2981	2940	2932	2800	2992	2936		

Tube Count for 3/4-in. OD Tubes on 1-in. □ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell ID in.	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	12	12	12		12	12	4		9	8	4		6	4		
6.065	21	16	16		16	16	12		16	16	12		8	8		
7.981	38	38	32		37	32	32	12	32	32	32	12	24	20		
10.02	61	60	52		57	56	52	24	56	52	52	24	44	40		
12.00	97	90	88		89	82	76	56	89	82	80	56	68	68		
13.25	117	116	112		97	94	88	80	104	104	96	80	90	88		
15.25	158	158	148		137	128	120	114	145	140	140	114	128	120		
17.25	216	208	188		177	176	164	160	188	184	180	160	176	168		
19.25	262	256	244		224	216	208	198	238	236	232	198	112	108		
21.25	316	316	308		274	270	268	260	304	292	284	260	138	134		
23.25	370	372	368		333	332	316	308	344	332	332	308	340	332		
25.00	442	432	428		414	406	392	344	398	386	366	344	400	388		
27.00	524	524	500		464	456	448	424	484	472	468	424	472	460		
29.00	602	596	580		570	562	548	496	554	532	510	496	554	544		
31.00	698	692	688		628	620	612	576	650	648	640	576	640	624		

Courtesy of TEMA.

(7) Prandtl number, Pr_s, is:

$$Pr_s = \frac{c\mu}{k} \tag{8-43}$$

(8) The heat transfer coefficient, h_o, can be expressed as:

$$\frac{h_o . D_e}{k} = 0.36\left(\frac{D_e G_s}{\mu}\right)^{0.55}\left(\frac{c\mu}{k}\right)^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{8-44}$$

Table 8-6
Tube Count for ¾-in. OD Tubes on 1-in. □ Pitch

Tube Count for ¾-in. OD Tubes on 1-in. □ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
33.00	782	768	768		742	732	732	668	730	712	682	668	724	720		
35.00	894	892	880		816	812	804	760	848	828	824	760	836	812		
37.00	1004	978	964		952	931	928	872	937	918	882	872	940	924		
39.00	1102	1096	1076		1062	1045	1026	972	1048	1028	996	972	1048	1040		
42.00	1283	1285	1270		1232	1222	1218	1140	1224	1200	1170	1140	1222	1204		
45.00	1484	1472	1456		1424	1415	1386	1336	1421	1394	1350	1336	1420	1400		
48.00	1701	1691	1670		1636	1634	1602	1536	1628	1598	1548	1536	1624	1604		
51.00	1928	1904	1888		1845	1832	1818	1764	1862	1823	1779	1764	1852	1820		
54.00	2154	2138	2106		2080	2066	2044	1992	2096	2048	2010	1992	2084	2064		
60.00	2683	2650	2636		2582	2566	2556	2476	2585	2552	2512	2476	2596	2564		

Tube Count for ¾-in. OD Tubes on 1-in. ◇ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	12	10	8		12	10	8						4	4		
6.065	21	18	16		16	12	8						10	8		
7.981	37	32	28		32	28	24						24	20		
10.02	61	54	48		52	46	40						42	36		
12.00	97	90	84		81	74	68						66	64		
13.25	113	108	104		97	92	84						86	80		
15.25	156	146	136		140	134	128						124	116		
17.25	208	196	184		188	178	168						174	164		
19.25	256	244	236		241	228	216						218	202		
21.25	314	299	294		300	286	272						272	260		
23.25	379	363	352		359	343	328						334	320		
25.00	448	432	416		421	404	392						390	380		
27.00	522	504	486		489	472	456						468	452		
29.00	603	583	568		575	556	540						550	532		
31.00	688	667	654		660	639	624						626	608		
33.00	788	770	756		749	728	708						720	700		
35.00	897	873	850		849	826	804						818	796		
37.00	1009	983	958		952	928	908						928	904		
39.00	1118	1092	1066		1068	1041	1016						1036	1016		
42.00	1298	1269	1250		1238	1216	1196						1220	1192		
45.00	1500	1470	1440		1432	1407	1378						1412	1384		
48.00	1714	1681	1650		1644	1611	1580						804	788		
51.00	1939	1903	1868		1864	1837	1804						1834	1804		
54.00	2173	2135	2098		2098	2062	2026						2072	2036		
60.00	2692	2651	2612		2600	2560	2520						2584	2544		

Courtesy of TEMA.

For turbulent flow, the viscosity ratio can be omitted, and Equation 8-44 becomes:

$$h_o = 0.36 \frac{k}{D_e} Re_s^{0.55} Pr_s^{0.33} \tag{8-45}$$

Figure 8-11 shows the shell side heat transfer coefficient as a function of the Reynolds number.

Table 8-7
Tube Count for 1-in. OD Tubes on $1^1/_4$-in. △ Pitch

Tube Count for 1-in. OD Tubes on $1^1/_4$-in. △ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	8	6	4		7	4	4						0	0		
6.065	14	14	8		10	10	4						4	4		
7.981	26	26	16		22	18	16	14	18	14	8	12	14	8		
10.02	42	40	36		38	36	28	24	33	28	16	18	26	24		
12.00	64	61	56		56	52	48	46	51	48	42	44	44	36		
13.25	85	76	72		73	72	60	44	73	68	52	44	56	52		
15.25	110	106	100		100	98	88	80	93	90	78	76	86	76		
17.25	147	138	128		130	126	116	104	126	122	112	102	114	104		
19.25	184	175	168		170	162	148	140	159	152	132	136	152	136		
21.25	227	220	212		212	201	188	176	202	192	182	172	192	176		
23.25	280	265	252		258	250	232	220	249	238	216	212	232	220		
25.00	316	313	294		296	294	276	250	291	278	250	240	270	256		
27.00	371	370	358		355	346	328	300	345	330	298	288	322	304		
29.00	434	424	408		416	408	392	360	400	388	356	348	378	364		
31.00	503	489	468		475	466	446	420	459	450	414	400	444	424		
33.00	576	558	534		544	529	510	498	526	514	484	464	508	492		
35.00	643	634	604		619	604	582	566	596	584	548	536	578	560		
37.00	738	709	684		696	679	660	646	672	668	626	608	660	632		
39.00	804	787	772		768	753	730	723	756	736	704	692	740	712		
42.00	946	928	898		908	891	860	840	890	878	834	808	872	836		
45.00	1087	1069	1042		1041	1017	990	968	1035	1008	966	948	1010	980		
48.00	1240	1230	1198		1189	1182	1152	1132	1181	1162	1118	1092	1156	1124		
51.00	1397	1389	1354		1348	1337	1300	1280	1350	1327	1277	1254	1322	1284		
54.00	1592	1561	1530		1531	1503	1462	1440	1520	1492	1436	1416	1496	1452		
60.00	1969	1945	1904		1906	1879	1842	1802	1884	1858	1800	1764	1866	1828		

Tube Count for 1-in. OD Tubes on $1^1/_4$-in. ◇ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	8	6	4		5	4	4						0	0		
6.065	12	10	8		12	10	8						4	4		
7.981	24	20	16		21	18	16						10	8		
10.02	37	32	28		32	32	28						24	10		
12.00	57	53	48		52	46	40						36	32		
13.25	70	70	64		61	58	56						50	44		
15.25	97	90	84		89	82	76						70	64		
17.25	129	120	112		113	112	104						96	88		
19.25	162	152	142		148	138	128						124	120		
21.25	205	193	184		180	174	168						156	152		
23.25	238	228	220		221	210	200						200	188		
25.00	275	264	256		261	248	236						232	220		
27.00	330	315	300		308	296	286						282	268		
29.00	379	363	360		359	345	336						330	320		
31.00	436	422	410		418	401	388						382	368		

Courtesy of TEMA.

Pressure Drop (ΔP)

(9) From the fluid Reynolds number, Re_s, obtain the friction factor, f_s, from Figure 8-12. A regression method of Figure 8-12 shows that for $\mathrm{Re}_s < 500$,

$$f_s = \frac{0.11183}{\mathrm{Re}_s^{0.59246}} \tag{8-46}$$

Table 8-8
Tube Count for 1-in. OD Tubes on 1¼-in. ◇ Pitch

Tube Count for 1-in. OD Tubes on 1¼-in. ◇ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
33.00	495	478	472		477	460	448						440	424		
35.00	556	552	538		540	526	508						498	484		
37.00	632	613	598		608	588	568						562	548		
39.00	705	685	672		674	654	640						630	620		
42.00	822	799	786		788	765	756						744	728		
45.00	946	922	912		910	885	866						872	852		
48.00	1079	1061	1052		1037	1018	1000						1002	980		
51.00	1220	1159	1176		1181	1160	1142						1138	1116		
54.00	1389	1359	1330		1337	1307	1292						1292	1264		
60.00	1714	1691	1664		1658	1626	1594						1604	1576		

Tube Count for 1-in. OD Tubes on 1¼-in. □ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
Shell	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	9	6	4		5	4	4	–	5	4	4	–	0	0		
6.065	12	12	12		12	6	4	–	12	6	4	–	4	4		
7.981	22	20	16		21	16	16	12	17	12	8	12	12	8		
10.02	38	38	32		32	32	32	18	30	30	16	18	24	20		
12.00	56	56	52		52	52	44	24	52	48	42	24	38	36		
13.25	69	66	66		61	60	52	50	61	56	52	50	52	48		
15.25	97	90	88		89	84	80	64	85	78	62	64	72	68		
17.25	129	124	120		113	112	112	96	108	108	104	96	98	96		
19.25	164	158	148		148	144	140	114	144	136	130	114	128	124		
21.25	202	191	184		178	178	172	156	173	166	154	156	166	156		
23.25	234	234	222		216	216	208	192	217	208	194	192	200	196		
25.00	272	267	264		258	256	256	212	252	240	230	212	240	232		
27.00	328	317	310		302	300	296	260	296	280	270	260	284	276		
29.00	378	370	370		356	353	338	314	345	336	310	314	332	332		
31.00	434	428	428		414	406	392	368	402	390	366	368	290	384		
33.00	496	484	484		476	460	460	420	461	452	432	420	442	436		
35.00	554	553	532		542	530	518	484	520	514	494	484	254	248		
37.00	628	621	608		602	596	580	550	588	572	562	548	574	560		
39.00	708	682	682		676	649	648	625	661	640	624	620	644	628		
42.00	811	811	804		782	780	768	730	776	756	738	724	758	748		
45.00	940	931	918		904	894	874	850	900	882	862	844	872	868		
48.00	1076	1061	1040		1034	1027	1012	980	1029	1016	984	972	1002	988		
51.00	1218	1202	1192		1178	1155	1150	1125	1170	1156	1126	1114	1146	1140		
54.00	1370	1354	1350		1322	1307	1284	1262	1310	1296	1268	1256	1300	1288		
60.00	1701	1699	1684		1654	1640	1632	1585	1641	1624	1598	1576	1620	1604		

Courtesy of TEMA.

for $Re_s > 500$,

$$f_s = \frac{0.1159}{Re_s^{0.18597}} \tag{8-47}$$

The shell side pressure drop, ΔP_s, is:

$$\Delta P_s = \left\{ \frac{f_s . G_s^2 . (ID/12) . (N+1)}{2 . g . \rho . D_e \phi_s} \right\} (N_s) \tag{8-48}$$

Table 8-9
Tube Count for $1\frac{1}{4}$-in. OD Tubes on $1\frac{9}{16}$-in. △ Pitch

Tube Count for $1\frac{1}{4}$-in. OD Tubes on $1\frac{9}{16}$-in. △ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
Shell ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	7	4	4		0	0	0	–					0	0		
6.065	8	6	4		7	6	4	–					0	0		
7.981	19	14	12		14	14	8	–					6	4		
10.02	29	26	20		22	20	16	–					14	12		
12.00	42	38	34		37	36	28	22					22	20		
13.25	52	48	44		44	44	36	28					32	28		
15.25	69	68	60		64	62	48	45					48	44		
17.25	92	84	78		85	78	72	69					64	60		
19.25	121	110	104		109	102	96	86					86	80		
21.25	147	138	128		130	130	116	112					114	104		
23.25	174	165	156		163	152	144	130					138	132		
25.00	196	196	184		184	184	172	164					162	152		
27.00	237	226	224		221	216	208	196					196	184		
29.00	280	269	256		262	252	242	228					232	220		
31.00	313	313	294		302	302	280	270					268	256		
33.00	357	346	332		345	332	318	305					310	296		
35.00	416	401	386		392	383	364	357					356	344		
37.00	461	453	432		442	429	412	407					404	388		
39.00	511	493	478		493	479	460	449					452	440		
42.00	596	579	570		576	557	544	512					534	522		
45.00	687	673	662		657	640	628	596					626	612		
48.00	790	782	758		756	745	728	696					720	700		
51.00	896	871	860		859	839	832	820					822	800		
54.00	1008	994	968		964	959	940	892					930	908		
60.00	1243	1243	1210		1199	1195	1170	1116					1160	1140		

Tube Count for $1\frac{1}{4}$-in. OD Tubes on $1\frac{1}{16}$-in. □ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
Shell ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	4	4	4		0	0	0	0	0	0	0	0	0	0		
6.065	6	6	4		6	6	4	0	6	6	4	0	0	0		
7.981	12	12	12		12	12	12	0	12	12	4	0	6	4		
10.02	24	22	16		21	16	16	12	21	12	8	12	12	8		
12.00	37	34	32		32	32	32	18	29	28	16	18	20	20		
13.25	45	42	42		38	38	32	24	38	34	34	24	28	28		
15.25	61	60	52		52	52	52	48	52	48	44	48	42	36		
17.25	80	76	76		70	70	68	50	70	66	56	50	56	56		
19.25	97	95	88		89	88	88	80	85	84	70	80	74	68		
21.25	124	124	120		112	112	112	96	108	108	100	96	98	96		
23.25	145	145	144		138	138	130	114	136	128	128	114	124	120		
25.00	172	168	164		164	164	156	136	154	154	142	136	140	136		

Courtesy of TEMA.

where G_s = lb/ft^{2}hr and $f_s = \mu/\mu_w \approx 1$

g = acceleration due to gravity, 4.18×10^8 ft/hr^2

ρ = density, lb/ft^3

N_s = number of shells per unit

Alternatively, ΔP_s can be expressed as:

$$\Delta P_s = \left\{ \frac{f_s . G_s^2 . (ID/12) . (N+1)}{5.22 \times 10^{10} . D_e . s . \phi_s} \right\} (N_s) \tag{8-49}$$

Table 8-10
Tube Count for $1^1/_4$-in. OD Tubes on $1^9/_{16}$-in. □ Pitch

Tube Count for $1^1/_4$-in. OD Tubes on $1/_{16}$-in. □ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
Shell ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
27.00	210	202	202		193	184	184	172	184	180	158	172	176	176		
29.00	241	234	230		224	224	216	198	217	212	204	198	200	196		
31.00	272	268	268		258	256	256	236	252	248	234	236	232	232		
33.00	310	306	302		296	296	282	264	289	276	270	264	272	268		
35.00	356	353	338		336	332	332	304	329	316	310	304	312	296		
37.00	396	387	384		378	370	370	358	372	368	354	340	348	348		
39.00	442	438	434		428	426	414	408	420	402	402	392	396	392		
42.00	518	518	502		492	492	484	464	485	476	468	464	472	456		
45.00	602	602	588		570	566	556	544	565	554	546	544	552	536		
48.00	682	681	676		658	648	648	620	653	636	628	620	628	620		
51.00	770	760	756		742	729	722	712	738	726	720	705	712	708		
54.00	862	860	856		838	823	810	804	837	820	812	804	808	804		
60.00	1084	1070	1054		1042	1034	1026	1008	1036	1028	1012	1008	1012	992		

Tube Count for $1^1/_4$-in. OD Tubes on $1^9/_{16}$-in. ◇ Pitch

	TEMA Type L or M				TEMA Type P				TEMA Type S				TEMA Type U			
	Fixed Tubesheet				Outside Packed Floating Head				Inside Floating Head				U-Tube			
	No. of Passes				No. of Passes				No. of Passes				No. of Passes			
Shell ID in.	1	2	4	6	1	2	4	6	1	2	4	6	2	4	6	8
5.047	5	4	4		0	0	0						0	0		
6.065	6	6	4		5	4	4						0	0		
7.981	13	10	8		12	10	8						4	4		
10.02	24	20	16		21	18	16						12	12		
12.00	37	32	28		32	28	28						20	20		
13.25	45	40	40		37	34	32						26	24		
15.25	60	56	56		52	52	48						40	36		
17.25	79	76	76		70	70	64						56	52		
19.25	97	94	94		90	90	84						74	68		
21.25	124	116	112		112	108	104						96	88		
23.25	148	142	136		140	138	128						120	112		
25.00	174	166	160		162	162	156						142	136		
27.00	209	202	192		191	188	184						170	164		
29.00	238	232	232		442	430	416						200	192		
31.00	275	264	264		261	249	244						228	220		
33.00	314	307	300		300	286	280						268	256		
35.00	359	345	334		341	330	320						306	296		
37.00	401	387	380		384	372	360						346	336		
39.00	442	427	424		428	412	404						390	380		
42.00	522	506	500		497	484	472						456	448		
45.00	603	583	572		575	562	552						542	528		
48.00	682	669	660		660	648	640						618	604		
51.00	777	762	756		743	728	716						708	692		
54.00	875	857	850		843	822	812						802	784		
60.00	1088	1080	1058		1049	1029	1016						1010	984		

Courtesy of TEMA.

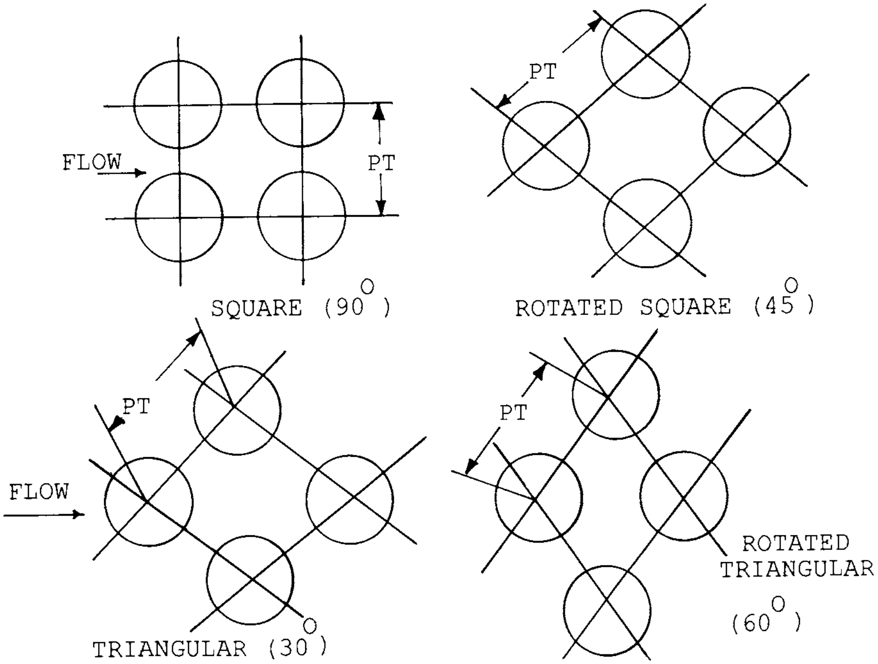


Figure 8-10. Tube layouts.

where G_s = lb/ft^{2}hr and $\phi_t = \mu/\mu_w \approx 1$
s = specific gravity
N = number of baffles
N_s = number of shells per unit.

If ΔP_s is unacceptable, assume a new baffle spacing.

(10) The overall heat transfer coefficient, U, is:

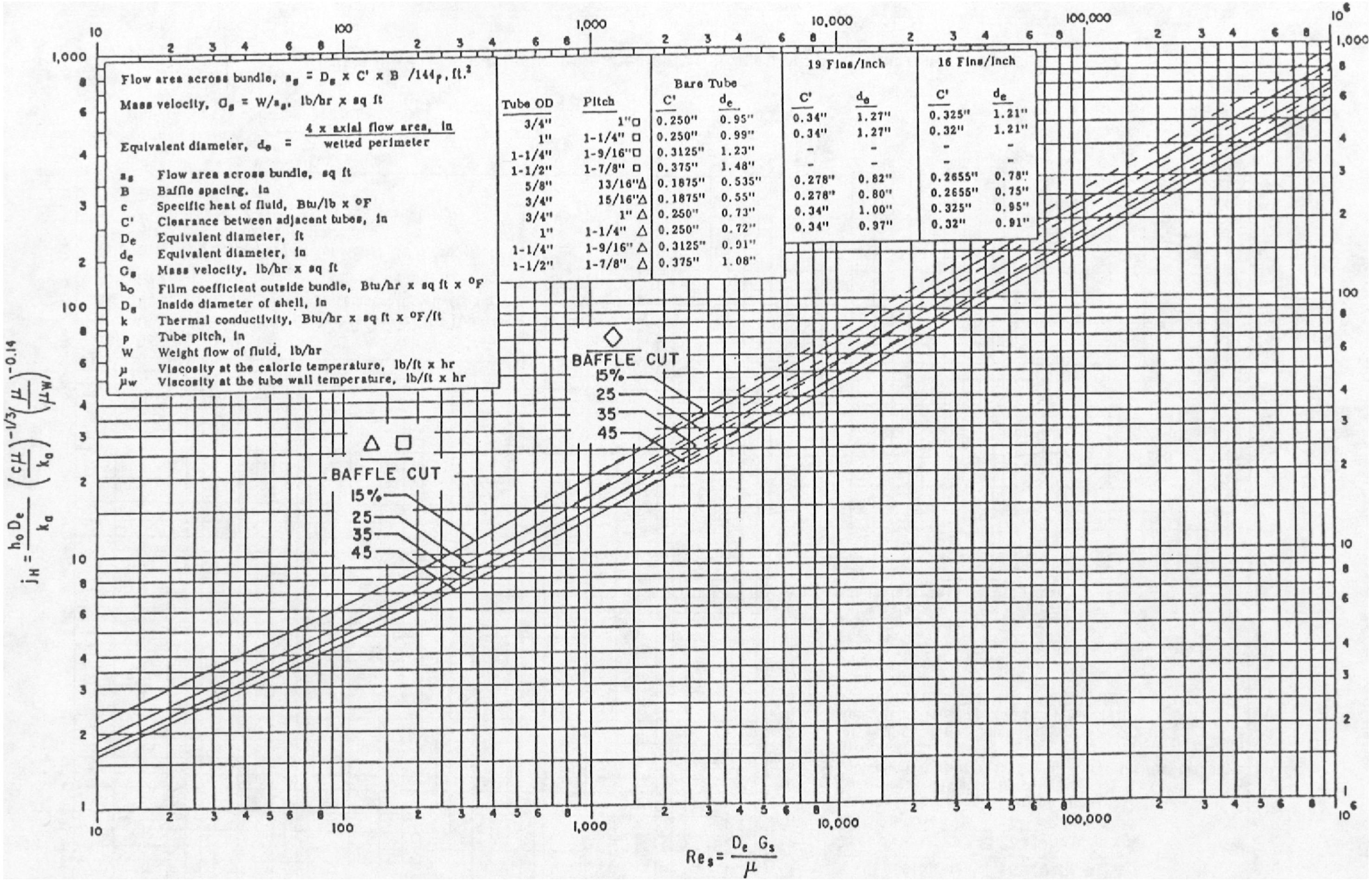
$$U = \frac{1}{\dfrac{1}{h_{io}} + \dfrac{1}{h_o} + F_T + F_s}, \quad \frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F}} \tag{8-50}$$

(11) The outside area of the heat exchanger unit A, ft^2 can be expressed as:

$$A = \left(\frac{OD_t}{12}.\pi.n.N_s.L\right) \tag{8-51}$$

(12) Heat load on unit Q, Btu/hr, is:

$$Q = U.A.\Delta t \tag{8-52}$$



Flow area across bundle, $a_s = D_s \times C' \times B / 144_p$, ft.^{2}

Mass velocity, $G_s = W/a_s$, lb/hr x sq ft

Equivalent diameter, $d_e = \frac{4 \text{ x axial flow area, in}}{\text{wetted perimeter}}$

a_s	Flow area across bundle, sq ft
B	Baffle spacing, in
c	Specific heat of fluid, Btu/lb x °F
C'	Clearance between adjacent tubes, in
D_e	Equivalent diameter, ft
d_e	Equivalent diameter, in
G_s	Mass velocity, lb/hr x sq ft
h_o	Film coefficient outside bundle, Btu/hr x sq ft x °F
D_s	Inside diameter of shell, in
k	Thermal conductivity, Btu/hr x sq ft x °F/ft
p	Tube pitch, in
W	Weight flow of fluid, lb/hr
μ	Viscosity at the caloric temperature, lb/ft x hr
μ_w	Viscosity at the tube wall temperature, lb/ft x hr

Tube OD	Pitch	Bare Tube		19 Fins/Inch		16 Fins/Inch	
		C'	d_e	C'	d_e	C'	d_e
3/4"	1" □	0.250"	0.95"	0.34"	1.27"	0.325"	1.21"
1"	1-1/4" □	0.250"	0.99"	0.34"	1.27"	0.32"	1.21"
1-1/4"	1-9/16" □	0.3125"	1.23"	-	-	-	-
1-1/2"	1-7/8" □	0.375"	1.48"	-	-	-	-
5/8"	13/16" △	0.1875"	0.535"	0.278"	0.82"	0.2655"	0.78"
3/4"	15/16" △	0.1875"	0.55"	0.278"	0.80"	0.2655"	0.75"
3/4"	1" △	0.250"	0.73"	0.34"	1.00"	0.325"	0.95"
1"	1-1/4" △	0.250"	0.72"	0.34"	0.97"	0.32"	0.91"
1-1/4"	1-9/16" △	0.3125"	0.91"				
1-1/2"	1-7/8" △	0.375"	1.08"				

Figure 8-11. Shell-side heat transfer parameter J_H versus N_{Re} for various baffle cuts.

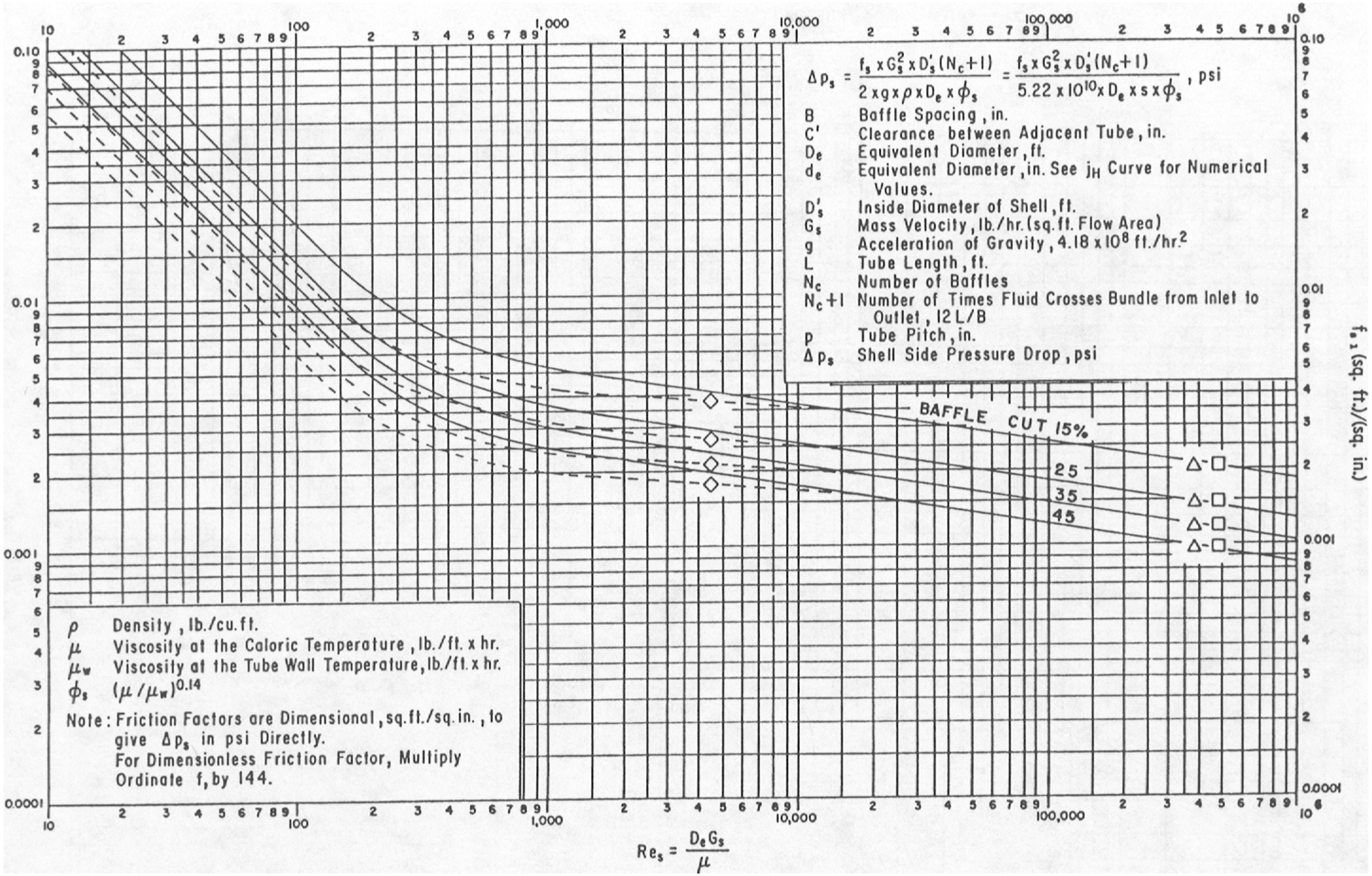


Figure 8-12. Friction factors for shell-side surfaces of low-finned and bare tubes.

Fouling

The scale or fouling resistances represent a necessary safety factor that increases the surface of the heat exchanger. This enables the full process duty requirements to be attained between cleaning periods. When an exchanger is first placed in operation there is no dirt or scale on the tubes; consequently, the overall resistance consists of the two film and the tube wall resistances. During operation, dirt or scale accumulates on the surface of the tubes and the overall heat transfer rate decreases as the dirt buildup increases. The rate of this scale or dirt depends on the cleanliness or fouling tendencies of the process fluids.

The fouling experienced in most CPI operations are due to:

Crystallization. When salts having an inverse solubility characteristic precipitate on a heat transfer surface hotter than the flowing fluid.

Sedimentation. Caused by deposits of particulate matter such as clay, sand, or rust.

Corrosion. When the heat transfer surface material reacts with the fluid to yield corrosion deposits.

Chemical reaction product buildup. Caused by organic products and polymers. The surface temperature and presence of reactants, particularly oxygen, can have a very significant effect on the rate of accumulation.

Coking. On high temperature surface results in hydrocarbon deposits.

Biofouling. Deposits formed when biological mechanisms attach and grow on the heat transfer surface. Untreated cooling water systems are particularly susceptible to biofouling.

The range of overall heat transfer coefficients (U) is about 10 – 200 Btu/hr ft^2°F. Table 8-11 lists the U-values for various types of equipment, and fouling factors of some flowing media are shown in Table 8-12. Table 8-13 illustrates a heat exhanger specification form. Factors governing the selection of process fluids in the tube and shell sides of an exchanger are illustrated in Table 8-14.

Nomenclature

A = outside area of the heat exchanger unit, ft^2

a_t = flow area, ft^2

(text continued on page 628)

Table 8-11
Ranges of Overall Heat Transfrer Coefficients in Various Types of Exchangers
[U Btu/hrft^2°F]

Equipment	Process	U
Shell-and-tube exchanger	gas (1atm)–gas (1atm)	1–6
	gas (250atm)–gas (250atm)	25–50
	liquid–gas (1atm)	2–12
	liquid–gas (250atm)	35–70
	liquid–liquid	25–200
	liquid–condensing vapor	50–200
Double-pipe exchanger	gas (1atm)–gas (1atm)	2–6
	gas (250atm)–gas (250atm)	25–90
	liquid–gas (250atm)	35–100
	liquid–liquid	50–250
Irrigated tube bank	water–gas (1atm)	3–10
	water–gas (250atm)	25–60
	water–liquid	50–160
	water–condensing vapor	50–200
Plate exchanger	water–gas (1atm)	3–10
	water–liquid	60–200
Spiral exchanger	liquid–liquid	120–440
liquid-condensing steam		160–600
Compact exchanger	gas (1atm)–gas (1atm)	2–6
	gas (1atm)–liquid	3–10
Stirred tank, jacketed	liquid–condensing steam	90–260
	boiling liquid–condensing steam	120–300
	water–liquid	25–60
Stirred tank, coil inside	liquid–condensing steam	120–440
	water–liquid	90–210

Source: S. M. Walas, Chemical Process Equipment—Selection and Design, Butterworths Series in Chemical Engineering.

Table 8-12
Recommended Minimum Fouling Resistances

Gases and Vapors	Fouling Factor
Centrifugal Compressor exhaust	0.001
Reciprocating Compressor exhaust	0.01
Reciprocating Compressor refrigerant vapor	0.0025
Centrifugal compressor refrigerant vapor	0.0015
Oil-free and clean high-quality steam	0.0003
Oil-free and clean low-quality steam	0.0005
Oil-bearing steam	0.001
Compressed air	0.002
Acid gas	0.001
Solvent vapors	0.001
Natural gas	0.001
Liquids	
Bay water	0.0025
Distilled water	0.0005
Hard well water	0.0033
Untreated cooling tower water	0.0033
Treated cooling tower water	0.0015
Engine jacket water	0.0012
Treated boiler feed water	0.0015
Fuel oils	0.006
Clean organic solvents	0.001
Vegetable oils	0.004
Refrigerant liquids	0.001
Industrial heat transfer oils	0.001
Hydraulic fluid	0.001
Natural gasoline and liquefied petroleum gases	0.001
Rich oil	0.001
Lean oil	0.002

Table 8-13
Heat Exchanger Specification Sheet (Courtesy of Procede)

Heat Exchanger data sheet (PROCEDE)	Equipment No. (Tag) Descript. (Func.) Sheet No.

Operating Data								1 2
SIZE		TYPE			No. OF UNITS			3
SHELLS PER UNIT		HORIZONTAL CONNECTED IN (parallel or series)						4
SURFACE PER UNIT		SURFACE PER SHELL						5

Performance of one Unit							6 7
	SHELL SIDE			TUBE SIDE			8
FLUID CIRCULATING							9
TOTAL FLUID ENTERING							10
	IN		OUT	IN		OUT	11
VAPOUR							12
LIQUID							13
STEAM							14
WATER							15
NON-CONDENSABLES							16
FLUID VAPOURISED OR CONDENSED							17
SPECIFIC GRAVITY LIQUID							18
Mol Wt VAPOUR							19
Mol Wt NON-CONDENSABLES							20
VISCOSITY LIQUID							21
LATENT HEAT							22
SPECIFIC HEAT							23
THERMAL CONDUCTIVITY							24
TEMPERATURE							25
OPERATING PRESSURE							26
VELOCITY							27
No. OF PASSES							28
PRESSURE DROP	ALLOW		CALC.	ALLOW		CALC.	29
FOULING RESISTANCE							30
HEAT EXCHANGED			MTD (CORRECTED)				31
TRANSFER RATE SERVICE			CLEAN				32

Construction of one Shell										33 34
DESIGN PRESSURE										35
TEST PRESSURE										36
DESIGN TEMPERATURE										37
METAL TEMPERATURE										38
TUBES		No. OD		THICKNESS		LENGTH		PITCH		39
SHELL		I.D.				SHELL COVER				40
CHANNEL		CHANNEL COVER				FLTNG HEAD COVER				41
TUBE SHEET STATIONARY						FLOATING				42
BAFFLES CROSS		TYPE				SPACING % CUT				43
TUBE SUPPORTS		TYPE				SPACING				44
LONG BAFFLE		TYPE				SEAL				45
IMPINGEMENT BAFFLE		TYPE				SEAL STRIPS				46
TYPE OF JOINT		TUBE				TUBE ATTACHMT				47
GASKETS SHELL IN		CHANNEL				FLOATING HEAD				48
CONNECTIONS SHELL IN		INTERCONN				SHELL OUT				49
CONNECTIONS CHANNEL IN		INTERCONN				CHANNEL OUT				50
CORROSION ALLOWABLE SHELL SIDE						TUBE SIDE				51
EXPANSION BELLOWS		BOLTS				NUTS				52
DESIGN CODE		X-RAY				S.R.				53
INSPECTION		PAINTING				INSULATION				54
WEIGHT OF ONE UNIT EMPTY		OPERATING				DATE OF ENQUIRY				55
DATE OF ORDER		ORDER No.				DRG. No.				56
INSPECTION FITTING ATTACHMENT BY		MANUFACTURER								57

Prepared				3				6				58
Checked				2				5				59
Approved				1				4				60
	Date	Engineering	Process	REV	By	Appr.	Date	REV	By	Appr.	Date	61

Service	Company	Address	62
Equipment No.			63
Project No.			64

Table 8-14
Factors Which Influence the Selection Process Fluids in a Shell and Tube Heat Exchanger

Tube Side	Shell Side
CORROSION: When special alloy materials are necessary to minimize corrosion. It is more economical to place the corrosive fluids in the tubes. Only the tubes, tube sheets and channel need to be alloy. In comparison, if the shell side was selected, the shell side and baffles would have to be alloy in addition to the tubes and tube sheets.	CONDENSING SERVICE: The large free area on the shell side permits minimum pressure drop arrangements as well as higher condensate loadings.
EXCESSIVE FOULING: If mechanical cleaning is desired, the fouling medium should be placed in the tube side. This enables the tubes to be cleaned without removing the bundle from the shell.	BOILING SERVICE: Vapor disengaging space may be provided on the shell side which eliminates the need for a separate dry drum.
HIGH TEMPERATURE: If high temperature service requires special alloy construction, the cost of an alloy shell and bonnet will be saved by using the tube side.	CRITICAL PRESSURE DROP: By varying the baffle, spacing, very low pressure drops may be attained.
HIGH PRESSURE: Tubes, tube sheets, and channel need be designed only for high pressure if the tube side is utilized. Also, integral tube sheet and channel design may be used, thus eliminating one gasketed joint.	VISCOUS FLUIDS: If mechanical cleaning is not required, higher heat transfer rates may be obtained by placing the viscous fluid on the shell side. Due to the flow pattern across the tube bank, turbulent flow may be maintained on the shell side at mass velocities which would yield laminar flow on the tube side.

Source: Morton [7]

(text continued from page 623)

a_s = flow area, ft^2
B = baffle spacing, inch
C = clearance between adjacent tube, inch
D_e = equivalent diameter, ft
F_c = temperature difference correction factor, $\Delta t = (F_c)(LMTD)$
F_T = tube side fouling factor, hr ft^2°F/Btu
F_S = shell side fouling factor, hr ft^2°F/Btu
f_t = tube side friction factor (ft^2/in^2)
f_s = shell side friction factor (ft^2/in^2)
G_t = tube side mass velocity, (lb/ft^2hr) or (lb/ft^2sec)
G_s = shell side mass velocity, (lb/ft^2hr)
g = acceleration due to gravity, 32.17 ft/sec^2 (4.18×10^8 ft/hr^2)
h_i, h_o = heat transfer coefficient for inside and outside fluids, respectively, Btu/hrft^2°F
h_{io} = value of hi when referred to the tube outside diameter,
ID = inside diameter, inch (ft)
j_H = factor for heat transfer, dimensionless.
k = thermal conductivity, Btu/ hrft°F
L = tube length, ft
LMTD = log mean temperature difference, °F
N = number of shell side baffles
N_s = number of shells per unit
N_t = number of tubes
n = number of tube passes
OD = outside diameter, inch
P = temperature group $(t_2 - t_1)/(T_1 - t_1)$
P_r = prandtl number, dimensionless
P_t = tube pitch, inch
ΔP_T, ΔP_t = total, tube side pressure drop, psi.
ΔP_r, ΔP_n = return and nozzle side pressure drops, psi
ΔP_s = shell side pressure drop, psi
Q = heat flow, Btu/hr
R = temperature group $(T_1 - T_2)/(t_2 - t_1)$, dimensionless
Re = reynolds number, dimensionless.
R_d = combined dirt factor, hr ft^2°F/Btu
T_1 = hot fluid inlet temperature, °F
T_2 = hot fluid outlet temperature, °F
t_1 = cold fluid inlet temperature, °F
t_2 = cold fluid outlet temperature, °F
Δt = true temperature difference, °F

U = overall heat transfer coefficient, Btu/hrft^2°F
V_n = nozzle side fluid velocity, ft/s
V_s = shell side fluid velocity, ft/s
V_t = tube side fluid velocity, ft/s
W = mass flow rate of hot fluid, lb/hr
w = mass flow rate of cold fluid, lb/hr
ϕ = viscosity ratio, $(\mu/\mu_w)^{0.14}$
μ = fluid viscosity, cP × 2.42 = lb/ft. hr.
ρ = fluid density, lb/ft^3

Subscripts

s = shell
t = tube

DOUBLE PIPE HEAT EXCHANGER

A double pipe exchanger consists of one or more pipes or tubes inside a pipe shell. Basically two straight pipe lengths are connected at one end to form a U or "hair-pin." Longitudinal fins may be used on the outside of the inner tube. The flow is true countercurrent, which can be beneficial when very close temperature approaches or very long temperature ranges are required. Such an exchanger is used in service when the heat duty is moderate (that is, $UA < 100{,}00$ Btu/hr°F), or when one stream is a viscous liquid, or when flow rates are small. This type of exchanger is suitable for high pressure applications because of their smaller diameters. Also, several hairpin sections provide for flexibility in matching heat exchanger requirements with changing process conditions. A double pipe exchanger is suited for "dirty" service because it is easy to dismantle and clean. In addition, a pipe exchanger can be considered in the following situations:

1. When the shell side coefficient is less than half that of the tube side; the annular side coefficient can be made comparable to the tube side.
2. When a high pressure can be catered for more economically in the annulus than in a larger diameter shell.
3. At duties requiring 100 – 200 ft^2 of the surface, which make it more economical.
4. When a true countercurrent flow can be obtained, thus eliminating temperature crosses that require multishell shell and tube units.

The equations required for the rating of a double pipe exchanger are as follows.

The Equations

Process Conditions Required

Hot fluid: T_1, T_2, W, C, μ, k, ΔP, R_D, s or ρ

Cold fluid: t_1, t_2, w, c, μ, k, ΔP, R_D, s or ρ

The diameter of the pipe must be given or assumed. The fluids' velocities must be in the range of 3–10 ft/sec. The following assumes that the cold fluid is in the inner pipe.

(1) The heat duty Q, Btu/hr, is:

$$Q = WC(T_1 - T_2) = wc(t_2 - t_1) \tag{8-53}$$

(2) The log mean temperature difference (LMTD).

$$\text{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left\{\dfrac{T_1 - t_2}{T_2 - t_1}\right\}} \tag{8-5}$$

Inner Pipe

(3) The flow area, a_p:

$$a_p = \frac{\pi D^2}{4}, \quad ft^2 \tag{8-54}$$

(4) The mass velocity, G_p

$$G_p = \frac{w}{a_p}, \quad \frac{lb}{ft^2 hr} \tag{8-55}$$

(5) The Reynolds number, Re_t

$$Re_t = \frac{D.G_p}{\mu} \tag{8-56}$$

(6) The Prandtl number, Pr_t

$$Pr_t = \frac{c.\mu}{k} \tag{8-57}$$

(7) The heat transfer coefficient, h_i, Btu/hrft^2°F

$$\frac{h_i . D}{k} = C\left(\frac{D . G_p}{\mu}\right)^{0.8}\left(\frac{c . \mu}{k}\right)^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{8-58}$$

h_i can be expressed by

$$h_i = C.\left(\frac{k}{D}\right) Re_t^{0.8}\ Pr_t^{0.33} \tag{8-59}$$

where $\mu/\mu_w = 1$
C = 0.021 for gases
C = 0.023 for non-viscous fluids
C = 0.027 for viscous fluids

converting h_i to h_{io}, the heat transfer coefficient referred to the pipe outside diameter, Btu/hrft^2°F

$$h_{io} = h_i\left(\frac{\text{inside dia. of inner pipe}}{\text{outside dia. of inner pipe}}\right)$$

$$= h_i . \frac{ID}{OD} \tag{8-60}$$

Annulus

(8) The flow area, a_a:

$$a_a = \frac{\pi(D_o^2 - D_i^2)}{4}, \quad ft^2 \tag{8-61}$$

(9) The equivalent diameter, D_e

$$D_e = \frac{4 \times \text{flow area}}{\text{wetted perimeter}}$$

$$= \frac{D_o^2 - D_i^2}{D_i}, \quad ft \tag{8-62}$$

(10) The mass velocity, G_a

$$G_a = \frac{w}{a_a}, \quad \frac{lb}{ft^2 hr} \tag{8-63}$$

(11) The Reynolds number, Re_a

$$Re_a = \frac{D_e . G_a}{\mu} \tag{8-64}$$

(12) The Prandtl number, Pr_a

$$Pr_a = \frac{c . \mu}{k} \tag{8-65}$$

(13) The heat transfer coefficient, h_o

If $Re_a < 2100$

$$h_o = 1.86 \frac{k}{D_e} Re_a^{0.33} Pr_a^{0.33} \left(\frac{D_e}{L} \right)^{0.33} \tag{8-66}$$

If $Re_a > 2100$

$$h_o = C . \frac{k}{D_e} Re_a^{0.8} Pr_a^{0.33} \tag{8-67}$$

(14) The overall coefficient, U, Btu/hr. ft.^{2} °F

$$\frac{1}{U} = \frac{1}{h_{io}} + \frac{1}{h_o} + R_D + R_w \tag{8-68}$$

(15) The heat transfer area, A, ft^2

$$A = \frac{Q}{U_D . LMTD} \tag{8-69}$$

Vapor Service

(16) The heat transfer coefficient, h_i, Btu/hrft^{2}° F

$$h_i = \frac{0.0144 C_p G^{0.8}}{D_e^{0.2}} \tag{8-70}$$

and

$$\frac{1}{h_{if}} = \frac{1}{h_i} + Fol \quad (h_i \text{ is corrected for fouling}) \tag{8-71}$$

Shell Side (Finned Tube)

Figure 8-13 shows examples of extended surfaces on one or both sides of heat exchangers.

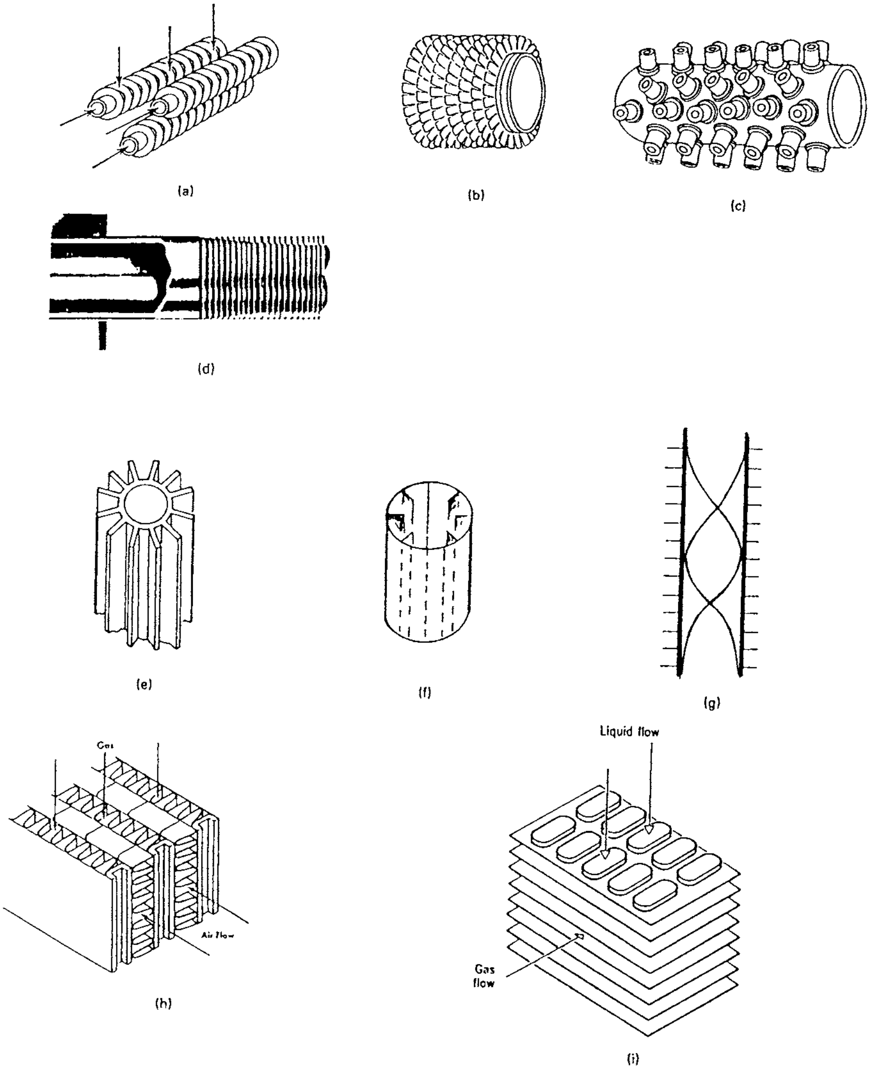


Figure 8-13. Examples of extended surfaces on one or both sides. (a) Radial fins. (b) Serrated radial fins. (c) Studded surface. (d) Joint between tubesheet and low fin tube with three times bare surface. (e) External axial fins. (f) Internal axial fins. (g) Finned surface with internal spiral to promote turbulence. (h) Plate fins on both sides. (i) Tubes and plate fins. Source: S. M. Walas, *Chemical Process Equipment: Selection and Design*, Butterworths Series in Chemical Engineering, 1988.

(17) The equivalent diameter, D_e, ft

$$D_e = \frac{4NFA}{\pi(D_{s,i} + D_{t,o}) - N\theta + 2HN} \tag{8-72}$$

(18) The net free cross-sectional area, NFA, shell side, ft^2

$$NFA = CSA - NH\theta \tag{8-73}$$

(19) The cross-sectional area without fins, CSA, ft^2

$$CSA = \frac{\pi}{4}(D_{s,i}^2 - D_{t,o}^2) \tag{8-74}$$

(20) Finned surface area, ft^2

$$A_f = 2HN \tag{8-75}$$

(21) Outside heat transfer area of tube, ft^2/ft (for finned tubes includes fin area)

$$A_o = \pi D_{t,o} + A_f \tag{8-76}$$

(22) Parameter for fin efficiency, X

$$X = H\left(\frac{h_{if}}{6K_t\theta}\right)^{0.5} \tag{8-77}$$

(23) The fin efficiency, e

$$e = \frac{\tanh X}{X} = \frac{1}{X}\left[\frac{\exp(X) - \exp(-X)}{\exp(X) + \exp(-X)}\right] \tag{8-78}$$

(24) The effective surface efficiency for fins, e_{eff},

$$e_{eff} = e\left(\frac{A_f}{A_o}\right) + \left(1 - \frac{A_f}{A_o}\right) \tag{8-79}$$

(25) The corrected film heat transfer coefficient, h_{ifd}, Btu/ft^{2}hr°F

$$h_{ifd} = (h_{if})(e_{eff}) \tag{8-80}$$

(26) The overall heat transfer coefficient, U, Btu/ft^{2}hr°F

$$\frac{1}{U} = \left(\frac{\Delta w}{K_t}\right)_{\text{tube wall}} + \frac{1}{h_i\left(\frac{A_i}{A_o}\right)_{\text{tube}}} + \frac{1}{(h_{ifd})_{\text{shell}}} \tag{8-81}$$

where

$$\frac{A_i}{A_o} = \frac{\pi D_{t,i}}{\pi D_{t,o} + 2HN} \tag{8-82}$$

Pressure Drop, ΔP

(27) The pressure drop in tubes is:

$$\Delta F = \frac{4fG^2L}{2g\rho^2 D} \quad \text{(ft of liquid)} \tag{8-83}$$

where

$$f = \frac{16}{Re} \text{ for } Re < 2,300 \tag{8-84}$$

Using, Wilson *et al.* [15] correlation for commercial pipe

$$f = 0.0035 + \frac{0.264}{Re^{0.42}} \text{ for } Re < 2,300 \tag{8-85}$$

$$\Delta P_p = \left(\frac{\Delta F.\rho}{144}\right), \quad \text{psi} \tag{8-86}$$

Annulus

For an annulus, D'_e is:

$$D'_e = \frac{4\pi(D_o^2 - D_i^2)}{4\pi(D_o + D_i)}$$

$$= D_o - D_i \tag{8-87}$$

Reynolds number, Re_a

$$Re_a = \frac{D'_e G_a}{\mu} \tag{8-88}$$

Pressure drop, ΔF_a, ft

$$\Delta F_a = \frac{4fG_a^2 L}{2g\rho^2 D'_e}, \quad \text{ft} \tag{8-89}$$

The pressure drop due to the reversal of flow in the annulus for each hairpin is:

$$\Delta F_r = \frac{v^2}{2g}, \quad \text{ft/hair pin} \tag{8-90}$$

The total annulus pressure drop is:

$$\Delta P_a = \left[\frac{(\Delta F_a + \Delta F_r)\rho}{144}\right], \quad \text{psi} \tag{8-91}$$

Nomenclature

A = cross-sectional area, ft^2
A_i = inside heat transfer area-tube, ft^2/ft
A_o = outside heat transfer area-tube, ft^2/ft (for finned tubes includes fin area)
A_f = finned transfer area, ft^2
a_p = flow area, ft^2
C = specific heat of hot fluid, Btu/lb°F
c = specific heat of cold fluid, Btu/lb°F
CSA = cross-sectional area, shell side without fins, ft^2
D = inside diameter, ft
D_i, D_o = for annuli, D_i is the outside diameter of inner pipe, D_o is the inside diameter of the outer pipe, inch
$D_{t,i}$ = tube inside diameter, inch
$D_{t,o}$ = tube outside diameter, inch
$D_{s,i}$ = shell inside diameter, inch
D_e = equivalent diameter for heat-transfer, ft
D_e = equivalent diameter for pressure drop, ft.
e = fin efficiency
e' = effective surface efficiency for fins
FOL = fouling factor, $hrft^2{}^\circ F/Btu$
f = friction factor, dimensionless
ΔF = pressure drop, ft

ΔF_a = annulus pressure drop, ft
ΔF_r = pressure drop due to reversal of flow in the annulus, ft
G = mass velocity, lb/ft^{2}hr
G_a = mass velocity in annulus, lb/ft^{2}hr
G_p = mass velocity of inner pipe, lb/ft^{2}hr
g = acceleration due to gravity, 32.2 ft/sec^2 (4.18×10^8 ft/hr^2)
H = fin height, inch
h_i, h_o = heat transfer film coefficient for inside fluid and outside fluid, respectively, Btu/hr.ft.^{2}°F
h_{io} = value of h_i when referred to the pipe outside diameter, Btu/hr. ft.^{2}°F
h_{if} = heat transfer film coefficient corrected for fouling, Btu/hr.ft.^{2}°F
h_{ifd} = corrected film heat transfer rate, Btu/hr.ft.^{2}°F
ID = inside diameter, inch or ft
j_H = heat transfer factor, dimensionless
k = fluid thermal conductivity, Btu/hr.ft.^{2}°F
K_t = thermal conductivity of tube material, Btu/hr.ft.^{2}°F
L = pipe length, ft
LMTD = log mean temperature difference, °F
NFA = net free cross-sectional area, shell side, ft^2
N = number of fins
OD = outside diameter, inch or ft
Pr = Prandtl number, dimensionless
ΔP = pressure drop, psi
Q = exchanger duty, Btu/hr
R_D = fouling resistance, hrft^2°F/Btu
Re = Reynolds number, dimensionless
R_w = wall resistance
s = specific gravity
T_1, T_2 = temperature of hot fluid, inlet and outlet respectively, °F
t_1, t_2 = temperature of cold fluid, inlet and outlet respectively, °F
U = overall heat transfer coefficient, Btu/hr.ft.^{2}°F
V = fluid velocity, ft/sec
W = mass flow rate of hot fluid, lb/hr
w = mass flow rate of cold fluid, lb/hr
X = parameter used in fin efficiency
ρ = fluid density, lb/ft^3
μ, μ_w = fluid viscosity (flowing and at wall), cP
θ = fin thickness (normally 0.035 inch)
π = 3.1415927

Subscripts

a = annulus
p = pipe

AIR COOLER DESIGN

Air coolers are widely used in the chemical process industries where there are shortages of cooling water and regulatory controls on thermal pollution. An economic comparison is often made between air and water cooling to determine which is advantageous. Air coolers can be used for cooling high pressure streams where the fluid is always inside the tubes. They minimize heat exchanger maintenance costs because descaling of the water-contact surface is eliminated. In addition, there is some savings in first cost because no additional surface area is required to allow for water side fouling between descaling. However, the exchangers are larger because the gas film coefficient is smaller. Air coolers eliminate problems of temperature rise and chemical pollution of water resources.

Air cooled heat exchangers have rectangular bundles containing several rows of tubes, horizontally aligned and vertically offset. Air flows vertically upward across the tube bank. The flow can be induced by fans above the bundle or forced by fans below the bundle. The heat transfer is countercurrent, because the hot fluid enters at the top of the bundle and flows downward through successive passes. The cost of an air cooler depends on the length of the tubes and the number of the tube rows.

A forced draft air cooler design has a power consumption advantage, if the temperature rise of the air is high. It also allows a more convenient and economical mounting arrangement when a number of bundles and services are to be combined in a single unit. In addition, it develops a high turbulence, and consequently, higher heat transfer coefficients. Conversely, an induced draft design provides a more even distribution of air across the bundles, and for a given bundle elevation, affords more space for location of additional plant equipment beneath the unit. Induced draft units are less likely to recirculate hot exhaust air, because the exit air velocity is two or three times that of a forced draft unit. These units give higher pressure drops and are more expensive. Figure 8-14 illustrates forced and induced air cooled exchanger arrangements.

Standard air coolers are in widths of 8, 10, 12, 16, or 20-ft lengths of 4-40ft, and stacks of 3–6 rows of tubes. Tubes are 0.75–1.0 inch OD

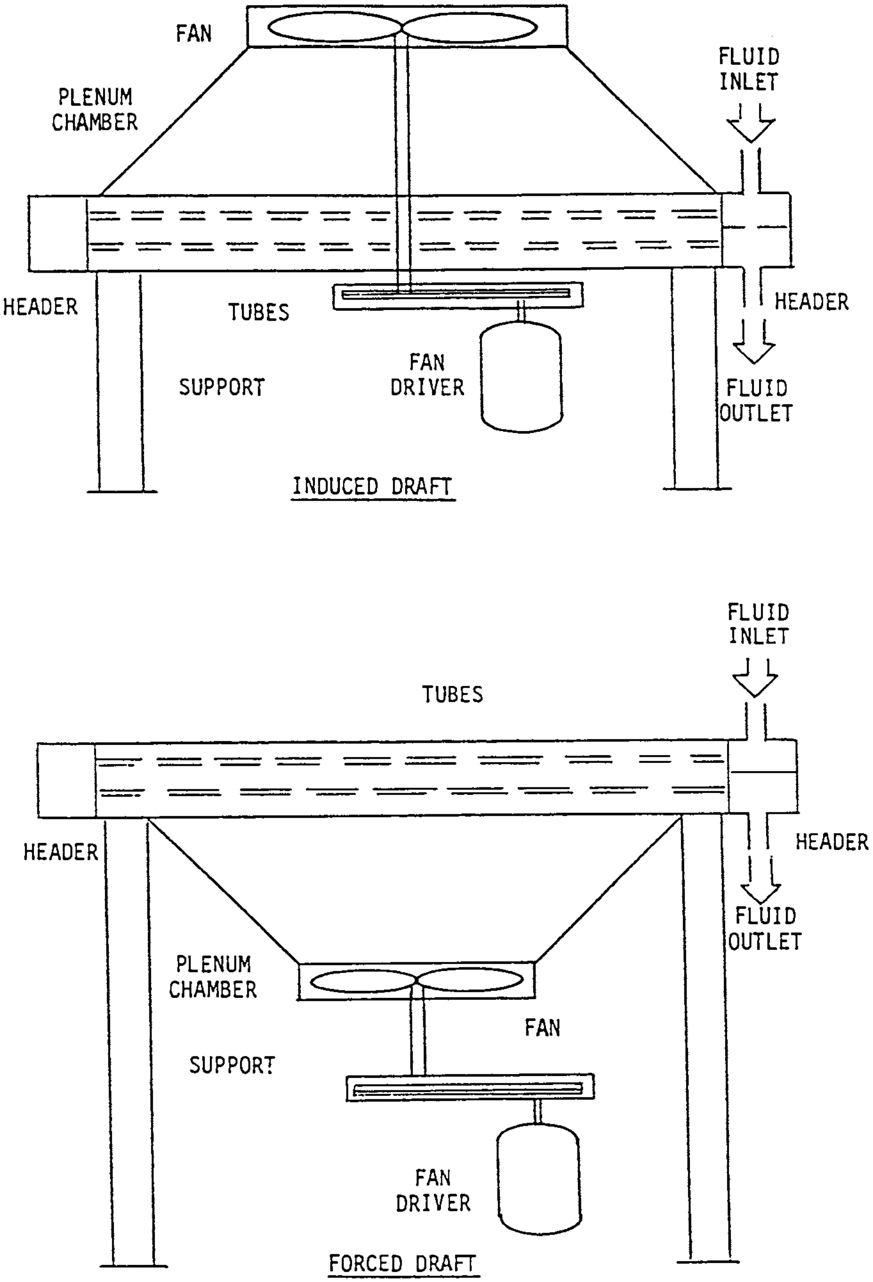


Figure 8-14. Forced and induced draft air cooled exchangers.

with 7–11 fins/inch each 0.5–0.625 in height and provide a total surface 15–20 times greater than the bare surface of the tube. Fans are 4–12 ft/diameter; developed pressures are 0.5–1.5 inch water, and require power inputs of 2–5 hp/MBtu/hr or about 7.5 hp/100 ft^2 of exchanger cross section. Spacings are 1.8 times the width of the cooler. Face velocities are about 10ft/sec at a depth of three rows and 8ft/sec at a depth of six rows. The rating methods for air cooled exchangers are outlined by Cook [16] and Ganapathy [17]. Here, the design of air coolers is based upon correlations, tables, and graphs presented by Smith [18] and Brown [19] and fitted to a series of equations developed by Blackwell [20].

The Equations

(1) The number of tube rows, R, is:

$$R = C_1 + C_2 \ln\left[\frac{T_2 - t_2}{U}\right] \tag{8-92}$$

where $C_1 = 3.1679$
$C_2 = 3.7948$

(2) The area ratio is:

$$\frac{A}{FA} = C_3(R)^{C_4} \tag{8-93}$$

where $C_3 = 1.2557$
$C_4 = 1.0031$

(3) The face velocity of air, FV, ft/min.

$$FV = C_5(C_6)^R \tag{8-94}$$

where $C_5 = 720.8542$
$C_6 = 0.9530$

Typical face velocities (FVs) used for design are in Table 8-15. These values result in air cooled heat exchangers that approach an optimum cost [21]. This takes into account the purchase cost, the cost of installation, and the cost of power to drive the fans.

Table 8-16 lists an estimate of the outlet air temperature, based on 90° to 95°F design ambient air temperature.

(4) Estimated air outlet temperature, t_1, °F

Table 8-15
Design Face Velocities for Air-Cooled Exchangers

	FACE VELOCITY, ft/min (m/sec.)		
Number of tube rows	8 fins/in. (315 fins/m) 2.375 in. (0.0603 m) pitch	10 fins/in. (394 fins/m) 2.375 in. (0.0635 m) pitch	10 fins/in. (394 fins/m) 2.5 in. (0.0635 m) pitch
3	650 (3.30)	625 (3.18)	700 (3.56)
4	615 (3.12)	600 (3.05)	600 (3.35)
5	585 (2.97)	575 (2.92)	625 (3.18)
6	560 (2.84)	550 (2.79)	600 (3.05)

Source: Chopey and Hicks [21].

Table 8-16
Estimated Outlet Air Temperature for Air-Cooled Exchangers

PROCESS INLET TEMPERATURE °C	OUTLET AIR TEMPERATURE °C		
	U=50	U=100	U=150
175	90	95	100
150	75	80	85
125	70	75	80
100	60	65	70
90	55	60	65
80	50	55	60
70	48	50	55
60	45	48	50
50	40	41	42

Source: Chopey and Hicks [21].

$$t_1 = 0.005U\left[\left(\frac{T_1 + T_2}{2}\right) - t_2\right] + t_2 \quad (8\text{-}95)$$

(5) The effective log mean temperature difference, °F

$$\text{LMTD} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left\{\dfrac{T_1 - t_2}{T_2 - t_1}\right\}} \quad (8\text{-}5)$$

(6) The heat duty Q, Btu/hr, is:

$$Q = wc\Delta t \quad (8\text{-}96)$$

where w = fluid flow rate, lb/hr
c = specific heat capacity, Btu/lb°F
Δt = temperature difference, °F

(7) The bare tube surface area based on the tube, OD, ft^2

$$A = \frac{Q}{(U)(\text{LMTD})} \quad (8\text{-}97)$$

(8) The face area of bundle FA, ft^2

$$FA = \frac{A}{C_3(R)^{C_4}} \quad (8\text{-}98)$$

(9) The calculated outlet air temperature, t_1', °F

$$t_1' = \frac{Q}{(1.08)(FA)(FV)} + t_2 \quad (8\text{-}99)$$

(10) The air flow over tubes F, std.ft^3/min

$$F = (FA)(FV) \quad (8\text{-}100)$$

(11) The ratio of the bare tube surface area based on the tube OD to the fan horsepower

$$\frac{A}{\text{Bhp}} = C_7 + C_8(R) \quad (8\text{-}101)$$

where $C_7 = 7.4212$
$C_8 = 12.5342$

(12) The ratio of air cooler weight to the face area of bundle is:

$$\frac{Wt}{FA} = C_9 + C_{10}(R) \tag{8-102}$$

where $C_9 = 36.4$
$C_{10} = 9.35$

(13) The tube bundle width, W, ft

$$W = \frac{FA}{L} \tag{8-103}$$

(14) The area available, A_v, ft^2

$$A_v = \pi . N_r . N_t . D_o . L, \quad ft^2 \tag{8-104}$$

where N_r = number of rows
N_t = number of tubes per row
= (tube bundle width)/(tube spacing) = W/s
L = tube length, ft
D_o = tube outside diameter, ft

If the area available, A_v, is less than the area required, A, increase the bundle width, and calculate the new outlet air temperature. Re-calculate LMTD, the new required area, and the new available area.

(15) The air-side heat transfer coefficient, h_a, Btu/hrft^2°F. The air side coefficient is determined on the basis of the outside surface of a bare tube. h_a is expressed as:

$$h_a = 8(FV)^{0.5} \text{ for 10 fins per inch} \tag{8-105}$$

$$h_a = 6.75(FV)^{0.5} \text{ for 8 fins per inch} \tag{8-106}$$

(16) The tube wall heat transfer coefficient h_w, Btu/hrft^2°F.

$$h_w = \frac{2.k}{D_o - D_i} \tag{8-107}$$

where k = thermal conductivity, Btu/hrft°F
D_o = outside diameter of tube, ft
D_i = inside diameter of tube, ft

(17) The overall heat transfer coefficient U, Btu/hrft^2°F is

$$\frac{1}{U} = \frac{1}{h_a} + \frac{1}{h_i(D_i/D_o)} + \frac{1}{h_w} + \frac{1}{h_s} \tag{8-108}$$

where h_i = inside of tube heat transfer coefficient
h_s = fouling coefficient

The Air-Side Pressure Drop, ΔP_a (inch H_2O)

The following equations are used to calculate the pressure drop on the air side [21].

$$\Delta P_a = 0.0047N_r(FV/100)^{1.8} \text{ for 10 fins per inch, 2.375-inch spacing} \quad (8\text{-}109)$$

$$\Delta P_a = 0.0044N_r(FV/100)^{1.8} \text{ for 8 fins per inch, 2.375-inch spacing} \quad (8\text{-}110)$$

$$\Delta P_a = 0.0037N_r(FV/100)^{1.8} \text{ for 10 fins per inch, 2.5 inch spacing} \quad (8\text{-}111)$$

where N_r = the number of tube rows
FV = face velocity, ft/min
ΔP_a = inch H_2O

Nomenclature

A = bare-tube surface area, ft^2
A_v = available area, ft^2
Bhp = fan horsepower
c = specific heat of fluid, Btu/lb°F
C_1, C_2, C_3 = constants
C_4, C_5, C_6 = constants
C_7, C_8, C_9 = constants
C_{10} = constant
D_i = inside diameter of tube, ft
D_o = outside diameter of tube, ft
F = air flow over tubes, $stdft^3/min$
FA = face area of bundle, ft^2
FV = face velocity of air, ft/min
h_a = air-side heat transfer coefficient, $Btu/hrft^2 °F$
h_i = inside of tube heat transfer coefficient, $Btu/hrft^2 °F$
h_s = fouling coefficient, $Btu/hrft^2 °F$
h_w = tube wall heat transfer coefficient, $Btu/hrft^2 °F$
k = thermal conductivity, Btu/hrft°F

L = pipe length, ft
LMTD = log mean temperature difference, °F
N_r = number of rows
N_t = number of tubes per row
ΔP_a = air-side pressure drop, inch H_2O
Q = exchanger duty, Btu/hr
R = number of tube rows
T_1 = outlet process fluid temperature, °F
T_2 = inlet process fluid temperature, °F
t_1 = estimated air outlet temperature, °F
t_1 = calculated outlet air temperature, °F
t_2 = inlet air temperature, °F
Δt = temperature difference, °F
U = overall heat transfer coefficient (based on bare-tube O.D.), $Btu/hrft^2 {}^\circ F$
W = tube bundle width, ft
w = fluid flow rate, lb/hr
Wt = air cooler weight, lb
$\pi = 3.1415926$

HEAT TRACER REQUIREMENTS FOR PIPELINES AND HEAT LOSS FROM INSULATED PIPELINES

Pipelines conveying viscous fluids are maintained at an elevated temperature by means of heat tracing. Pipelines containing vapors may also be heat traced to prevent components from condensing out. The heat loss from pipes is often reduced by thermal insulation. The thickness of insulation depends on an economic analysis involving both capital cost and the cost of heat loss from the insulated line. Water lines are commonly insulated to avoid freezing. However, heat is inevitably lost from insulated lines, and if the cooling resulting from this heat loss cannot be tolerated, heat tracing the lines becomes necessary. There are cases where blockages occur in pipelines, which cannot be unblocked by flushing with a solvent or by blowing in steam or air, unless they are heat traced.

Many types of fluid heating media are used for heat tracing, such as steam, hot oil, or Dowtherm. Electric heating tape may be used. Steam tracing is selected for about 60 percent of pipe footage in chemical process plants Lam and Sandberg [22] have provided a comprehensive checklist and criteria between steam and electric tracing. Table 8-17 lists a typical checklist for a petroleum refinery plant.

Table 8-17
Checklist to Decide Between Steam and Electric Heat Tracing

	Electric	Steam
PRE-EXISTING PROJECT CONSTRAINTS		
Heat tracing recommended in company (Yes/no) engineering practices	Yes	Yes
Plant preference	—	Yes
PROJECT DESIGN PHASE CRITERIA		
Total feet of traced pipe	4,700	4,700
Cost of electricity ($/kWh) and steam energy ($/1,000 lb)	$0.067	Consider free
Estimated annual maintenance cost per foot of tracing ($/ft.)	$1.67	$1.33
Number of heat-tracing circuits required	50	65
Needed accuracy of temperature control (degrees)	±50°	±50°
Temperature control cost per circuit for needed accuracy ($)	No extra	No extra
Cost of monitoring one circuit in distributed control system ($)	NA*	NA*
Design time per circuit (h)	0.5	1.5
Design tools available for engineers (Good, Fair, Poor, None)	Good	Good
Capital cost of steam capacity, condensate return, etc. ($)	—	Low
Capital cost of required electrical power ($)	Low	—
Other		
PROJECT INSTALLATION CRITERIA		
Labor cost to install tracing and accessories ($/ft)	$30.00	$40.00
Training time per plant laborer (h)	20	20
Labor and overhead costs ($/h)	$23.50	$23.50
Total installed heat-tracing costs ($/ft)	$62.00	$74.00
Other		
PROJECT OPERATION CRITERIA		
Annual maintenance required (h/ft.)	0.03	0.05
Annual cost for replacement parts ($/ft.)	$1.00	$0.80
Total annual maintenance cost ($)	$6,182	$6,807
Total annual operating cost ($)	$7,179	$6,807
Other		

**NA = not applicable, as the plant does not have a distributed control system capable of monitoring heat tracing*

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The length of a traced line varies from a few feet in a process area to a few thousand feet between offsites and the process area, as well as to hundreds of miles involving underground pipelines conveying crude oil. The most common steam tracing lines are 3/8-inch and 1/2-inch o.d. copper or stainless steel tubing. Larger tubing of 5/8-inch and 3/4-inch o.d. can be used, but is more expensive. The 3/8-inch tube is more easily plugged by debris or sediment, and is therefore used less than 1/2-inch tubing. Copper is preferred for its heat transfer characteristics, but stainless steel generally provides better resistance in corrosive situations. The length of a single trace tube (for example, from steam supply valve to steam trap) is limited by the pressure drop in the trace. In addition, the trap should have a condensate drainage capacity to match the heating load. At steam pressure of 100 psig or higher, Kohli [23] recommends that the length of a single trace should not exceed 200 ft. Conversely, if the steam pressure is lower, a tracer length of 100 ft is recommended. The trace tube is wired to the pipeline to provide greater contact. The conductive heat transfer rate is often low, but this may be increased by putting a layer of heat conducting cement (graphite mixed with sodium silicate or other binders) between the trace and the pipeline. This results in better surface for conductive heat transfer. Figure 8-15 shows various configurations of tracer and lagging.

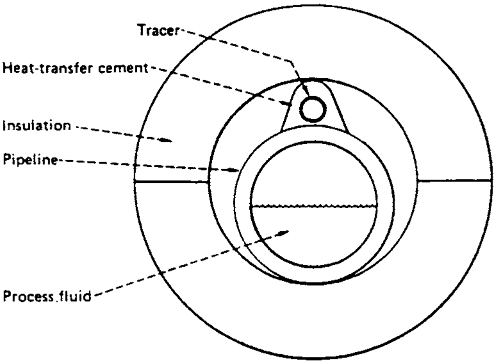
The following equations will allow the design engineer to calculate the heat loss and tracing requirements for any given pipeline, using any hot fluid medium as the heat source. The equations will calculate:

- The surface temperature of insulated traced pipe.
- Total heat transferred per 100ft of pipe.
- Total heat transferred for the entire pipeline.
- Flow rate of hot media.
- Total number of heat tracers required with and without transfer cement.

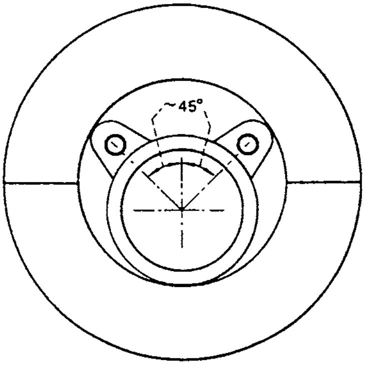
Kern [3] and others have shown that the heat transferred through an insulated pipe involves four resistances:

1. The film resistance on the inside wall of the pipe.
2. Heat resistance through the pipewall.
3. Heat resistance through the insulation.
4. Air film resistance on the outside of the insulation.

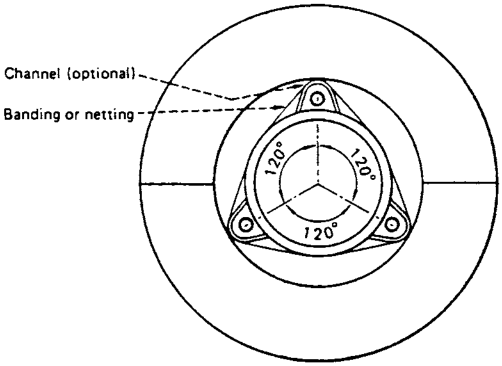
The first two resistances are negligible, and therefore are neglected.



Single tracer



Two tracers



Three tracers

Figure 8-15. Configuration of heat tracers and lagging.

The Equations

(1) The average temperature of the hot medium, °F

$$T_{m,avg} = 0.5(T_{mi} + T_{mo}) \tag{8-112}$$

(2) The average temperature of pipe and tracer, °F

$$T_{avg} = 0.5(T_{m,avg} + T_p) \tag{8-113}$$

(3) The inside diameter of insulation, inch

$$D_i = OD + TAL \tag{8-114}$$

(4) The outside diameter of insulation, inch

$$D_o = D_i + 2.T_k \tag{8-115}$$

(5) Heat lost per foot of pipe Q, Btu/hr.ft

$$Q = \frac{2\pi K_i (T_a - T_s)}{\ln\left(\frac{D_o}{D_i}\right)} \tag{8-116}$$

The heat lost per foot of pipe can be expressed in terms of the film heat transfer coefficient to air corrected for wind, Btu/hrft^2°F

$$Q = \frac{h_a \pi D_o (T_s - T_{air})}{12} \tag{8-117}$$

Using Equations 8-116 and 8-117 and rearranging the terms gives

$$\frac{2\pi K_i (T_a - T_s)}{\ln\left(\frac{D_o}{D_i}\right)} = \frac{h_a \pi D_o (T_s - T_{air})}{12} \tag{8-118}$$

That is,

$$T_a - T_s = C(T_s - T_{air}) \tag{8-119}$$

where

$$C = (h_a)\left(\frac{D_o}{12}\right)\left(\frac{1}{2K_i}\right)\left(\ln\frac{D_o}{D_i}\right) \tag{8-120}$$

Equation 8-119 can be expressed in terms of T_s as follows:

$$T_s(1 + C) = T_a + CT_{air} \tag{8-121}$$

and

$$T_s = \frac{T_a + CT_{air}}{1 + C} \tag{8-122}$$

Equations 8-120 and 8-122 involve two unknowns, h_a and T_s. An initial value of h_a is assumed and T_s is calculated. McAdams [24] indicates that h_a usually varies from 1.64 to 5.30 for pipes in still air, depending upon pipe size, surface, andair temperature. Table 8-18 gives values of h_a for pipes in still air, and Table 8-19 lists the correction factor for h_a at different wind velocities.

(6) The combined convective and radiative heat transfer coefficient $(h_c + h_r)$ is given by

$$h_c + h_r = \frac{564}{D_o^{0.19}\left[273 - (T_s - T_{air})\right]} \tag{8-123}$$

(7) The wind factor, WF:

$$WF = C_0 + C_1(T_s - T_{air}) + C_2(T_s - T_{air})^2 \tag{8-124}$$

Table 8-18
Values of h_a for Pipes in Still Air
$(t_s - t_a)$ °F (For an unlagged pipe $t_s = t_w$)

Nominal pipe dia., inch.	50	100	150	200	250	300	400	500
1/2	2.12	2.48	2.76	3.10	3.41	3.75	4.47	5.30
1	2.03	2.38	2.65	2.98	3.29	3.62	4.33	5.16
2	1.93	2.27	2.52	2.85	3.14	3.47	4.18	4.99
4	1.84	2.16	2.41	2.75	3.01	3.33	4.02	4.83
8	1.76	2.06	2.29	2.60	2.89	3.20	3.83	4.68
12	1.71	2.01	2.24	2.54	2.82	3.12	3.83	4.61
24	1.64	1.93	2.15	2.45	2.72	3.03	3.70	4.48

Source: McAdams [24].

Table 8-19
Correction Factor for h_a at Different Wind Velocities
$(t_s - t_a)$, °F (For an unlagged pipe, $t_S = t_W$)

Wind velocity, m/hr	100	200	300	400	500
2.5	1.46	1.43	1.40	1.36	1.32
5.0	1.74	1.69	1.64	1.59	1.53
10.0	2.16	2.10	2.02	1.93	1.84
15.0	2.50	2.42	2.33	2.27	2.08
20.0	2.76	2.69	2.58	2.45	2.30
25.0	2.98	2.89	2.78	2.64	2.49
30.0	3.15	3.06	2.94	2.81	2.66
35.0	3.30	3.21	3.10	2.97	2.81

Source: Kohli [23]

where $C_0 = 2.814$
$C_1 = -0.00038857$
$C_2 = -0.0000012857$

For zero wind condition,

$$C_0 = 1.0$$

$$C_1 = 0.0$$

$$C_2 = 0.0$$

(8) The new film heat transfer coefficient to air corrected for wind, h_a(Btu/hrft$^{2\circ}$ F)

$$h_a = (h_c + h_r)(WF) \quad (8\text{-}125)$$

(9) The total heat lost from pipeline, Q_t, Btu/hr

$$Q_t = (Q)(L_{TOTAL}) \quad (8\text{-}126)$$

where L_{TOTAL} = total length of pipe, ft

(10) The flow rate of hot medium W, lb/hr

$$W = \frac{Q_t}{C_p(T_{mi} - T_{mo})} \quad (8\text{-}127)$$

(11) The number of tracers required without heat transfer cement is

$$N_{TWOC} = \frac{Q}{a(T_{m,avg} - T_p)} \tag{8-128}$$

where a = thermal conductance tracer to pipe without cement, Btu/hr°F(ft of pipe)

(12) The number of tracers required with heat transfer cement:

$$N_{TWC} = \frac{Q}{b(T_{m,avg} - T_p)} \tag{8-129}$$

where b = thermal conductance tracer to pipe with cement, Btu/hr°F(ft. of pipe)

Table 8-20 lists the values of a and b.

Blackwell [20] recommends approximately 1 1/4 inch between pipe and insulation to accommodate a 1/2-inch tracer line and heat transfer cement. He further recommends twice this value for three or more tracers. A 3/8 inch to 1 inch of space may be required for smaller tracers. Tracers are normally spaced equidistantly around the pipe, and are run parallel to it. In the case of heat lost from an insulated pipeline without tracing, the hot medium inlet and outlet temperatures are set to equal the temperature of the pipe.

Nomenclature

a = thermal conductance, tracer to pipe without heat transfer cement, Btu/hr°F(ft of pipe)

b = thermal conductance, tracer to pipe with cement, Btu/hr°F(ft of pipe)

C_0, C_1, C_2 = constants for wind factor equation

Table 8-20
Thermal Conductance Tracer to Pipe

Tube size, inch	a	b
3/8	0.295	3.44
1/2	0.393	4.58
5/8	0.490	5.73

Source: Kohli [23].

C_p = specific heat of hot medium, Btu/lb°F
D_i = inside diameter of insulation, inch
D_o = outside diameter of insulation, inch
h_a = film heat transfer coefficient to air (corrected for wind), (Btu/hrft^2°F)
$h_c + h_r$ = combined convective and radiative heat transfer coefficients, (Btu/hrft^2°F)
K_i = thermal conductivity of insulation, Btu/hrft^2(°F/ft)
L_{TOTAL} = total pipeline length, ft
N_{TWC} = number of tracers required with heat transfer cement
N_{TWOC} = number of tracers required without heat transfer cement
Q = heat lost per ft of pipe, Btu/hr ft
Q_t = total heat lost from pipeline, Btu/hr
T_a = average temperature of pipe and tracer, °F
T_{air} = air temperature, °F
TAL = allowance for tracer diameter, inch
$T_{m\,avg}$ = average temperature of hot medium, °F
T_{mi} = inlet temperature of hot medium, °F
T_{mo} = outlet temperature of hot medium, °F
T_p = temperature in pipe, °F
T_s = outside surface temperature of insulation, °F
W = flow rate of hot medium, lb/hr
W_F = wind factor

BATCH HEATING AND COOLING OF FLUIDS

Heating or cooling of process fluids in a batch operated vessel is common in the chemical process industries. The process is an unsteady state in nature, because the heat flow, the temperature, or both vary with time at a fixed point. The time required for the heat transfer can be modified by increasing the agitation of the batch fluid, the rate of circulation of the heat transfer medium in a jacket or coil or both or the heat transfer area. Bondy and Lippa [25] have compiled a collection of correlations of heat transfer coefficients in agitated vessels. Batch processes are sometimes disadvantageous because:

- Use of the heating or cooling medium is intermittent.
- The liquid being processed is not readily available.
- The requirements for treating time requires holdup.
- Cleaning or regeneration is an integral part of the total operating period.

The variables in batch heating or cooling processes are surface requirement, time, and temperature. Heating a batch may be by external means, such as a jacket or coil, or by withdrawing and recirculating it through an external heat exchanger. In either case, assumptions are made to facilitate calculation:

1. The overall heat transfer coefficient, U, is constant for the process and over the entire surface.
2. Liquid flow rates are at steady state.
3. Specific heats are constant for the process.
4. The heating or cooling medium has a constant inlet temperature.
5. Agitation gives a uniform batch fluid temperature.
6. There is no phase change.
7. Heat losses are negligible.

Batch Heating: Internal Coil, Isothermal Heating Medium

When an agitated batch containing M of fluid with specific heat, c, and initial temperature, t, is heated with an isothermal condensing heating medium, T_1, the batch temperature t_2, at any time, θ, can be derived by the differential heat balance. For an unsteady state operation as shown in Figure 8-16, the total number of heat transferred is q′, and per unit time, θ, is:

$$\begin{array}{cccc} \text{I} & \text{II} & \text{III} & \text{IV} \\ dq = & \dfrac{dq'}{d\theta} = & Mc\dfrac{dt}{d\theta} = & UA\Delta t \\ & & \begin{array}{l}\text{Accumu-}\\ \text{lation in}\\ \text{the batch}\end{array} & \begin{array}{l}\text{Transfer}\\ \text{rate}\end{array} \end{array} \tag{8-130}$$

$$\Delta t = T_1 - t \tag{8-131}$$

Equating III and IV gives

$$Mc\frac{dt}{d\theta} = UA\Delta t \tag{8-132}$$

Rearranging Equation 8-132 gives:

$$\frac{dt}{\Delta t} = \frac{UA}{Mc}.d\theta \tag{8-133}$$

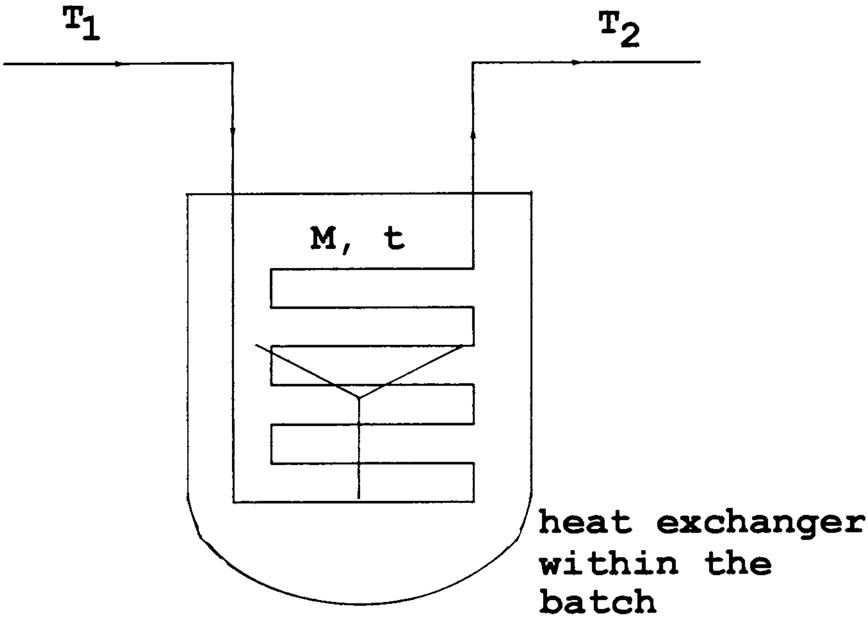


Figure 8-16. Agitated batch vessel.

$$\int_{t_1}^{t_2} \frac{dt}{T_1 - t} = \frac{UA}{Mc} \int_0^{\theta} d\theta \qquad (8\text{-}134)$$

Integrating Equation 8-134 from t_1 to t_2 while the time passes from 0 to θ yields:

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \frac{UA}{Mc} . \theta \qquad (8\text{-}135)$$

where A = heat transfer surface
c = specific heat of liquid
M = weight of batch liquid
T_1 = heating medium temperature
t_1 = initial batch temperature
t_2 = final batch temperature
U = overall heat transfer coefficient
θ = time

Batch Cooling : Internal Coil Isothermal Cooling Medium

Consider the same arrangement containing M of liquid with specific heat, c, and initial temperature, T_1, cooled by an isothermal vaporizing medium of temperature, t_1. If T is the batch temperature at any time, θ, then

$$\frac{dq'}{d\theta} = -Mc\frac{dT}{d\theta} = UA\Delta t \tag{8-136}$$

where

$$\Delta t = T - t_1 \tag{8-137}$$

Then

$$-Mc\frac{dT}{d\theta} = UA\Delta t \tag{8-138}$$

Substituting Equation 8-137 into Equation 8-138 and rearranging gives:

$$-\int_{T_1}^{T_2}\frac{dT}{T - t_1} = \int_0^{\theta}\frac{UA}{Mc}.d\theta \tag{8-139}$$

Integrating from T_1 to T_2 while the time passes from 0 to θ gives:

$$\ln\left(\frac{T_1 - t_1}{T_2 - t_1}\right) = \frac{UA}{Mc}.\theta \tag{8-140}$$

where A = heat transfer surface
c = specific heat of liquid
M = weight of batch liquid
T_1 = initial batch temperature
T_2 = final batch temperature
t_1 = cooling medium temperature
U = overall heat transfer coefficient
θ = time

Batch Heating with Non-Isothermal Heating Medium

The non-isothermal heating medium has a constant flow rate, W_h, specific heat, C_h, and inlet temperature, T_1, but a variable outlet temperature. For an unsteady state operation,

$$\overset{\text{I}}{\frac{dq'}{d\theta}} = \overset{\text{II}}{Mc\frac{dt}{d\theta}} = \overset{\text{III}}{W_hC_h(T_1 - T_2)} = \overset{\text{IV}}{UA\Delta t_{LMTD}} \tag{8-141}$$

The log mean temperature difference, Δt_{LMTD} is:

$$\Delta t_{LMTD} = \frac{T_1 - T_2}{\ln\left(\dfrac{T_1 - t}{T_2 - t}\right)} \tag{8-142 }$$

Equating III and IV in Equation 8-141 and rearranging gives:

$$\frac{W_hC_h(T_1 - T_2)}{UA} = \frac{T_1 - T_2}{\ln\left(\dfrac{T_1 - t}{T_2 - t}\right)} \tag{8-143}$$

Equation 8-143 becomes:

$$\ln\left(\frac{T_1 - t}{T_2 - t}\right) = \frac{UA}{W_hC_h} \tag{8-144}$$

$$\frac{T_1 - t}{T_2 - t} = e^{UA/W_hC_h} \tag{8-145}$$

Rearranging Equation 8-145 gives:

$$T_2 = t + \frac{T_1 - t}{e^{UA/W_hC_h}} \tag{8-146}$$

where

$$K_1 = e^{UA/W_hC_h} \tag{8-147}$$

Equating II and III in Equation 8-141 and substituting Equation 8-146 in Equation 8-141 gives:

$$Mc\frac{dt}{d\theta} = W_hC_h\left(T_1 - \left\{t + \frac{T_1 - t}{K_1}\right\}\right) \tag{8-148}$$

$$= W_hC_h\left(\frac{K_1 - 1}{K_1}\right)(T_1 - t) \qquad (8\text{-}149)$$

$$\int_{t_1}^{t_2} \frac{dt}{T_1 - t} = \int_0^{\theta} \frac{W_hC_h}{Mc}\left(\frac{K_1 - 1}{K_1}\right)d\theta \qquad (8\text{-}150)$$

Rearranging and integrating Equation 8-150 from t_1 to t_2 while the time passes from 0 to θ gives:

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{W_hC_h}{Mc}\right)\left(\frac{K_1 - 1}{K_1}\right)\theta \qquad (8\text{-}151)$$

where A = heat transfer surface
c = specific heat of batch liquid
C_h = heating medium specific heat
M = weight of batch liquid
T_1 = heating medium temperature
t_1 = initial batch temperature
t_2 = final batch temperature
U = overall heat transfer coefficient
W_h = heating medium flow rate
θ = time

Batch Cooling: Non-Isothermal Cooling Medium

When cooling a batch with internal coil and a non-isothermal cooling medium, the following equation can be applied.

$$\frac{dq'}{d\theta} = -Mc\frac{dT}{d\theta} = W_cC_c(t_2 - t_1) = UA\Delta t_{LMTD} \qquad (8\text{-}152)$$

where $K_2 = e^{UA/W_cC_c}$

and

$$\ln\left(\frac{T_1 - t_1}{T_2 - t_1}\right) = \left(\frac{W_cC_c}{Mc}\right)\left(\frac{K_2 - 1}{K_2}\right)\theta \qquad (8\text{-}153)$$

where A = heat transfer surface
c = specific heat of liquid

C_c = coolant specific heat
M = weight of batch liquid
T_1 = initial batch temperature
T_2 = final batch temperature
t_1 = initial coolant temperature
U = overall heat transfer coefficient
W_c = coolant flow rate
θ = time

Batch Heating Through An External Heat Exchanger, Isothermal Heating Medium

Figure 8-17 illustrates the arrangement in which the fluid in the tank is heated by an external heat exchanger. The heating medium is isothermal, therefore any type of exchanger with steam in the shell and tubes can be used. The variable temperature out of the exchanger, t′,will differ from the variable tank temperature, t. An energy balance around the tank and the heat exchanger gives:

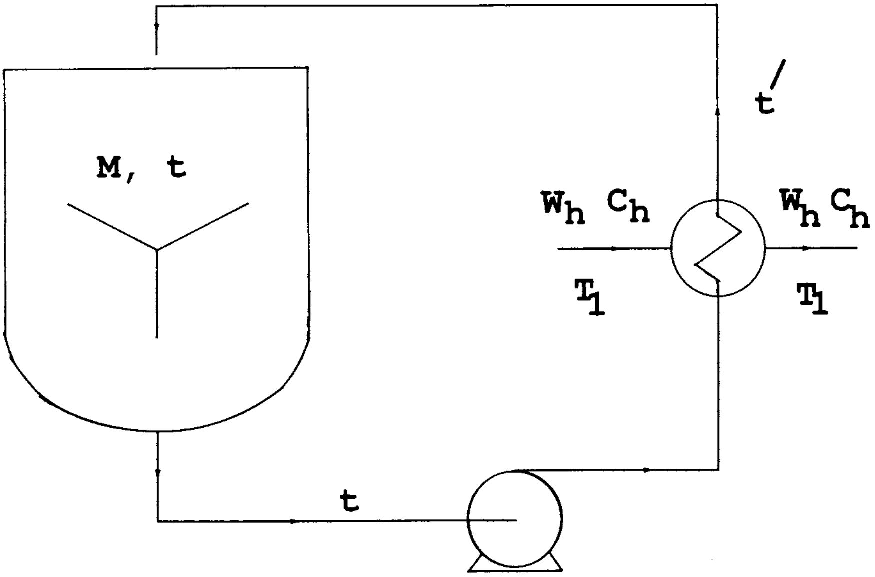


Figure 8-17. Batch heating through an external heat exchanger, isothermal heating medium.

$$\frac{dq'}{dt} = \underset{\substack{\text{Heat}\\ \text{accumu-}\\ \text{lation in}\\ \text{the batch}}}{\overset{\text{I}}{Mc\frac{dt}{d\theta}}} = \underset{\substack{\text{Heat enter-}\\ \text{ing the}\\ \text{batch by}\\ \text{recirculation}}}{\overset{\text{II}}{W_hC_h(t' - t)}} = \underset{\substack{\text{Transfer}\\ \text{rate in the}\\ \text{external}\\ \text{exchanger}}}{\overset{\text{III}}{UA\Delta t_{LMTD}}} \tag{8-154}$$

The log mean temperature difference, Δt_{LMTD} is:

$$\Delta t_{LMTD} = \frac{(T_1 - t_1) - (T_1 - t')}{\ln\left(\dfrac{T_1 - t_1}{T_1 - t'}\right)} \tag{8-155}$$

$$= \frac{t' - t_1}{\ln\left(\dfrac{T_1 - t_1}{T_1 - t'}\right)} \tag{8-156}$$

Equating II and III in Equation 8-154 gives:

$$W_hC_h(t' - t) = UA\Delta t_{LMTD} \tag{8-157}$$

That is:

$$W_hC_h(t' - t) = UA\frac{(t' - t)}{\ln\left\{\dfrac{T_1 - t_1}{T_1 - t'}\right\}} \tag{8-158}$$

Rearranging Equation 8-158 gives

$$\ln\left(\frac{T_1 - t}{T_1 - t'}\right) = \frac{UA}{W_hC_h} \tag{8-159}$$

Equation 8-159 can be expressed as:

$$T_1 - t = e^{UA/W_hC_h}(T_1 - t') \tag{8-160}$$

where

$$\begin{aligned} K_3 &= e^{UA/W_hC_h} \\ T_1 - t &= K_3(T_1 - t') \end{aligned} \qquad (8\text{-}161)$$

Therefore

$$t' = T_1 - \left(\frac{T_1 - t}{K_3}\right) \qquad (8\text{-}162)$$

Equating I and II in Equation 8-154

$$Mc\frac{dt}{d\theta} = W_hC_h(t' - t) \qquad (8\text{-}163)$$

Substituting Equation 8-162 into Equation 8-163 and rearranging gives:

$$\frac{Mc}{W_hC_h} \cdot \frac{dt}{d\theta} = \left\{T_1 - \left(\frac{T_1 - t}{K_3}\right)\right\} - t \qquad (8\text{-}164)$$

$$= \frac{(K_3 - 1)(T_1 - t)}{K_3} \qquad (8\text{-}165)$$

$$\int_{t_1}^{t_2} \frac{dt}{T_1 - t} = \left(\frac{K_3 - 1}{K_3}\right)\left(\frac{W_hC_h}{Mc}\right)\int_0^{\theta} d\theta \qquad (8\text{-}166)$$

Rearranging and integrating Equation 8-166 from t_1 to t_2 while the time passes from 0 to θ gives:

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{K_3 - 1}{K_3}\right)\left(\frac{W_cC_h}{Mc}\right)\theta \qquad (8\text{-}167)$$

where A = heat transfer surface
c = specific heat of batch liquid
C_h = heating medium specific heat
M = weight of batch liquid
T_1 = heating medium temperature
t_1 = initial batch temperature

t_2 = final batch temperature
U = overall heat transfer coefficient
W_h = heating medium flow rate
θ = time

Batch Cooling Through an External Heat Exchanger, Isothermal Cooling Medium

When cooling a batch with an external heat exchanger and an isothermal cooling medium, the equation is:

$$\ln\left(\frac{T_1 - t_1}{T_2 - t_1}\right) = \left(\frac{W_c C_c}{Mc}\right)\left(\frac{K_4 - 1}{K_4}\right)\theta \tag{8-168}$$

where $K_4 = e^{UA/W_cC_c}$
A = heat transfer surface
c = specific heat of liquid
C_c = coolant specific heat
M = weight of batch liquid
T_1 = initial batch temperature
T_2 = final batch temperature
t_1 = initial coolant temperature
U = overall heat transfer coefficient
W_c = coolant flow rate
θ = time

Batch Cooling: External Heat Exchanger (Countercurrent Flow), Non-isothermal Cooling Medium

When cooling a batch with an external heat exchanger and a non-isothermal cooling medium, the following equation can be used.

$$\ln\left(\frac{T_1 - t_1}{T_2 - t_1}\right) = \left(\frac{K_5 - 1}{M}\right)\left(\frac{W_b W_c C_c}{K_5 W_c C_c - W_b c}\right)\theta \tag{8-169}$$

where $K_5 = \exp\{UA(1/W_bc - 1/W_cC_c)\}$
A = heat transfer surface
c = specific heat of liquid
C_c = coolant specific heat
M = weight of batch liquid

T_1 = initial batch temperature
T_2 = final batch temperature
t_1 = initial coolant temperature
U = overall heat transfer coefficient
W_b = batch flow rate
W_c = coolant flow rate
θ = time

Batch Heating: External Heat Exchanger and Non-isothermal Heating Medium

When heating a batch with an external heat exchanger and non-isothermal heating, the following equation applies:

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{K_6 - 1}{M}\right)\left(\frac{W_b W_h C_h}{K_6 W_h C_h - W_b c}\right)\theta \qquad (8\text{-}170)$$

where $K_6 = \exp\{UA(1/W_b c - 1/W_h C_h)\}$
A = heat transfer surface
c = specific heat of batch liquid
C_h = heating medium specific heat
M = weight of batch liquid
T_1 = heating medium temperature
t_1 = initial batch temperature
t_2 = final batch temperature
U = overall heat transfer coefficient
W_b = batch flow rate
W_h = heating medium flow rate
θ = time

Batch Heating: External Heat Exchanger (1-2 Multipass Heat Exchangers), Non-isothermal Heating Medium

The procedure used for batch heating with external 1-2 multipass heat exchangers with non-isothermal heating media involves using the same heat balance as defined by the following equation:

$$\frac{dq'}{d\theta} = \overset{\text{I}}{Mc\frac{dt}{d\theta}} = \overset{\text{II}}{W_b c(t' - t)} = \overset{\text{III}}{W_h C_h (T_1 - T_2)} = \overset{\text{IV}}{UA\Delta t_{LMTD}} \qquad (8\text{-}171)$$

Equating I and II in Equation 8-171

$$Mc\frac{dt}{d\theta} = W_b c(t' - t) \tag{8 -172}$$

Rearranging Equation 8-172 gives:

$$t' = t + \frac{M}{W_b} \cdot \frac{dt}{d\theta} \tag{8-173}$$

The parameter S can be defined by

$$S = \frac{t' - t}{T_1 - t} = \left(\frac{M}{W_b}\right)\left(\frac{1}{T_1 - t}\right)\frac{dt}{d\theta} \tag{8-174}$$

The parameter R can be defined by equating II and III in Equation 171

$$R = \frac{T_1 - T_2}{t' - t} = \frac{W_b c}{W_h C_h} \tag{8-175}$$

Rearranging Equation 8-174 gives:

$$\int_{t_1}^{t_2} \frac{dt}{T_1 - t} = \frac{S.W_b}{M}\int_0^{\theta} d\theta \tag{8-176}$$

Integrating from t_1 to t_2, as the time passes from 0 to θ yields:

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{S.W_b}{M}\right)\theta \tag{8-177}$$

and

$$S = \frac{2(K_7 - 1)}{K_7\left\{R + 1 + (R^2 + 1)^{0.5}\right\} - \left\{R + 1 - (R^2 + 1)^{0.5}\right\}} \tag{8-178}$$

where $K_7 = \exp\{(UA/W_b c)(R^2 + 1)^{0.5}\}$

A = heat transfer surface

c = specific heat of batch liquid

C_h = heating medium specific heat

M = weight of batch liquid

T_1 = initial temperature of heating medium

t_1 = initial batch temperature

t_2 = final batch temperature

U = overall heat transfer coefficient
W_b = batch flow rate
W_h = heating medium flow rate
θ = time

Batch Heating and Cooling: External Heat Exchanger (2-4 Multipass Heat Exchangers)

The same procedure can be used as in 1-2 multipass heat exchangers. The equation for batch heating with external 2–4 multipass heat exchangers and non-isothermal heating media is

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{S.W_b}{M}\right)\theta \tag{8-177}$$

where

$$S = \frac{2(K_8 - 1)\left[1 + \{(1 - S)(1 - RS)\}^{0.5}\right]}{(K_8 - 1)(R + 1) + (K_8 + 1)(R^2 + 1)^{0.5}} \tag{8-179}$$

and

$$K_8 = \exp\left\{\frac{UA}{2w_b c}(R^2 + 1)^{0.5}\right\} \tag{8-180}$$

Because S cannot be expressed explicitly, Equation 8-179 can be solved only by trial and error, assuming different values of S until an equality is attained. The equations for batch heating and cooling are the same as those developed for the 1-2 multipass exchangers, except that the value of S from Equation 8-179 replaces the value of S from Equation 8-178.

PROBLEMS AND SOLUTIONS

Problem 8-1

Kerosene leaves the bottom of a distillation column at 390°F and will be cooled to 200°F by crude oil from storage at 100°F and heated to 170°F. Calculate the number of shell passes required, the F-factor, and the corrected LMTD.

Hot kerosene inlet temperature = 390°F

Hot kerosene outlet temperature = 200°F

Crude oil inlet temperature = 100°F

Crude oil outlet temperature = 170°F

Solution

The computer program PROG81 calculates the required number of shell passes, the F-factor, the Log Mean Temperature Difference (LMTD), and the Corrected Mean Temperature Difference (CMTD). Table 8-21 shows the input data and computer output of the problem. The number of shells required is 1, the F-factor is 0.8917, the LMTD is 152.2°F and the corrected LMTD is 135.7°F.

Problem 8-2

Acetone (s = 0.79) at 250°F is to be sent to storage at 100°F and at a rate of 60,000 lb/hr. The heat will be received by 185,000 lb/hr of 100 percent acetic acid (s = 1.07) coming from storage at 90°F and heated to 150°F. Pressure drops of 10.0 psi are available for both fluids. Assuming that the fouling factor on the tube side is 0.001 and that on the shell side is 0.003, calculate the heat transfer coefficients for the tube and shell sides, the overall heat transfer coefficient for the exchanger, outside area of unit, and the heat transferred.

Available for the service are a large number of 1-2 exchangers having 21 1/4 in. ID shells with 270 tubes 3/4 in. OD, 14 BWG, 16 ft long

Table 8-21
Input Data and Computer Output for the Corrected Mean Temperature Difference in a Shell and Tube Heat Exchanger

```
DATA81.DAT
-------------
390.0  200.0
100.0  170.0
1.
```

```
         THE CORRECTED LMTD IN A SHELL AND TUBE HEAT EXCHANGER
********************************************************************************
     HOT FLUID INLET TEMPERATURE, oF:                         390.000
     HOT FLUID OUTLET TEMPERATURE, oF:                        200.000
     COLD FLUID INLET TEMPERATURE, oF:                        100.000
     COLD FLUID OUTLET TEMPERATURE, oF:                       170.000
     NUMBER OF SERIES EXCHANGER SHELLS:                       1.
     THE NUMBER OF SHELLS REQUIRED:                           1.
     THE F- FACTOR:                                            .8917
     THE LOG MEAN TEMPERATURE DIFFERENCE,oF:                152.1959
     THE CORRECTED LMTD, oF:                                135.7112
--------------------------------------------------------------------------------
```

and laid on 1-in. square pitch. The bundles are arranged for two tube passes with segmental baffles spaced 5 in. apart.

Physical property data:

Physical property	Acetone	Acetic Acid
Viscosity, cP	0.20	0.85
Density, lb/ft^3	49.296	66.768
Specific heat, Btu/lb.°F	0.63	0.51
Thermal conductivity, Btu/lb.ft^2(°F/ft)	0.095	0.098

Solution

Exchanger:

Hot Fluid (Acetone)	Cold Fluid (Acetic Acid)
Shell side	Tube side
ID=21 1/4 in.	Number and length = 270, 16'0"
Baffle space = 5in.	OD, BWG, pitch = 3/4in., 14 BWG, 1 in. square.
Passes = 1	Passes = 2

Heat Balance:

Heat lost by acetone to storage = heat gained by acetic acid from storage

that is,

$$W.C_p.(T_2 - T_1) = w.c_p.(t_2 - t_1)$$

$$(60{,}000)(0.57)(250 - 100) = w(0.51)(150 - 90)$$

$$w \approx 168{,}000 \text{ lb/hr}$$

The computer program PROG82 rates the shell and tube heat exchanger using 168,000 lb/hr of acetic acid in the tube side. Table 8-22 gives the input data and computer output of the heat exchanger design. A minimum of three shell passes is required to permit the transfer of heat with the temperatures given by the process. The overall heat transfer coefficient is 79 Btu/hrft^2°F, and the heat transfer surface is 2545 ft^2. Three exchangers are sufficient for the heat transfer, although the pressure

Table 8-22
Input Data and Computer Output for the Rating of a Shell and Tube Heat Exchanger

```
DATA82.DAT
--------------------------
ACETIC ACID
270.0  0.584  0.75   1.0
S
16.0   2.0    0.001  90.0
150.0  0.51   0.85   66.768
0.098  168000.0
ACETONE
1.0    21.25   38.0   5.0
0.003  250.0   100.0  0.63
0.20   49.296  0.095  60000.0
```

```
                   *SHELL AND TUBE HEAT EXCHANGER RATING*
*****************************************************************************
                                             TUBE SIDE          SHELL SIDE
-----------------------------------------------------------------------------
 FLUID TYPE:                                ACETIC ACID        ACETONE
 FLUID FLOW RATE , lb/hr.:                    168000.               60000.
 SPECIFIC HEAT CAPACITY, Btu/lb.oF:            .510                 .630
 FLUID DENSITY, lb/ft^3:                     66.768               49.296
 FLUID VISCOSITY, cP:                          .850                 .200
 FLUID THERMAL COND. Btu/ft.h.oF:              .098                 .095
 FLUID INLET TEMPERATURE, oF:                   90.                 250.
 FLUID OUTLET TEMPERATURE, oF:                 150.                 100.
 INSIDE DIAMETER, inch:                        .584               21.250
 OUTSIDE DIAMETER, inch:                       .750
 TUBE PITCH, inch:                            1.000            SQUARE PITCH
 TUBE LENGTH, ft.:                           16.000
 NUMBER OF TUBES:                            270.
 NUMBER OF PASSES:                           6.                   3.
 NUMBER OF BAFFLES:                                              38.
 BAFFLE SPACING, inch:                                           5.0
 FLUID VELOCITY, ft/sec.:                     2.783                1.833
 REYNOLDS NUMBER:                             15828.               53072.
 PRANDTL NUMBER:                            10.7048              3.2097
 FRICTION FACTOR (ft^2/in^2):               .00024               .00153
 HEAT COEFF., Btu/hr.ft^2.oF:                 211.8                253.4
 PRESSURE DROP, psi:                        1.5682               3.4464
 FOULING FACTOR:                             .0010                .0030
 APPROACH FACTOR, F:                         .8749
 LOG MEAN TEMP. DIFF. oF:                    39.09
 CORRECTED MEAN TEMP. DIFF. oF:              34.20
 OVERALL HEAT COEFF., Btu/hr.ft^2.oF:          79.0
 OUTSIDE AREA OF UNIT, ft^2:                 2544.7
 HEAT LOAD ON UNIT, Btu/hr:                   5140800.
 HEAT TRANSFERRED, Btu/hr:                    6870014.
-----------------------------------------------------------------------------
```

drop on the shell side is higher than the permissible pressure drop. Fewer exchangers will be inadequate for the service.

Problem 8-3

Petroleum distillate oil (28° API) is to be cooled in a double pipe finned tube exchanger with cooling-tower water under the following conditions:

Tube side: Water flow = 23,310 lb/hr
T_{in} = 80°F T_{out} = 120°F
Fol = 0.003 μ = 0.72 cP
K = 0.366 Btu/fthr°F
C_p = 1 Btu/lb °F
Density = 62.3 lb/ft^3
Number of passes = 5

Shell side: Oil flow = 18,000 lb/hr
T_{in} = 250°F T_{out} = 150°F
Fol = 0.001 μ = 2.45cP
K = 0.074 Btu/ft hr°F
C_p = 0.518 Btu/lb°F
Density = 45 lb/ft^3
Number of passes = 1

Exchanger size:
Shell side: 3 in. (3.068 in. ID, 3.5 in. OD)
Tube side: 1 1/2 in. (1.61 in. ID, 1.9 in. OD)
Tube length: 12 ft
Fins: 24, 0.5 in. high x 0.035 in. wide
Thermal conductivity of tube material

K = 25 Btu/fthr°F

Pressure drops of 10 psi are allowable on both streams, and the fouling factors of 0.001 for the distillate oil and 0.003 for the water are required. Calculate the overall heat transfer coefficient, and the exchanger fin efficiency.

Solution

Exchanger:

Hot Fluid (Oil)	Cold Fluid (Water)
Shell side	Tube side
ID = 3.068 in.	ID = 1.61 in. OD = 1.9 in.
	Tube length = 12′0″
Passes = 1	Passes = 5

Physical property data:

Physical property	Oil	Water
Viscosity, cP	2.45	0.72
Density, lb/ft^3	45.0	62.3
Specific heat, Btu/lb.°F	0.518	1.00
Thermal conductivity, Btu/lbft2(°F/ft)	0.074	0.366

Heat Balance:

Heat lost by oil = heat gained by water

that is,

$$Q = W.Cp.(T_1 - T_2) = w.cp.(t_2 - t_1)$$

$$Q = (18000)(0.518)(250 - 150) = w(1)(120 - 80)$$

$$932400 = 40w$$

$$w = 23310 \text{ lb/hr}$$

The flow of water required to cool the oil is 23310 lb/hr. The computer program PROG83 rates the double pipe heat exchanger using either fin tubes or bare tubes. Table 8-23 lists the input data and output of the computer program. The fin efficiency is 43.3 percent and the computed overall heat transfer coefficient is 27.3 $Btu/hrft^2{}^\circ F$. The pressure drops have not been exceeded, and the double pipe exchanger will be satisfactory for the service.

Problem 8-4

Calculate a preliminary air-cooler design using the following data.

A light hydrocarbon liquid is to be cooled from 170°F to 135°F in an air cooler. The heat transfer rate is 5.0 MM Btu/hr, and the estimated overall heat transfer is 60 Btu/hr $ft^2{}^\circ F$. The design dry bulb air temperature is 85°F, and the tube length is 40ft.

Solution

The computer program PROG84 calculates the air cooled heat exchanger area, the face area and the fan horsepower. Table 8-24 shows both the input data and computer output of the design calculations. The exchanger area is 1602 ft^2 and the LMTD is 52°F. Face area of the bundle

Table 8-23
Input Data and Computer Output for the Double Pipe or Longitudinal Finned Tube Heat Exchanger

```
DATA83.DAT
------------------------
WATER
LIQUID
1.61   1.9    23310.0
1.0    0.72   0.366
80.0   120.0  0.003
62.3   12.0   5
OIL
FINS
LIQUID
24
3.068   3.5    18000.0
0.518   2.45   0.074
250.0   150.0  0.001
0.5     0.035
25.0    45.0  1

                 DOUBLE PIPE HEAT EXCHANGER RATING
                 USING BARE-TUBES/LONGITUDINAL FINNED TUBES
                 FORCED CONVECTION WITH NO CHANGE OF PHASE
*****************************************************************************
                                                TUBE SIDE          SHELL SIDE
-----------------------------------------------------------------------------
 FLUID NAME:                                        WATER           OIL
 TYPE OF PHASE FLOW:                                LIQUID          LIQUID
 FLUID FLOW RATE, lb/hr.:                          23310.          18000.
 SPECIFIC HEAT CAPACITY, Btu/Ib.oF:               1.000            .518
 FLUID DENSITY, lb/ft^3.:                        62.300          45.000
 FLUID VISCOSITY, cP:                              .720           2.450
 FLUID THERMAL COND., Btu/Ib.oF:                   .366            .074
 FLUID INLET TEMPERATURE, oF:                    80.000         250.000
 FLUID OUTLET TEMPERATURE, oF:                  120.000         150.000
 INSIDE DIAMETER, inch:                           1.610           3.068
 OUTSIDE DIAMETER, inch:                          1.900           3.500
 FOULING FACTOR:                                   .003            .001
 TUBE LENGTH, ft.:                               12.000
 NUMBER OF TUBE PASSES:                         5
 NUMBER OF FINS:                               24
 FIN HEIGHT, inch:                                 .500
 FIN THICKNESS, inch:                              .035
 THERMAL COND. TUBE MATERIAL, Btu/hr.ft.oF:      25.000
 FLUID VELOCITY, ft/sec.:                         7.351           3.867
 REYNOLDS NUMBER:                               126958.            3759.
 PRANDTL NUMBER:                                4.7607          41.503
 FRICTION FACTOR (ft^2/in^2):                   .000031         .000042
 PRESSURE DROP, psi.:                            2.9424           .5943
 FIN MODULUS:                                     2.258
 FIN EFFICIENCY, %:                              43.335
 EFFECTIVE SURFACE EFFICIENCY, %:                44.486
 LOG MEAN TEMP. DIFF., oF:                        96.92
 HEAT TRANSFER FILM COEFF. CORRECTED
 FOR FOULING:, Btu/hr.ft^2.oF:                   264.33          107.04
 OVERALL HEAT TRANSFER COEFF., Btu/hr.ft^2.       27.26
 HEAT LOAD ON UNIT, Btu/hr.:                      932400.0
 HEAT TRANSFER SURFACE ft^2.:                   352.932
-----------------------------------------------------------------------------
```

is 283ft^2, and the fan horsepower is 25.2 bhp. The required air flow is 164266 std ft^3/min.

Problem 8-5

Determine the number of tracers required to maintain 100 ft of 8-in. (Schedule 40) process line (ID = 7.981 in.) at 500°F. Hot tracing

Table 8-24
Input Data and Computer Output for An Air-Cooled Heat Exchanger Design

```
DATA84.DAT
------------------------
170.0   135.0      85.0
60.0    5000000.0  40.0


                    AN AIR-COOLED HEAT EXCHANGER DESIGN
*****************************************************************************
     INLET PROCESS FLUID TEMPERATURE, oF:                           170.0
     OUTLET PROCESS FLUID TEMPERATURE, oF:                          135.0
     INLET AIR TEMPERATURE, oF:                                      85.0
     OVERALL HEAT-TRANSFER COEFFICEINT, Btu/hr.ft^2.oF:              60.0
     HEAT LOAD, Btu/hr.:                                             5000000.
     TUBE LENGTH, ft.:                                               40.0
     NUMBER OF TUBE ROWS:                                           4.5
     RATIO OF BARE-TUBE SURFACE TO FACE AREA OF BUNDLE:             5.7
     FACE VELOCITY OF AIR, ft./min.:                              580.740
     ESTIMATED AIR OUTLET TEMPERATURE, oF:                        105.250
     EFFECTIVE LOG MEAN TEMPERATURE DIFFERENCE, oF:                57.058
     BARE-TUBE SURFACE AREA BASED ON TUBE OD, ft^2:                1460.5
     FACE AREA OF BUNDLE, ft^2:                                     257.9
     CALCULATED OUTLET AIR TEMPERATURE, oF:                       115.916
     THE DIFFERENCE BETWEEN THE CALCULATED AIR
     OUTLET TEMPERATURE AND THE ESTIMATED AIR OUTLET
     TEMPERATURE IS GREATER THAN 0.5                             TAO-TAO1 >0.5
     EFFECTIVE LOG MEAN TEMPERATURE DIFFERENCE, oF:                52.015
     BARE-TUBE SURFACE AREA BASED ON TUBE OD, ft^2:                1602.1
     FACE AREA OF BUNDLE, ft^2:                                     282.9
     CALCULATED OUTLET AIR TEMPERATURE, oF:                       113.184
     CALCULATED BARE-TUBE SURFACE AREA
     BASED ON TUBE OUTSIDE DIAMETER, ft^2:                         1602.1
     FACE AREA OF BUNDLE, ft^2:                                     282.9
     AIR FLOW OVER TUBES, std.ft^3/min.:                           164266.
     FAN HORSEPOWER, bhp:                                            25.2
     AIR-COOLER WEIGHT, lb:                                        22169.8
     TUBE BUNDLE WIDTH, ft.:                                          7.1
-----------------------------------------------------------------------------
```

medium is available at 630°F and has a heat capacity of 0.53 Btu/lb°F. The process line is covered with 2.5 in. of insulation, and this insulation has a thermal conductivity of 0.033 Btu/(hr)(ft^2)(°F/ft). Design for 0°F air temperature and 20 mph winds. Use 1/2 in. tracers, the hot medium outlet temperature is 550°F. Allow approximately 1 1/4 in. between pipe and insulation to accommodate a 1/2 in. in tracer line and heat transfer cement. Assuming the trial film heat transfer coefficient is 4.0 Btu/hrft^2 °F, and the thermal conductances tracer to 1/2 in. pipe are a = 0.393 and b = 4.58 Btu/hr °F(ft of pipe).

Solution

The computer program PROG85 calculates the heat tracer requirements and heat loss for an insulated pipe line either with tracing or without tracing. Table 8-25 lists the input data and computer output of the

Table 8-25
Input Data and Computer Output for Tracer Requirements for Pipelines

```
DATA85.DAT
---------------------------
100.0    500.0  630.0
550.0    0.0    7.981
1.25     2.5    0.033
0.53     4.0    0.393  4.58
```

```
         HEAT TRACER REQUIREMENTS FOR PIPELINES AND
         HEAT LOSS FROM AN INSULATED PIPELINE WITH TRACING
****************************************************************************
     TOTAL PIPELINE LENGTH, ft.:                                 100.0
     TEMPERATURE IN PIPE, oF:                                    500.0
     HOT-MEDIUM INLET TEMPERATURE, oF:                           630.0
     HOT MEDIUM OUTLET TEMPERATURE, oF:                          550.0
     AIR TEMPERATURE, oF:                                           .0
     OUTSIDE DIAMETER OF PIPE, in.:                              7.981
     ALLOWANCE FOR TRACER DIAMETER, in.:                          1.25
     INSULATION THICKNESS, in.:                                   2.50
     THERMAL CONDUCTIVITY OF INSULATION, Btu/hr.ft^2(oF/ft        .033
     SPECIFIC HEAT OF HOT MEDIUM, Btu/Ib.oF:                      .530
     FILM HEAT TRANSFER COEFFICIENT TO AIR
     CORRECTED FOR WIND, Btu/ft^2.hr.oF:                         4.000
     THERMAL CONDUCTANCE TRACER TO PIPE
     WITHOUT CEMENT, Btu/hr.oF.ft of pipe:                        .393
     THERMAL CONDUCTANCE TRACER TO PIPE
     WITH CEMENT, Btu/hr.oF.ft of pipe:                          4.580
     OUTSIDE SURFACE TEMPERATURE OF INSULATION, oF:             16.972
     THE COMBINED CONVECTIVE AND RADIATIVE
     HEAT TRANSFER COEFFICIENT, Btu/h.oF.ft^2:                   1.330
     WIND FACTOR:                                                2.807
     HEAT TRANSFER COEFFICIENT TO AIR
     CORRECTED FOR THE WIND, Btu/hr.ft^2.oF:                     3.734
     HEAT LOSS PER FOOT OF PIPE, Btu/hr.ft:                    252.934
     TOTAL HEAT LOSS FROM PIPELINE, Btu/hr.:                 25293.430
     FLOW RATE OF HOT MEDIUM, lb/hr.:                          596.543
     THE NUMBER OF TRACERS WITHOUT HEAT TRANSFER CEMENT:          7.15
     THE NUMBER OF TRACERS WITH HEAT TRANSFER CEMENT:              .61
----------------------------------------------------------------------------
```

```
     HEAT LOSS FROM AN INSULATED PIPE WITHOUT TRACING
****************************************************************************
     OUTSIDE SURFACE TEMPERATURE OF INSULATION, oF:             15.202
     THE COMBINED CONVECTIVE AND RADIATIVE
     HEAT TRANSFER COEFFICIENT, Btu/h.oF.ft^2:                   1.344
     WIND FACTOR:                                                2.808
     HEAT TRANSFER COEFFICIENT TO AIR
     CORRECTED FOR THE WIND, Btu/hr.ft^2.oF:                     3.774
     HEAT LOSS PER FOOT OF PIPE, Btu/hr.ft:                    206.652
     TOTAL HEAT LOSS FROM PIPELINE, Btu/hr.:                 20665.240
```

problem. The approximate number of tracers without the heat transfer cement of an 8-inch (Schedule 40) process line is 7. The heat transfer cement reduces the number required to 1. The circulation rate of the tracing medium is 596.5 lb/hr, and the heat lost from 100 ft. of pipe line is 25293.4 Btu/hr.

Problem 8-6
(Internal Coil, Isothermal Heating Medium)

A tank containing 55,000 lb (24947.6 kg) of material with a specific heat of 0.5 Btu/lb °F (2.093 kJ/kg.K) is heated from 72°F (295.4K) to 260°F (399.8K). The tank contains a heating coil with a heat transfer surface of 110 ft^2 (10.22m^2), and the overall heat transfer coefficient from the coil to the tank contents is 150 Btu/(hr)(ft^2)(°F)(851.7 W/m^2.K). Calculate the time required to heat the tank contents with steam condensing at 350°F (449.8K).

Solution

When heating a batch reactor with an internal coil under isothermal condition, Equation 8-135 applies:

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \frac{UA}{Mc}.\theta \tag{8-135}$$

The time, θ, required to heat the tank contents with steam condensing at 350°F is,

$$\theta = \frac{\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right)}{\left(\frac{UA}{Mc}\right)}, \quad hr$$

$$= \frac{\ln\left(\frac{350 - 72}{350 - 260}\right)}{\left(\frac{150 \times 110}{55,000 \times 0.5}\right)}$$

$$= 1.87\ hr$$

Problem 8-7
Batch Cooling: External Heat Exchanger (Counterflow), Non-isothermal Cooling Medium

For the tank described in PROBLEM 8-6, calculate the time required to cool the batch from 260°F (399.8K) to 150°F (338.7K), if an external heat exchanger with a heat transfer surface of 250ft^2 (23.23m^2) is available. The batch material is circulated through the exchanger at the rate of 30,000 lb/hr (13608 kg/h). Cooling water is available at a temperature of 85°F (302.6K) and a flow rate of 10,000 lb/hr (4536 kg/h). The overall heat transfer coefficient in the heat exchanger is 250 Btu/hr ft^2 °F (1419.5 W/m^2 K).

Solution

Equation 8-169 applies when cooling a batch with an external heat exchanger and a non-isothermal cooling medium.

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{K_5 - 1}{M}\right)\left(\frac{W_b W_c C_c}{K_5 W_c C_c - W_b c}\right)\theta \tag{8-169}$$

where

$$K_5 = \exp\left\{UA\left(\frac{1}{W_b c} - \frac{1}{W_c C_c}\right)\right\}$$

Using the values in Table 8-26, K_5 is calculated as follows:

$$K_5 = \exp\left\{250 \times 250\left(\frac{1}{30,000 \times 0.5} - \frac{1}{10,000 \times 1.0}\right)\right\}$$

$$= 0.1245$$

The time, θ, required to cool the batch is determined from Equation 8-169,

$$\ln\left\{\frac{260 - 85}{260 - 85}\right\} = \left(\frac{0.125 - 1}{55,000}\right)$$

$$\times\left(\frac{30,000(10,000)(1.0)}{0.1245(10,000)(1.0) - (30,000)(0.5)}\right)\theta$$

$$\theta = 2.854 \text{ hr}$$

Table 8-26

A =250	W_b = 30,000	M =55,000	C =0.5	T_2 = 150°F
U =250	W_c = 10,000	C_c = 1.0	T_1 = 260°F	t_1 = 85°F

Problem 8-8

8000 gal (30.28m^3) of liquid hydrocarbon under pressure at 350°F (449.8K) is required for a batch extraction process. The storage temperature of the liquid is 100°F (310.9K). Available as a heating medium is a 12,000 lb/hr (5443.2 kg/h) 28° API oil stream at a temperature of 400°F (477.6K). A pump connected to the batch is capable of circulating 50,000 lb/hr (22680.0 kg/h) of the hydrocarbon. Available for the service is 400 ft^2 (37.16m^2) of clean double pipe exchanger surface that gives a U_c of 50 Btu/hrft^2°F (283.9 W/m^2.K) in counterflow streams.

Calculate for the flow rates:

1. The time required to heat the agitated batch using the double pipe countercurrent flow exchanger.
2. The time required using a 1-2 exchanger with the same surface and coefficient.
3. The time required using a 2-4 exchanger with the same surface and coefficient.

Physical property data:

Liquid hydrocarbon
Specific gravity: 0.88
Specific heat capacity: 0.48 Btu/lb °F (2.01kJ/kg.K)

28° API oil:
Specific heat capacity: 0.6 Btu/lb °F (2.51 kJ/kg.K)

Solution

Volume of liquid hydrocarbon in the batch = 8000 gal
Specific gravity = 0.88

$$\text{Mass (M) of liquid hydrocarbon in the batch} = 8000 \times 0.88 \times 8.34$$
$$= 58713.6$$
$$\approx 59{,}000 \text{ lb.}$$

Table 8-27

$V = 8000$	$W_h = 12{,}000$	$C_h = 0.6$	$A = 400$	$t_1 = 100°F$
$W_b = 50{,}000$	$U_c = 50$	$c = 0.48$	$T_1 = 400°F$	$t_2 = 350°F$

(1) The time required to heat the agitated batch using the double pipe countercurrent exchanger can be determined from Equation 8-170.

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{K_6 - 1}{M}\right)\left(\frac{W_b W_h C_h}{K_6 W_h C_h - W_b c}\right)\theta$$

where

$$K_6 = \exp\left\{UA\left(\frac{1}{W_b c} - \frac{1}{W_h C_h}\right)\right\}$$

$$W_b c = (50,000)(0.48)$$

$$= 24,000$$

$$W_h C_h = (12,000)(0.60)$$

$$= 7,200$$

$$K_6 = \exp\left\{(50 \times 400)\left(\frac{1}{24,000} - \frac{1}{7,200}\right)\right\}$$

$$= 0.143$$

$$\ln\left(\frac{400 - 100)}{400 - 300}\right) = \left(\frac{0.143 - 1}{59,000}\right)\left(\frac{(50,000)(12,000)}{}\right)$$

$$\ln\left(\frac{400 - 100)}{400 - 350}\right) = \left(\frac{0.143 - 1}{59,000}\right)\left(\frac{(50,000)(12,000)(0.6)}{(0.143)(7,200) - 24,000}\right)\theta$$

$$\theta = 7.87\text{ hr}$$

(2) Equation 8-177 applies for the time to heat the agitated batch using a 1-2 exchanger.

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \left(\frac{S.W_b}{M}\right)\theta \tag{8-177}$$

and

$$S = \frac{2(K_7 - 1)}{K_7\left\{R + 1 + (R^2 + 1)^{0.5}\right\} - \left\{R + 1 - (R^2 + 1)^{0.5}\right\}} \tag{8-178}$$

where

$$K_7 = \exp\left\{\frac{UA}{W_b c}(R^2 + 1)^{0.5}\right\}$$

and

$$R = \frac{W_b c}{W_h C_h}$$

$$= \frac{24,000}{7,200}$$

$$= 3.33$$

$$K_7 = \exp\left\{\frac{(50)(400)}{24,000}(3.33^2 + 1)^{0.5}\right\}$$

$$= 18.127$$

Substituting the value of K_7 into Equation 8-178 gives,

$$S = \frac{2(18.127 - 1)}{18.127\left\{3.33 + 1 + (3.33^2 + 1)^{0.5}\right\} - \left\{3.33 + 1 - (3.33^2 + 1)^{0.5}\right\}}$$

$$= 0.2435$$

The value of S in Equation 8-177 gives

$$\ln\left(\frac{400 - 100)}{400 - 350}\right) = \left(\frac{0.2435 \times 50,000}{59,000}\right)\theta$$

$$\theta = 8.68 \text{ hr}$$

(3) Equations 8-177, 8-179, and 8-180 apply for the time to heat the agitated batch using a 2-4 exchanger.

$$S = \frac{2(K_8 - 1)\left\{1 + [(1 - S)(1 - RS)]^{0.5}\right\}}{(K_8 - 1)(R + 1) + (K_8 + 1)(R^2 + 1)^{0.5}} \tag{8-179}$$

and

$$K_8 = \exp\left\{\frac{UA}{2W_b c}(R^2+1)^{0.5}\right\} \tag{8-180}$$

Equation 8-179 is an implicit equation involving S on both sides, and can be solved by trial and error until an equality is reached. Rearranging Equation 8-179 gives

$$\begin{aligned} &\text{LHS} \qquad\qquad\qquad\qquad \text{RHS} \\ &S\{(K_8-1)(R+1)+(K_8+1)(R^2+1)^{0.5}\} \\ &\qquad = 2(K_8-1)\{1+[(1-S)(1-RS)]^{0.5}\} \end{aligned} \tag{8-181}$$

$$K_8 = \exp\left\{\left(\frac{50\times 400}{2\times 50{,}000\times 0.48}\right)(3.33^2+1)^{0.5}\right\}$$

$$= 4.2576$$

$$R = 3.33$$

Substituting S = 0.262 in Equation 8-177 gives

$$\ln\left(\frac{400-100)}{400-350}\right) = \left(\frac{0.262\times 50{,}000}{59{,}000}\right)\theta$$

$$\theta = 8.07\ \text{hr}$$

Table 8-28

S	LHR	RHS
0.260	8.418	8.566
0.261	8.45	8.539
0.262	8.588	8.573
0.263	8.515	8.485

References

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```
      PROGRAM PROG81

C     THIS PROGRAM CALCULATES THE CORRECTED L.M.T.D. IN SHELL-AND-TUBE
C     HEAT EXCHANGERS

C     THE PROGRAM CALCULATES:
C     1.  THE IDEAL AND TRUE MEAN TEMPERATURE DIFFERENCE FOR ONE
C         OR MORE EXCHANGER IN SERIES.
C     2.  THE PROGRAM WILL INCREASE THE NUMBER OF EXCHANGER SHELL
C         UNTIL A 'REASONABLE' F-FACTOR IS OBTAINED THUS ELIMINATING
C         THE NEED FOR THE CHARTS AND GRAPHS NORMALLY USED TO CALCULATE
C         F-FACTORS FOR SHELL-AND-TUBE HEAT EXCHANGERS.
C
C         THE PROGRAM IS BASED ON THE FOLLOWING ASSUMPTIONS:
C
C     1.  THE HOT AND COLD FLUIDS FLOW COUNTERCURRENT TO EACH OTHER.
C     2.  THE OVERALL HEAT TRANSFER COEFFICIENT (U) IS CONSTANT
C         THROUGHOUT THE HEAT EXCHANGER.
C     3.  THE FLOW RATE OF EACH FLUID IS CONSTANT.
C     4.  THE SPECIFIC HEAT OF EACH FLUID IS CONSTANT.
C     5.  THERE IS NO CONDENSATION OF VAPOR OR BOILING OF LIQUID
C         IN ANY PART OF THE EXCHANGER.
C     6.  HEAT LOSSES ARE NEGLIGIBLE.
C     7.  THERE IS EQUAL HEAT TRANSFER SURFACE IN EACH PASS.
C     8.  THE TEMPERATURE OF THE SHELL-SIDE FLUID IN ANY SHELL-SIDE
C         PASS IS UNIFORM OVER ANY CROSS-SECTION.
C
C     *****************************************************************
C     TH1     = HOT FLUID INLET TEMPERATURE, oF.
C     TH2     = HOT FLUID OUTLET TEMPERATURE, oF.
C     TC1     = COLD FLUID INLET TEMPERATURE, oF.
C     TC2     = COLD FLUID OUTLET TEMPERATURE, oF.
C     N       = NUMBER OF SERIES EXCHANGER SHELLS REQUIRED.
C     LMTD    = LOG MEAN TEMPERATURE DIFFERENCE.
C     F       = CORRECTION FACTOR.
C     DELT1   = TH2-TC1, oF.
C     DELT2   = TH1-TC2, oF.
C     DELT    = LMTD.
C     *****************************************************************

      REAL LMTD, N

      OPEN (UNIT=3, FILE='DATA81.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT=1, FILE='PRN')

C     READ THE HOT FLUID INLET TEMPERATURE, oF: TH1
C     READ THE HOT FLUID OUTLET TEMPERATURE, oF: TH2
C     READ THE COLD FLUID INLET TEMPERATURE, oF: TC1
C     READ THE COLD FLUID OUTLET TEMPERATURE, oF: TC2
C     READ THE INITIAL NUMBER OF SERIES EXCHANGER SHELLS REQUIRED: N

      READ (3, *, ERR=19) TH1, TH2
      READ (3, *, ERR=19) TC1, TC2
      READ (3, *, ERR=19) N
      GO TO 10
```

```
18      WRITE (*, 100)
100     FORMAT (6X, 'DATA FILE DOES NOT EXIST')
        GO TO 999

19      WRITE (*, 110)
110     FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999

10      WRITE (1, 120)
120     FORMAT (///,10X,'THE CORRECTED LMTD IN A SHELL AND TUBE HEAT',\)

        WRITE (1, 130)
130     FORMAT (' EXCHANGER',/1H ,78(1H*))


        WRITE (1, 140) TH1, TH2
140     FORMAT(6X,'HOT FLUID INLET TEMPERATURE, oF:', T60, F9.3,/,6X,
     *          'HOT FLUID OUTLET TEMPERATURE, oF:',T60, F9.3)

        WRITE (1, 150) TC1, TC2
150     FORMAT(6X,'COLD FLUID INLET TEMPERATURE, oF:',T60, F9.3,/,6X,
     *          'COLD FLUID OUTLET TEMPERATURE, oF:', T60, F9.3)

        WRITE (1, 160) N
160     FORMAT(6X,'NUMBER OF SERIES EXCHANGER SHELLS:',T60,F4.0)


        P = (TC2-TC1)/(TH1-TC1)
        R = (TH1-TH2)/(TC2-TC1)
        RSQRT = (R**2+1.)**0.5

15      IF (R .EQ. 1.0) THEN
        GO TO 25
        ELSE
        VAL1 = 1.0-((P*R-1.0)/(P-1.0))**(1./N)
        VAL2 = R-((P*R-1.0)/(P-1.0))**(1./N)
        P1 = VAL1/VAL2
        ENDIF

        VAL3 = (2.0/P1)-1.0-R+RSQRT
        VAL4 = (2.0/P1)-1.0-R-RSQRT

        A = VAL3/VAL4

        IF ( A .LT. 0.0) THEN
        GO TO 30
        ELSE
        VAL5 = (RSQRT/(R-1.0))*ALOG((1.0-P1)/(1.0-P1*R))
        F = VAL5/ALOG(A)
        ENDIF

        GO TO 40

30      N = N+1

        GO TO 15

25      P2 = P/(N-P*(N-1.))
        VAL6 = (2.0/P2)-2.0+RSQRT
```

```
        VAL7 = (2.0/P2)-2.0-RSQRT
        B = VAL6/VAL7
        IF (B .LT. 0.0) THEN
        GO TO 30
        ELSE
        VAL8 = (RSQRT*P2)/(1.0-P2)
        F = VAL8/ALOG(B)
        ENDIF

 40     IF ( F .GT. 0.75) THEN
        GO TO 45
        ELSE
        N = N+1
        GO TO 15
        ENDIF

 45     DELT1 = TH1-TC2
        DELT2 = TH2-TC1
        IF (DELT1 .EQ. DELT2) THEN
        GO TO 50
        ELSE

C       CALCULATE THE LOG MEAN TEMPERATURE DIFFERENCE

        LMTD = (DELT1-DELT2)/ALOG(DELT1/DELT2)
        ENDIF
        GO TO 55

 50     DELT = LMTD

C       CALCULATE THE CORRECTED LOG MEAN TEMPERATURE DIFFERENCE

 55     CLMTD = F*LMTD

        WRITE (1, 170) N, F, LMTD, CLMTD
 170    FORMAT (6X,'THE NUMBER OF SHELLS REQUIRED:',T60, F4.0,/,6X,
     *         'THE F- FACTOR:',T60, F8.4,/,6X,
     *         'THE LOG MEAN TEMPERATURE DIFFERENCE,oF:',T60,F8.4,/,6X,
     *         'THE CORRECTED LMTD, oF:',T60, F8.4)

        WRITE (1, 180)
 180    FORMAT (1H ,78(1H-))


C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE (3,STATUS='KEEP')
        CLOSE (1)
 999    STOP
        END
```

```
      PROGRAM PROG82

C     ************************************************************
C     THIS PROGRAM RATES A SHELL AND TUBE HEAT EXCHANGER WITH
C     EITHER A SINGLE SHELL PASS AND ANY MULTIPLE OF TWO TUBE
C     PASSES OR TWO OR MORE SHELL PASSES.
C     THE PROGRAM ASSUMES THAT THERE IS NO CHANGE OF PHASE.
C
C     THE PROGRAM USES DEVELOPED CORRELATIONS FOR FRICTION FACTORS
C     IN BOTH THE SHELL AND TUBE SIDES.  HEDRICK'S CORRELATION
C     (Chem. Eng. June, 1990) FOR ESTIMATING THE HEAT TRANSFER
C     COEFFICIENT FOR TUBES IN THE TRANSITION REGION IS EMPLOYED
C     IN THE PROGRAM.
C     ***********************************************************

C     NOMENCLATURE:                    TUBE SIDE
C
C      1.     FLUID TYPE                                =      FTS
C      2.     NUMBER OF TUBES                           =      NT
C      3.     TUBE INSIDE DIA., inch                    =      TID
C      4.     TUBE OUTSIDE DIA., inch                   =      TOD
C      5.     TUBE PITCH, inch                          =      TP
C      6.     PITCH TYPE (TRIANGLE/SQUARE)              =      T/S
C      7.     TUBE LENGTH, ft.                          =      TL
C      8.     NUMBER OF PASSES                          =      TNP
C      9.     FOULING FACTOR                            =      TFF
C      10.    INLET TEMPERATURE, oF                     =      TT1
C      11.    OUTLET TEMPERATURE, oF                    =      TT2
C      12.    SPECIFIC HEAT CAPACITY (Btu/lboF)         =      TSHC
C      13.    VISCOSITY, cP                             =      TVIS
C      14.    DENSITY, lb/ft^3.                         =      TDEN
C      15.    FLUID THERMAL CONDUCTIVITY, (Btu/ft.h.oF)=       TFK
C      16.    MASS FLOWRATE, lb/hr.                     =      TW
C
C             NOMENCLATURE:            SHELL SIDE
C
C      1.     FLUID TYPE                                =      FSS
C      2.     NUMBER OF SHELL PASSES                    =      NS
C      3.     SHELL INSIDE DIA., inch                   =      SID
C      4.     NUMBER  OF BAFFLES                        =      NB
C      5.     BAFFLE SPACING, inch                      =      BSP
C      6.     FOULING FACTOR                            =      SFF
C      7.     INLET TEMPERATURE, oF                     =      TS1
C      8.     OUTLET TEMPERATURE, oF                    =      TS2
C      9.     SPECIFIC HEAT CAPACITY, (Btu/lb.oF)       =      SSHC
C      10.    VISCOSITY, cP                             =      SVIS
C      11.    DENSITY, lb/ft.^3                         =      SDEN
C      12.    FLUID THERMAL CONDUCTIVITY, (Btu/ft.h.oF)=       SFK
C      13.    MASS FLOWRATE, lb/hr.                     =      SW
C      **********************************************************

      PARAMETER (PI = 3.1415927, G=32.174)


      CHARACTER*30 FTS,FSS
      CHARACTER TYPE
C
      COMMON/TUBE1/ FTS, TYPE
      COMMON/TUBE2/ NT, TID, TOD, TP, TL, TNP
```

```
        COMMON/TUBE3/ TFF, TT1, TT2, TSHC, TVIS, TDEN
        COMMON/TUBE4/ TFK, TW
        COMMON/TUBE5/ RET, PRT, TFRF, HT, TV
        COMMON/TUBE6/ TDELP, TRDELP, TOTDP

        COMMON/SHELL1/ FSS
        COMMON/SHELL2/ NS, SID, NB, BSP, SFF
        COMMON/SHELL3/ TS1, TS2, SSHC, SVIS, SDEN
        COMMON/SHELL4/ SFK, SW
        COMMON/SHELL5/ RES, PRS, SFRF, HS, SV
        COMMON/SHELL6/ SDELP

        COMMON/OUT/ Q, AREA, F, LMTD, U, Q1, CMTD

        REAL NT, NS, NB, LMTD

        OPEN (UNIT = 3, FILE='DATA82.DAT', STATUS='OLD', ERR= 18)
        OPEN (UNIT = 1, FILE='PRN')


C       READ THE TUBE SIDE HEAT EXCHANGER PARAMETERS


C       READ THE FLUID TYPE: FTS

        READ (3, 11, ERR=19)FTS
 11     FORMAT (A)

C       READ THE NUMBER OF TUBES: NT
C       READ THE TUBE INSIDE DIAMETER, inch: TID
C       READ THE TUBE OUTSIDE DIAMETER, inch: TOD
C       READ THE TUBE PITCH, inch: TP
C       READ THE TYPE OF PITCH (TRIANGULAR: T) or (SQUARE: S): TYPE


        READ (3, *, ERR=19) NT, TID, TOD, TP
        READ (3, 12, ERR=19) TYPE
 12     FORMAT (A)


C       READ THE TUBE LENGTH, ft.: TL
C       READ THE NUMBER OF PASSES: TNP
C       READ THE TUBE SIDE FOULING FACTOR: TFF
C       READ THE INLET TEMPERATURE, oF: TT1
C       READ THE OUTLET TEMPERATURE, oF: TT2
C       READ THE SPECIFIC HEAT CAPACITY OF FLUID, (Btu/lb.oF): TSHC
C       READ THE FLUID VISCOSITY, cP: TVIS
C       READ THE FLUID DENSITY, lb/ft^3: TDEN
C       READ THE FLUID THERMAL CONDUCTIVITY, Btu/hr.ft.oF.: TFK
C       READ THE FLUID FLOWRATE, lb/hr.: TW


        READ (3, *, ERR=19) TL, TNP, TFF, TT1
        READ (3, *, ERR=19) TT2, TSHC, TVIS, TDEN
        READ (3, *, ERR=19) TFK, TW

C       READ THE SHELL SIDE HEAT EXCHANGER PARAMETERS


C       READ THE FLUID TYPE: FSS
```

```
        READ (3, 13, ERR=19)FSS
 13     FORMAT (A)

C       READ THE NUMBER OF SHELL: NS
C       READ THE SHELL SIDE INSIDE DIAMETER, inch: SID
C       READ THE NUMBER OF BAFFLES: NB
C       READ THE BAFFLE SPACING, inch: BSP
C       READ THE SHELL SIDE FOULING FACTOR, SFF
C       READ THE INLET TEMPERATURE, oF: TS1
C       READ THE OULET TEMPERATURE, oF: TS2
C       READ THE SHELL SIDE SPECIFIC HEAT CAPACITY, Btu/lb.oF.: SSHC
C       READ THE FLUID VISCOSITY, cP: SVIS
C       READ THE FLUID DENSITY, lb/ft^3.: SDEN
C       READ THE FLUID THERMAL CONDUCTIVITY, Btu/hr.ft.oF.: SFK
C       READ THE FLUID FLOWRATE, lb/hr.: SW.


        READ (3, *, ERR=19) NS, SID, NB, BSP
        READ (3, *, ERR=19) SFF, TS1, TS2, SSHC
        READ (3, *, ERR=19) SVIS, SDEN, SFK, SW

        GO TO 15

 18     WRITE (*, 20)
 20     FORMAT (3X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999
 19     WRITE (*, 21)
 21     FORMAT (3X, 'DATA VALUE DOES NOT EXIST')
        GO TO 999


C       TUBE SIDE CALCULATION

 15     CALL TUBE


C       SHELL SIDE CALCULATION

        CALL SHELL

C       CALCULATE THE HEAT LOAD

        Q = TW*TSHC*ABS(TT2-TT1)

C       CALCULATE THE LOG MEAN TEMPERATURE DIFFERENCE (LMTD)

        VAL1 = (TS1-TT2)-(TS2-TT1)
        VAL2 = ALOG((TS1-TT2)/(TS2-TT1))
        LMTD = ABS(VAL1/VAL2)


C       CALCULATE THE APPROACH FACTOR

        R = (TS1-TS2)/(TT2-TT1)
        P = (TT2-TT1)/(TS1-TT1)


        IF (NS .EQ. 1.0 .AND. R .EQ. 1.0) THEN
        PX = P/(NS-NS*P+P)
```

```
        SUM1 = (PX*(R*R+1.0)**0.5)/(1.0-PX)
        SUM2 = 2.0/PX-1.0-R+(R*R+1.0)**0.5
        SUM3 = 2.0/PX-1.0-R-(R*R+1.0)**0.5
        SUM4 = ALOG(SUM2/SUM3)


        F = SUM1/SUM4

        GO TO 100

        ELSEIF (NS .EQ. 1.0 .AND. R .GT. 1.0) THEN
 55     SUM5 = ((R*P-1.0)/(P-1.0))**(1.0/NS)
        PX = (1.0-SUM5)/(R-SUM5)
        SUM6 = (R*R+1.0)**0.5/(R-1.0)
        SUM7 = ALOG((1.0-PX)/(1.0-R*PX))
        SUM41 = ((2.0/PX)-1.0-R+(R*R+1.0)**0.5)
        SUM42 = ((2.0/PX)-1.0-R-(R*R+1.0)**0.5)

        IF (SUM41 .LT. 0.0 .OR. SUM42 .LT. 0.0) THEN
        NS = NS+1.
        TNP = TNP+2.
        GO TO 55
        ELSE
        SUM43 = ALOG(SUM41/SUM42)
        ENDIF

        F = (SUM6*SUM7)/SUM43

        IF (F .LT. 0.8) THEN
        NS = NS+1.0
        TNP = TNP+2.
        GO TO 55
        ELSE
        END IF

        GO TO 100

        ELSEIF (NS .GE. 2.0 .AND. NT .GE. 4.0) THEN

        SUM8 = (R*R+1.0)**0.5/(2.0*(R-1.0))
        SUM9 = ALOG((1.0-P)/(1.0-P*R))
        SUM10 = 2/P-1.0-R+((2/P)*((1.0-P)*(1-P*R))**0.5)+(R*R+1.)**0.5
        SUM11 = 2/P-1.0-R+((2/P)*((1.0-P)*(1.-P*R))**0.5)-(R*R+1.)**0.5

        F = (SUM8*SUM9)/ALOG(SUM10/SUM11)
        ENDIF

C       CORRECTED MEAN TEMPERATURE DIFFERENCE

 100    CMTD = F*LMTD

C       CALCULATE THE OVERALL HEAT TRANSFER COEFFICIENT
C       Btu/hr.ft^2.oF

        U = 1.0/(1./HT+1./HS+TFF+SFF)

C       CALCULATE THE OUTSIDE AREA OF THE HEAT EXCHANGER UNIT ft^2.

        AREA = (TOD/12.0*PI*NT*NS*TL)
```

```
      Q1 = AREA*U*CMTD

      CALL RESULT


C     FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)

      CLOSE (UNIT =3, STATUS='KEEP')
      CLOSE (UNIT = 1)
 999  STOP
      END
```

```
C     *******************************************************************
C     *THIS PROGRAM CALCULATES THE TUBE SIDE HEAT TRANSFER COEFFICIENT,   *
C     *REYNOLDS NUMBER, PRANDTL NUMBER, FRICTION FACTOR AND PRESSURE DROP.*
C     *******************************************************************


      SUBROUTINE TUBE

      PARAMETER (PI = 3.1415927, G=32.174)
      CHARACTER*30 FTS,FSS
      CHARACTER TYPE

      COMMON/TUBE1/ FTS, TYPE
      COMMON/TUBE2/ NT, TID, TOD, TP, TL, TNP
      COMMON/TUBE3/ TFF, TT1, TT2, TSHC, TVIS, TDEN
      COMMON/TUBE4/ TFK, TW
      COMMON/TUBE5/ RET, PRT, TFRF, HT, TV
      COMMON/TUBE6/ TDELP, TRDELP, TOTDP

      COMMON/SHELL1/ FSS
      COMMON/SHELL2/ NS, SID, NB, BSP, SFF
      COMMON/SHELL3/ TS1, TS2, SSHC, SVIS, SDEN
      COMMON/SHELL4/ SFK, SW
      COMMON/SHELL5/ RES, PRS, SFRF, HS, SV
      COMMON/SHELL6/ SDELP

      COMMON/OUT/ Q, AREA, F, LMTD, U, Q1, CMTD

      REAL NT, NS, NB, LMTD

C     CALCULATE THE FLOW AREA: TFA, ft^2

      TFA = (PI*TID**2*NT)/(4.0*144.0*TNP)

C     CALCULATE THE MASS VELOCITY, lb/hr.ft^2

      GT = TW/TFA

C     CALCULATE THE REYNOLDS NUMBER: RET

      RET = (GT*TID)/(12.0*2.42*TVIS)

C     CALCULATE THE PRANDTL NUMBER: PRT

      PRT = (TSHC*TVIS*2.42)/TFK

C     CHECK THAT THE REYNOLDS NUMBER IS IN THE TRANSITION REGION
C     (i.e. 2000<RET<10,000)

      IF (RET .GT. 2000.0 .AND. RET .LT. 10000.0) THEN
      X1 = RET/1000.0
      X2 = 10.0*TID/TL
      X3 = (1.0-(X1/10.0)**0.256)
      X4 = X2**X3
      B1 = (-3.08+3.075*X1+(0.32567*X1**2)-(0.02185*X1**3))*X4
      HT = (16.1/TOD)*(B1*TFK*PRT**0.33)

      GO TO 110

      ELSE IF (RET .GT. 10000.0) THEN
```

```
       HT = 0.027*TFK*(12.0/TID)*(RET**0.8)*(PRT**0.33)
       ENDIF

 110   HT = HT*TID/TOD

C      CALCULATE THE TUBE FRICTION FACTOR

       IF (RET .GT. 1000.0) THEN
       TFRF = 0.0029/(RET**0.25603)
       ELSE
       ENDIF

C      CALCULATE THE FLUID VELOCITY, ft./s.

       TV = GT/(3600.0*TDEN)

C      CALCULATE THE TUBE SIDE PRESSURE DROP, psi.

       TDELP = (TFRF*(GT/3600.0)**2*TL*TNP)/(2.0*G*TDEN*TID/12.0)

C      CALCULATE THE PRESSURE DROP OF RETURN LOSSES, psi.
C      USING FRANK'S CORRELATION.

       TRDELP = (2.5*TNP*TDEN*TV**2)/(2*G*144.0)

C      CALCULATE THE TOTAL PRESSURE DROP EXCLUDING THE NOZZLE IN THE
C      TUBE SIDE, psi.

       TOTDP = TDELP+TRDELP

       RETURN
       END
```

```
C       *****************************************************************
C       *THIS PROGRAM CALCULATES THE SHELL SIDE HEAT TRANSFER           *
C       *COEFFICIENT, REYNOLDS NUMBER, PRANDTL NUMBER, FRICTION FACTOR *
C       *AND PRESSURE DROP.                                             *
C       *****************************************************************

        SUBROUTINE SHELL

        PARAMETER (PI = 3.1415927, G=32.174)
        CHARACTER*30 FTS, FSS
        CHARACTER TYPE

        COMMON/TUBE1/ FTS, TYPE
        COMMON/TUBE2/ NT, TID, TOD, TP, TL, TNP
        COMMON/TUBE3/ TFF, TT1, TT2, TSHC, TVIS, TDEN
        COMMON/TUBE4/ TFK, TW
        COMMON/TUBE5/ RET, PRT, TFRF, HT, TV
        COMMON/TUBE6/ TDELP, TRDELP, TOTDP

        COMMON/SHELL1/ FSS
        COMMON/SHELL2/ NS, SID, NB, BSP, SFF
        COMMON/SHELL3/ TS1, TS2, SSHC, SVIS, SDEN
        COMMON/SHELL4/ SFK, SW
        COMMON/SHELL5/ RES, PRS, SFRF, HS, SV
        COMMON/SHELL6/ SDELP

        COMMON/OUT/ Q, AREA, F, LMTD, U, Q1, CMTD

        REAL NT, NS, NB, LMTD

C       CHECK WHETHER PITCH TYPE IS TRIANGULAR OR SQUARE


        IF (TYPE .EQ. 'T' .OR. TYPE .EQ. 't') THEN

        DE = ((1.72*TP**2)-(0.5*PI*TOD**2))/(0.5*PI*12.0*TOD)

        GO TO 120

        ELSE IF (TYPE .EQ. 'S' .OR. TYPE .EQ. 's') THEN

        DE = 4.*((TP**2)-(PI*TOD**2/4.0))/(PI*12.0*TOD)
        ENDIF

C       CALCULATE THE TUBE CLEARANCE, inch

 120    TC = TP-TOD

C       CALCULATE THE SHELL FLOW AREA, ft^2.

        IF (NS .GE. 2.0 .AND. NT .GE. 4.0) THEN

        SFA = (0.5*(SID*TC*BSP))/(144.0*TP)

        GO TO 130

        ELSE

        SFA = (SID*TC*BSP)/(144.0*TP)
        ENDIF
```

```
C        CALCULATE THE SHELL SUPERFICIAL FLOW RATE, lb/ft^2.hr.

 130     GS = SW/SFA

C        CALCULATE THE SHELL VELOCITY, ft./sec.

         SV = SW/(3600.0*SDEN*SFA)

C        CALCULATE THE REYNOLDS NUMBER

         RES = (DE*GS)/(2.42*SVIS)

C        CALCULATE THE PRANDTL NUMBER

         PRS = (2.42*SSHC*SVIS)/SFK


C        CALCULATE THE SHELL SIDE HEAT TRANSFER COEFFICIENT

         HS = 0.36/DE*SFK*(RES**0.55)*(PRS**0.333)

C        CHECK WHETHER THE SHELL'S REYNOLDS NUMBER IS LESS OR GREATER
C        THAN 500

         IF (RES .LT. 500.0) THEN

         SFRF = 0.11183/(RES**0.59246)

         GO TO 140

         ELSEIF (RES .GT. 500.0) THEN

         SFRF = 0.01159/(RES**0.18597)
         ENDIF


C        CALCULATE THE SHELL SIDE PRESSURE DROP, psi.

 140     VAL1 = SFRF*(GS/3600.0)**2*SID/12.0*(NB+1.)
         VAL2 = 64.4*SDEN*DE
         SDELP = (VAL1/VAL2)*NS

C
         RETURN
         END
```

```
C      ***************************************************************
C      THIS PROGRAM PRINTS THE RESULTS OF THE SHELL AND TUBE HEAT
C      EXCHANGER ONTO A PRINTER
C      ***************************************************************

       SUBROUTINE RESULT
       CHARACTER*30 FTS,FSS
       CHARACTER TYPE

       COMMON/TUBE1/ FTS, TYPE
       COMMON/TUBE2/ NT, TID, TOD, TP, TL, TNP
       COMMON/TUBE3/ TFF, TT1, TT2, TSHC, TVIS, TDEN
       COMMON/TUBE4/ TFK, TW
       COMMON/TUBE5/ RET, PRT, TFRF, HT, TV
       COMMON/TUBE6/ TDELP, TRDELP, TOTDP

       COMMON/SHELL1/ FSS
       COMMON/SHELL2/ NS, SID, NB, BSP, SFF
       COMMON/SHELL3/ TS1, TS2, SSHC, SVIS, SDEN
       COMMON/SHELL4/ SFK, SW
       COMMON/SHELL5/ RES, PRS, SFRF, HS, SV
       COMMON/SHELL6/ SDELP

       COMMON/OUT/ Q, AREA, F, LMTD, U, Q1, CMTD

       REAL NT, NS, NB, LMTD

       WRITE (1, 150)
 150   FORMAT (///,18X,'*SHELL AND TUBE HEAT EXCHANGER RATING*')

       WRITE (1, 160)
 160   FORMAT (78(1H*))

       WRITE (1, 170)
 170   FORMAT (40X,'TUBE SIDE',10X,'SHELL SIDE')

       WRITE (1, 180)
 180   FORMAT (78(1H-))

       WRITE (1, 190) FTS, FSS
 190   FORMAT (2X,'FLUID TYPE:',T40, A15, T60, A15)

       WRITE (1, 200) TW, SW
 200   FORMAT (2X,'FLUID FLOW RATE , lb/hr.:',T40, F10.0,T60,F10.0)

       WRITE (1, 210) TSHC, SSHC
 210   FORMAT (2X,'SPECIFIC HEAT CAPACITY, Btu/lb.oF:',T40, F8.3,T60,
     *        F8.3)

       WRITE (1, 220)TDEN, SDEN
 220   FORMAT (2X,'FLUID DENSITY, lb/ft^3:',T40,F8.3,T60,F8.3)

       WRITE (1, 230) TVIS, SVIS
 230   FORMAT (2X,'FLUID VISCOSITY, cP:',T40,F8.3,T60,F8.3)

       WRITE (1, 240) TFK, SFK
 240   FORMAT (2X,'FLUID THERMAL COND. Btu/ft.h.oF:',T40,F8.3,T60,F8.3)

       WRITE (1, 250) TT1, TS1
 250   FORMAT (2X,'FLUID INLET TEMPERATURE, oF:',T40,F8.0,T60,F8.0)
```

```
      WRITE (1, 260) TT2, TS2
260   FORMAT (2X,'FLUID OUTLET TEMPERATURE, oF:',T40,F8.0,T60,F8.0)

      WRITE (1, 270) TID, SID
270   FORMAT (2X,'INSIDE DIAMETER, inch:',T40,F8.3,T60,F8.3)

      WRITE (1, 280) TOD
280   FORMAT (2X,'OUTSIDE DIAMETER, inch:',T40,F8.3)

      IF (TYPE .EQ. 'T' .OR. TYPE .EQ. 't') THEN

      WRITE (1, 290) TP
290   FORMAT (2X,'TUBE PITCH, inch:',T40,F8.3,T60,'TRIANGULAR PITCH')
      ELSEIF (TYPE .EQ. 'S' .OR. TYPE .EQ. 's') THEN

      WRITE (1, 300) TP
300   FORMAT (2X,'TUBE PITCH, inch:',T40,F8.3,T60,'SQUARE PITCH')
      ENDIF

      WRITE (1, 310) TL
310   FORMAT (2X,'TUBE LENGTH, ft.:',T40,F8.3)

      WRITE (1, 315) NT
315   FORMAT (2X,'NUMBER OF TUBES:', T40, F6.0)

      WRITE (1, 320) TNP, NS
320   FORMAT (2X,'NUMBER OF PASSES:',T40,F4.0,T60,F4.0)

      WRITE (1, 340) NB
340   FORMAT (2X,'NUMBER OF BAFFLES:',T60,F4.0)

      WRITE (1, 350) BSP
350   FORMAT (2X,'BAFFLE SPACING, inch:',T60,F4.1)

      WRITE (1, 360) TV, SV
360   FORMAT (2X,'FLUID VELOCITY, ft/sec.:',T40,F8.3,T60,F8.3)

      WRITE (1, 370) RET, RES
370   FORMAT (2X,'REYNOLDS NUMBER:',T40,F9.0,T60,F9.0)

      WRITE (1, 380) PRT, PRS
380   FORMAT (2X,'PRANDTL NUMBER:',T40,F8.4,T60,F8.4)

      WRITE (1, 390) TFRF, SFRF
390   FORMAT (2X,'FRICTION FACTOR (ft^2/in^2):',T40,F8.5,T60,F8.5)

      WRITE (1, 400) HT, HS
400   FORMAT (2X,'HEAT COEFF., Btu/hr.ft^2.oF:',T40,F9.1,T60,F9.1)

      WRITE (1, 410) TOTDP, SDELP
410   FORMAT (2X,'PRESSURE DROP, psi:',T40,F8.4,T60,F8.4)

      WRITE (1, 420) TFF, SFF
420   FORMAT (2X,'FOULING FACTOR:',T40,F8.4,T60,F8.4)

      WRITE (1, 430) F
430   FORMAT (2X,'APPROACH FACTOR, F:', T40, F8.4)
```

```
        WRITE (1, 440) LMTD
 440    FORMAT (2X,'LOG MEAN TEMP. DIFF. oF:',T40,F8.2)

        WRITE (1, 450) CMTD
 450    FORMAT (2X,'CORRECTED MEAN TEMP. DIFF. oF:',T40,F8.2)


        WRITE (1, 460) U
 460    FORMAT (2X,'OVERALL HEAT COEFF., Btu/hr.ft^2.oF:',T40,F9.1)

        WRITE (1, 470) AREA
 470    FORMAT (2X,'OUTSIDE AREA OF UNIT, ft^2:',T40,F9.1)

        WRITE (1, 480) Q
 480    FORMAT (2X,'HEAT LOAD ON UNIT, Btu/hr:',T40,F12.0)

        WRITE (1, 490) Q1
 490    FORMAT (2X,'HEAT TRANSFERRED, Btu/hr:',T40,F12.0)

        WRITE (1, 500)
 500    FORMAT (1H ,78(1H-))

C       FORM FEED THE PRINTING PAPER TO THE TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
        PROGRAM PROG83

C       ********************************************************************
C       THIS PROGRAM RATES DOUBLE PIPE HEAT EXCHANGERS USING
C       BARE TUBES OR LONGITUDINAL FINNED TUBES.
C       THE PROGRAM CALCULATES THE HEAT LOAD, THE LOG MEAN TEMPERATURE
C       DIFFERENCE FOR COUNTER CURRENT FLOW, THE CORRECTED FILM HEAT TRANSFER
C       COEFFICIENTS IN BOTH THE TUBE AND THE SHELL SIDES, THE OVERALL HEAT
C       TRANSFER COEFFICIENT AND THE HEAT TRANSFER SURFACE. THE PROGRAM
C       FURTHER CALCULATES THE FRICTION FACTOR (Using correlations given by
C       Dennis Wright: Basic Programs for chemical engineers, Van Nostrand
C       Reinhold Company, NY 1986) AND THE PRESSURE DROP IN THE TUBE AND THE
C       SHELL SIDES OF THE DOUBLE PIPE HEAT EXCHANGERS.
C       ********************************************************************
C       HI      = HEAT-TRANSFER FILM COEFFICIENT, Btu/ft^2 oF.h
C       K       = FLUID THERMAL CONDUCTIVITY, Btu/ft.h.oF
C       RE      = REYNOLDS NUMBER
C       PR      = PRANDTL NUMBER
C       DEQ     = EQUIVALENT DIAMETER, ft.
C       VIS     = FLUID VISCOSITY (FLOWING), cP.
C       VISW    = FLUID VISCOSITY (AT WALL), cP.
C       VIST    = FLUID VISCOSITY (TUBE SIDE), cP.
C       VISS    = FLUID VISCOSITY (SHELL SIDE - bare tube), cP.
C       VISF    = FLUID VISCOSITY (SHELL SIDE - finned tube), cP.
C       J       = HEAT-TRANSFER FACTOR
C       G       = MASS FLOW RATE, lb/h.ft^2.
C       CP      = FLUID SPECIFIC HEAT, Btu/lb.oF.
C       AREA    = HEAT TRANSFER SURFACE AREA, ft^2.
C       IDT     = INSIDE-TUBE DIAMETER, in.
C       IDF     = INSIDE DIAMETER (finned tube), in.
C       FOL     = FOULING FACTOR
C       HIF     = HEAT-TRANSFER FILM COEFFICIENT CORRECTED
C                 FOR FOULING, Btu/ft^2.oF.h.
C       IDS     = INSIDE SHELL DIAMETER, in.
C       ODT     = OUTSIDE TUBE DIAMETER, in.
C       DELTW   = TUBE WALL THICKNESS, ft.
C       KT      = THERMAL CONDUCTIVITY OF TUBE MATERIAL, Btu/ft.h.oF.
C       AI      = INSIDE HEAT-TRANSFER AREA-TUBE, ft^2/ft.
C       AO      = OUTSIDE HEAT-TRANSFER AREA-TUBE, ft^2/ft (FOR FINNED
C                 TUBES INCLUDES FIN AREA).
C       UO      = OVERALL HEAT-TRANSFER COEFFICIENT, Btu/h.ft^2.oF.
C       NFA     = NET FREE CROSS-SECTIONAL AREA, SHELL SIDE, ft^2.
C       AF      = FINNED TRANSFER AREA, ft^2 .
C       X       = PARAMETER USED IN FIN EFFICIENCY CALCULATION
C       FE      = FIN EFFICIENCY (%).
C       ESEF    = EFFECTIVE SURFACE EFFICIENCY FOR FINS (%).
C       HIFD    = CORRECTED FILM HEAT-TRANSFER RATE, Btu/ft^2.h.oF
C       TDEN    = TUBE SIDE FLUID DENSITY, lb/ft^3.
C       SDEN    = SHELL SIDE FLUID DENSITY, lb/ft^3.
C       NTP     = NUMBER OF TUBE PASSES.
C       NSP     = NUMBER OF SHELL PASSES (bare-tube).
C       NFP     = NUMBER OF SHELL PASSES (finned-tube).
C       FOLT    = FOULING FACTOR OF THE TUBE SIDE.
C       FOLS    = FOULING FACTOR OF THE SHELL SIDE (bare-tube).
C       FOLF    = FOULING FACTOR OF THE SHELL SIDE (finned-tube).
C       FTTUBE  = FLUID NAME IN THE TUBE SIDE.
C       FTSHELL = FLUID NAME IN THE SHELL SIDE
C       FLUIDT  = FLUID PHASE FLOW IN THE TUBE SIDE.
```

```
C     FLUIDS  = FLUID PHASE FLOW IN THE SHELL SIDE.
C     TUBE    = CHECKS TO DETERMINE WHETHER THE DOUBLE PIPE HEAT
C               EXCHANGER IS BARE-TUBED OR FINNED-TUBE.
C     LMTD    = LOG MEAN TEMPERATURE DIFFERENCE (oF).
C     TL      = TUBE LENGTH, ft.
C     WT      = FLUID FLOWRATE TUBE SIDE, lb/hr.
C     WS      = FLUID FLOWRATE SHELL SIDE (BARE-TUBE), lb/hr.
C     WF      = FLUID FLOWRATE SHELL SIDE (FINNED-TUBE), lb/hr.
C     ****************************************************************

      CHARACTER*30 FLUIDT, FLUIDS, FLUIDF, TUBE, FTTUBE, FTSHELL
      EXTERNAL HTFCV,HTFCL,HTFCJ

      REAL IDTF, IDSF, IDFF, ODTF, ODSF, ODFF
      REAL IDT,ODT,KT
      REAL IDS,ODS,KS,KST
      REAL IDF,ODF,KF,KFT
      REAL LMTD

      COMMON TUBE
      COMMON/DATA/FTTUBE, FTSHELL, TDEN, SDEN
      COMMON/DATA1/FLUIDT,IDT,ODT,WT,CPT,VIST,KT,TT1,TT2,FOLT,TL,NTP
      COMMON/DATA2/FLUIDS,IDS,ODS,WS,CPS,VISS,KS,TS1,TS2,FOLS,KST,NSP
      COMMON/DATA3/FLUIDF,IDF,ODF,WF,CPF,VISF,KF,TF1,TF2,FOLF,
     * FHT,FTHICK,NF,KFT,NFP
      COMMON/DATA4/ PI
      COMMON/DATA5/ IDTF, IDSF, IDFF, ODTF, ODSF, ODFF

      COMMON/RES1/VELT,RET,PRT,FRICTT,DROPT,HTFT,HIFTU
      COMMON/RES2/VELS,RES,PRS,FRICTS,DROPS,HTFS,HIFS
      COMMON/RES3/VELF,REF,PRF,FRICTF,DROPF,HTFF,HIFF,X,FE,ESEF,HIFD,
     * UO

      COMMON/RES4/ LMTD, AREA, Q

      OPEN (UNIT=3, FILE='DATA83.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT= 1, FILE='PRN')

      PI = 3.1415927


C     TUBE-SIDE HEAT-TRANSFER CALCULATIONS

C     INPUT NAME OF FLUID IN THE TUBE SIDE

      READ (3, 9, ERR=19) FTTUBE
 9    FORMAT (A)

C     INPUT FLUID PHASE FLOW (e.g. liquid/vapor)

      READ (3, 11, ERR=19) FLUIDT
 11   FORMAT (A)


C     READ THE INSIDE TUBE DIAMETER, inch.: IDT
C     READ THE OUTSIDE TUBE DIAMETER, inch.: ODT
C     READ THE FLUID FLOWRATE IN THE TUBE SIDE, lb/hr.: WT
C     READ THE FLUID SPECIFIC HEAT CAPACITY, Btu/lb.oF.: CPT
C     READ THE FLUID VISCOSITY, cP: VIST
C     READ THE FLUID THERMAL CONDUCTIVITY, KT: Btu/hr.ft.oF: KT
```

```
C       READ THE FLUID INLET TEMPERATURE, oF: TT1
C       READ THE FLUID OUTLET TEMPERATURE, oF: TT2
C       READ THE TUBE SIDE FOULING FACTOR: FOLT
C       READ THE TUBE SIDE FLUID DENSITY, lb/ft^3: TDEN
C       READ THE TUBE LENGTH, ft.: TL
C       READ THE NUMBER OF TUBE PASSES: NTP


        READ (3, *, ERR=19) IDT, ODT, WT
        READ (3, *, ERR=19) CPT, VIST, KT
        READ (3, *, ERR=19) TT1, TT2, FOLT
        READ (3, *, ERR=19) TDEN, TL, NTP

        GO TO 10


C       CHECK WHETHER THE HEAT EXCHANGER IS BARE-TUBE OR FINNED-TUBE
C       i.e., WHETHER THE HEAT EXCHANGER HAS FINS

C       INPUT NAME OF FLUID IN THE SHELL SIDE

 5      READ (3, 14, ERR=19) FTSHELL
 14     FORMAT (A)


        READ (3, 22, ERR=19) TUBE
 22     FORMAT (A)

        IF (TUBE .EQ. 'FINS' .OR. TUBE .EQ. 'fins') THEN


        GO TO 33
        ELSEIF (TUBE .EQ. 'BARE-TUBE'.OR. TUBE .EQ. 'bare-tube') THEN

C       READ DATA VALUES FOR THE SHELL-SIDE BARE-TUBE


C       INPUT FLUID PHASE FLOW (e.g. liquid/vapor)

        READ (3, 34, ERR=19) FLUIDS
 34     FORMAT(A)

C       READ THE INSIDE DIAMETER, inch.: IDS
C       READ THE OUTSIDE DIAMETER, inch.: ODS
C       READ THE FLUID FLOWRATE, lb/hr.: WS
C       READ THE FLUID SPECIFIC HEAT CAPACITY, Btu/lb.oF: CPS
C       READ THE FLUID VISCOSITY, cP.: VISS
C       READ THE FLUID THERMAL CONDUCTIVITY, Btu/ft.hr.oF: KS
C       READ THE FLUID INLET TEMPERATURE, oF: TS1
C       READ THE FLUID OUTLET TEMPERATURE, oF: TS2
C       READ THE SHELL SIDE FOULING FACTOR: FOLS
C       READ THE TUBE THERMAL CONDUCTIVITY, Btu/ft.hr.oF: KST
C       READ THE FLUID DENSITY, lb/ft^3.: SDEN
C       READ THE NUMBER OF SHELL PASSES: NSP


        READ (3, *, ERR=19) IDS, ODS, WS
        READ (3, *, ERR=19) CPS, VISS, KS
        READ (3, *, ERR=19) TS1, TS2, FOLS
        READ (3, *, ERR=19) KST, SDEN, NSP
```

```
        ENDIF

C       CALCULATE THE LOG MEAN TEMPERATURE DIFFERENCE, LMTD (oF)

        CALL LOGMTD (TS1, TS2, TT1, TT2, LMTD)

        GO TO 20

C       READ DATA VALUES FOR THE SHELL-SIDE FINNED TUBE

C       INPUT PHASE FLOW OF FLUID IN THE SHELL SIDE (e.g. Liquid/vapor)

 33     READ (3, 44, ERR=19) FLUIDF
 44     FORMAT (A)


C       READ THE NUMBER OF FINS: NF
C       READ THE INSIDE DIAMETER, inch.: IDF
C       READ THE OUTSIDE DIAMETER, inch.: ODF
C       READ THE FLUID FLOWRATE, lb/hr.: WF
C       READ THE FLUID SPECIFIC HEAT, Btu/lb.oF: CPF
C       READ THE FLUID VISCOSITY, cP.: VISF
C       READ THE FLUID THERMAL CONDUCTIVITY, Btu/hr.ft.oF: KF
C       READ THE FLUID INLET TEMPERATURE, oF: TF1
C       READ THE FLUID OUTLET TEMPERATURE, oF: TF2
C       READ THE FLUID FOULING FACTOR: FOLF
C       READ THE FINS HEIGHT, inch.: FHT
C       READ THE FINS THICHNESS, inch.: FTHICK
C       READ THE TUBE SIDE THERMAL CONDUCTIVITY, Btu/hr.ft.oF: KFT
C       READ THE FLUID DENSITY, lb/ft^3: SDEN
C       READ THE NUMBER OF PASSES: NFP


        READ (3, *, ERR=19) NF
        READ (3, *, ERR=19) IDF, ODF, WF
        READ (3, *, ERR=19) CPF, VISF, KF
        READ (3, *, ERR=19) TF1, TF2, FOLF
        READ (3, *, ERR=19) FHT, FTHICK
        READ (3, *, ERR=19) KFT, SDEN, NFP


C       CALCULATE THE LOG MEAN TEMPERATURE DIFFERENCE, LMTD (oF)

        CALL LOGMTD (TF1, TF2, TT1, TT2, LMTD)

C       CALCULATE THE HEAT LOAD ON UNIT, Btu/hr.

        Q = WF*CPF*(TF1-TF2)

C       SHELL-SIDE CALCULATIONS (FINNED-TUBE)


        GO TO 30

 18     WRITE (*, 100)
 100    FORMAT(//,6X,'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 110)
```

```
 110     FORMAT(//,6X,'ERROR MESSAGE IN THE DATA VALUE')
         GO TO 999

C        TUBE-SIDE CALCULATIONS

 10      CALL PROG1
         GO TO 5

C        SHELL-SIDE CALCULATIONS (BARE-TUBE)

 20      CALL PROG2

         GO TO 40

C        SHELL-SIDE CALCULATIONS (FINNED-TUBE)

 30      CALL PROG3


C        CALCULATE THE HEAT TRANSFER SURFACE AREA, (AREA, ft^2).

 40      AREA = Q/(UO*LMTD)


         CALL RESULTS


         CLOSE (3, STATUS='KEEP')
         CLOSE (1)

 999     STOP
         END

C       *****************************************************************
C        PROGRAM CALCULATES HEAT-TRANSFER FILM COEFFICIENT IN THE TUBE
C        SIDE HEAT EXCHANGER
C        ******************************************************************

         SUBROUTINE PROG1

         CHARACTER*30 FLUIDT, FTTUBE, FTSHELL,FLUIDF

         REAL IDT, ODT, KT
         REAL IDTF, IDSF, IDFF, ODTF, ODSF, ODFF
         REAL IDF, ODF, KF, KFT

         COMMON/DATA/FTTUBE, FTSHELL, TDEN, SDEN
         COMMON/DATA1/FLUIDT,IDT,ODT,WT,CPT,VIST,KT,TT1,TT2,FOLT,TL,NTP
         COMMON/DATA3/FLUIDF,IDF,ODF,WF,CPF,VISF,KF,TF1,TF2,FOLF,
     *   FHT,FTHICK,NF,KFT,NFP
         COMMON/DATA4/PI
         COMMON/DATA5/IDTF, IDSF, IDFF, ODTF, ODSF, ODFF

         COMMON/RES1/VELT,RET,PRT,FRICTT,DROPT,HTFT,HIFTU

         IDTF = IDT/12.0
         ODTF = ODT/12.0
         DEQT = IDTF

C        CALCULATE THE CROSS-SECTIONAL AREA OF TUBE
```

```
          AT = (PI*IDTF**2)/4.0

C         CALCULATE THE MASS VELOCITY, lb/ft^2.hr.

          GT = WT/AT

C         CALCULATE THE FLUID VELOCITY, ft./sec.

          VELT = GT/(3600.0*TDEN)

C         CALCULATE THE REYNOLDS NUMBER

          RET = (GT*DEQT)/(2.42*VIST)

C         CALCULATE THE PRANDTL NUMBER

          PRT = (CPT*2.42*VIST)/KT


C         CALCULATE THE FRICTION FACTOR (Dennis Wright: Basic Programs
C         for chemical engineers: Van Nostrand Reinhold Company, NY 1986).

          IF (RET .GT. 2100.0) THEN

          FRICTT = 0.00033/(RET**0.2)
          ELSEIF (RET .LT. 2100.0 ) THEN
          FRICTT = 16/RET
          ENDIF

C         CALCULATE THE PRESSURE DROP

          DROPT = (4.0*FRICTT*TL*NTP*(GT/3600.0)**2)/(64.4*TDEN*DEQT)


C         CHECK WHETHER FLUID IN THE TUBE SIDE IS LIQUID OR VAPOR.

          IF (FLUIDT .EQ. 'LIQUID'.OR. FLUIDT .EQ. 'liquid') THEN
          GO TO 30
          ELSEIF (FLUIDT .EQ. 'VAPOR' .OR. FLUIDT .EQ. 'vapor') THEN

C         CALCULATE THE HEAT-TRANSFER FILM COEFFICIENT IN THE VAPOR STATE

          HTFT = HTFCV (CPT,GT,DEQT)
          ENDIF

          GO TO 90

 30       IF(RET .LT. 2100.0) THEN
          GO TO 50
          ELSE
          HTFT = HTFCL (RET,PRT,KT,DEQT)
          ENDIF

          GO TO 90


 50       HTFT = HTFCJ (RET, PRT, KT, DEQT, TL)
```

```
C       CALCULATE THE HEAT-TRANSFER FILM COEFFICIENT CORRECTED FOR
C       FOULING, Btu/hr.ft^2.oF

 90     HIFTU = HTFT/(1.0+HTFT*FOLT)

        RETURN
        END

C       ****************************************************************
C       PROGRAM CALCULATES HEAT-TRANSFER FILM COEFFICIENT IN THE SHELL
C       SIDE (BARE-TUBE) AND THE OVERALL HEAT TRANSFER COEFFICIENT OF
C       THE HEAT EXCHANGER
C       ****************************************************************

        SUBROUTINE PROG2

        CHARACTER*30  FLUIDS, FLUIDT, FTSHELL,FTTUBE
        REAL IDS, IDT, ODS, ODT, KS, KT
        REAL IDTF, IDSF, IDFF, ODTF, ODSF, ODFF
        REAL LMTD

        COMMON/DATA/FTTUBE, FTSHELL, TDEN, SDEN
        COMMON/DATA1/FLUIDT,IDT,ODT,WT,CPT,VIST,KT,TT1,TT2,FOLT,TL,NTP
        COMMON/DATA2/FLUIDS,IDS,ODS,WS,CPS,VISS,KS,TS1,TS2,FOLS,KST,NSP
        COMMON/DATA4/PI
        COMMON/DATA5/IDTF, IDSF, IDFF, ODTF, ODSF, ODFF

        COMMON/RES1/VELT,RET,PRT,FRICTT,DROPT,HTFT,HIFTU
        COMMON/RES2/VELS,RES,PRS,FRICTS,DROPS,HTFS,HIFS

        COMMON/RES4/LMTD, AREA, Q

        IDSF = IDS/12.0
        ODSF = ODS/12.0
        DEQS = IDSF-ODTF
        RATIO1 = IDT/ODT

C       CALCULATE THE CROSS-SECTIONAL AREA

        AS = (PI*IDSF**2)/4.0

C       CALCULATE THE MASS VELOCITY, Ib/ft^2.hr.

        GS = WS/AS

C       CALCULATE THE FLUID VELOCITY, ft./sec.

        VELS = GS/(3600.0*SDEN)

C       CALCULATE THE REYNOLDS NUMBER

        RES = (GS*DEQS)/(2.42*VISS)

C       CALCULATE THE PRANDTL NUMBER

        PRS = (CPS*2.42*VISS)/KS

C       CALCULATE THE FRICTION FACTOR (Dennis Wright: Basic Programs for
C       chemical engineers, Van Nostrand Reinhold Company, NY 1986.)
```

```
C       CALCULATE THE FRICTION FACTOR

        CALL FFACTOR (RES, FRICTS)


C       CALCULATE THE PRESSURE DROP, psi.

        CALL PDROP (FRICTS, TL, NSP, GS, SDEN, DEQS, DROPS)


        IF (FLUIDS .EQ. 'LIQUID' .OR. FLUIDS .EQ. 'liquid') THEN

        GO TO 30

        ELSEIF (FLUIDS .EQ. 'VAPOR' .OR. FLUIDS .EQ. 'vapor') THEN

C       CALCULATE THE HEAT TRANSFER FILM COEFFICIENT IN THE VAPOR STATE

        HTFS = HTFCV(CPS,GS,DEQS)
        ENDIF

        GO TO 90


 30     IF (RES .LT. 2100.0) THEN
        GO TO 50
        ELSE
        HTFS = HTFCL (RES,PRS,KS,DEQS)
        ENDIF
        GO TO 90


 50     HTFS = HTFCJ (RES, PRS, KS, DEQS, TL)

C       CALCULATE THE HEAT-TRANSFER FILM COEFFICIENT CORRECTED
C       FOR FOULING.

 90     HIFS = HTFS/(1.0+HTFS*FOLS)

C       CALCULATE THE OVERALL HEAT TRANSFER COEFFICIENT.

        DELTW = (ODT/12.)-(IDT/12.0)
        RATIO2 = (DELTW/KST)+(1.0/(HIFTU*RATIO1))+(1.0/HIFS)
        UO = 1.0/RATIO2

        RETURN
        END

C       ****************************************************************
C       PROGRAM CALCULATES HEAT-TRANSFER FILM COEFFICIENT IN THE
C       SHELL SIDE (FINNED-TUBE) AND THE OVERALL HEAT TRANSFER
C       COEFFICIENT OF THE HEAT EXCHANGER.
C       *****************************************************************

        SUBROUTINE PROG3

        CHARACTER*30 FLUIDT,FLUIDF,FTSHELL,FTTUBE


        REAL IDF,ODF,KF,KFT,KT,NFA,IDT,ODT
```

```
      REAL IDTF, IDSF, IDFF, ODTF, ODSF, ODFF

      COMMON/DATA/FTTUBE, FTSHELL, TDEN, SDEN
      COMMON/DATA1/FLUIDT,IDT,ODT,WT,CPT,VIST,KT,TT1,TT2,FOLT,TL,NTP
      COMMON/DATA3/FLUIDF,IDF,ODF,WF,CPF,VISF,KF,TF1,TF2,FOLF,
     * FHT,FTHICK,NF,KFT,NFP
      COMMON/DATA4/PI
      COMMON/DATA5/IDTF, IDSF, IDFF, ODTF, ODSF, ODFF

      COMMON/RES3/VELF,REF,PRF,FRICTF,DROPF,HTFF,HIFF,X,FE,ESEF,HIFD,
     * UO

      IDFF = IDF/12.0
      ODFF = ODF/12.0
      ODTF = ODT/12.0
      AF = (2.0*FHT*FLOAT(NF))/12.0
      AO = (PI*ODTF)/12.0+AF

C     CALCULATE CROSS-SECTIONAL AREA, SHELL SIDE WITHOUT FINS, ft^2.

      CSA = (PI*(IDFF**2-ODTF**2))/4.0

C     CALCULATE NET FREE CROSS-SECTIONAL AREA, SHELL SIDE, ft^2.

      NFA = CSA-(FHT*FTHICK*FLOAT(NF))/144.0

C     CALCULATE THE CROSS-SECTIONAL AREA.

      CAF = (PI*IDFF**2)/4.0

C     CALCULATE THE MASS VELOCITY, lb/ft^2.hr.

      GF = WF/NFA

C     CALCULATE THE FLUID VELOCITY, ft./sec.

      VELF = GF/(3600.0*SDEN)

C     CALCULATE THE WETTED PERIMETER.

      DENOM = (PI*(IDFF+ODTF))-(FTHICK*FLOAT(NF))/12.0+AF
      DEQF = (4.0*NFA)/DENOM

C     CALCULATE THE REYNOLDS NUMBER

      REF = (GF*DEQF)/(2.42*VISF)

C     CALCULATE THE PRANDTL NUMBER

      PRF = (CPF*2.42*VISF)/KF

C     CALCULATE THE FRICTION FACTOR

      CALL FFACTOR (REF, FRICTF)

C     CALCULATE THE PRESSURE DROP

      CALL PDROP (FRICTF, TL, NFP, GF, SDEN, DEQF, DROPF)

C     CHECK WHETHER THE FLUID IN THE SHELL SIDE IS LIQUID OR VAPOR.
```

```
        IF(FLUIDF .EQ. 'LIQUID' .OR. FLUIDF .EQ. 'liquid') THEN

        GO TO 30

        ELSEIF (FLUIDF .EQ. 'VAPOR' .OR. FLUIDF .EQ. 'vapor') THEN

C       CALCULATE THE HEAT-TRANSFER FILM COEFFICIENT IN THE VAPOR STATE.

        HTFF = HTFCV (CPF, GF, DEQF)
        ENDIF

        GO TO 90

 30     IF ( REF .LT. 2100.0) THEN
        GO TO 50
        ELSE
        HTFF = HTFCL (REF, PRF, KF, DEQF)
        ENDIF
        GO TO 90

 50     HTFF = HTFCJ (REF, PRF, KF, DEQF, TL)

C       CALCULATE THE HEAT-TRANSFER FILM COEFFICIENT CORRECTED
C       FOR FOULING.

 90     HIFF = HTFF/(1.0+HTFF*FOLF)

C       CALCULATE THE OVERALL HEAT-TRANSFER COEFFICIENT.

C       CALCULATE THE PARAMETER X, USED IN THE FIN EFFICIENCY

        X = FHT*(HIFF/(6.0*KFT*FTHICK))**0.5

C       CALCULATE THE FIN EFFICIENCY

        VAL1 = EXP(X)-EXP(-X)
        VAL2 = EXP(X)+EXP(-X)
        FE = (1.0/X*(VAL1/VAL2))

C       CALCULATE THE EFFECTIVE SURFACE EFFICIENCY FOR FINS
        ESEF = FE*(AF/AO)+(1.0-AF/AO)

C       CALCULATE THE CORRECTED FILM HEAT TRANSFER RATE

        HIFD = HIFF*ESEF

C       CONVERT THE FIN EFFICIENCY AND EFFECTIVE SURFACE EFFICIENCY
C       TO PERCENTAGES.

        FE = 100.0*FE
        ESEF = 100.0*ESEF

C       CALCULATE OVERALL HEAT TRANSFER COEFFICIENT.

        DELTW = (ODT/12.0)-(IDT/12.0)
        RATIO3 = (PI*IDT)/((PI*ODT)+AF)
        RATIO4 = (DELTW/KFT)+(1.0/(HIFF*RATIO3))+(1.0/HIFD)
        UO = 1.0/RATIO4
```

```
      RETURN
      END

C
C     *****************************************************************
C     THIS PROGRAM CALCULATES THE LOG MEAN TEMPERATURE DIFFERENCE,
C     LMTD (oF)
C     *****************************************************************

      SUBROUTINE LOGMTD (TH1, TH2, TC1, TC2, LMTD)
      REAL LMTD

      DELT1 = TH1 - TC2
      DELT2 = TH2 - TC1
      LMTD = ABS((DELT1 - DELT2)/ALOG (DELT1/DELT2))

      RETURN
      END

C     *****************************************************************
C     THIS SUBPROGRAM EVALUATES THE HEAT TRANSFER FILM COEFFICIENT
C     IN THE VAPOR STATE OF A DOUBLE PIPE HEAT EXCHANGER.
C     ******************************************************************

      FUNCTION HTFCV (CP1, G1, DEQ1)

      HTFCV = (0.0144*CP1*(G1**0.8))/(DEQ1**0.2)

      RETURN
      END

C     *****************************************************************
C     THIS SUBPROGRAM EVALUATES THE HEAT TRANSFER FILM COEFFICIENT
C     IN THE LIQUID STATE OF A DOUBLE PIPE HEAT EXCHANGER.
C     *****************************************************************

      FUNCTION HTFCL (RE1, PR1, K1, D1)

      REAL K1
      HTFCL = 0.023*(RE1**0.8)*(PR1**0.333)*(K1/D1)*1.0

      RETURN
      END

C     *****************************************************************
C     THIS SUBPROGRAM EVALUATES THE HEAT TRANSFER FILM COEFFICIENT
C     FOR REYNOLDS NUMBER LESS THAN 2100.0 OF A DOUBLE PIPE
C     HEAT EXCHANGER
C     *****************************************************************

      FUNCTION HTFCJ (RE, PR, K1, D1, TL1)

      REAL K1

      HTFCJ = 1.86*(RE**0.333)*(PR**0.333)*(K1/D1)*(D1/TL1)**0.333

      RETURN
      END
C
C     ******************************************************************
```

```
C       CALCULATE THE FRICTION FACTOR IN THE SHELL SIDE OF THE DOUBLE
C       PIPE HEAT EXCHANGER  (Dennis Wright: Basic Programs for chemical
C       engineers, Van Nostrand Reinhold company, NY 1986)
C       ******************************************************************

        SUBROUTINE FFACTOR (RE, FACTOR)

        IF (RE .GT. 2100) THEN

        FACTOR = 0.00033/(RE**0.25)

        ELSEIF (RE .LT. 2100) THEN

        FACTOR = 16.0/RE
        ENDIF
        RETURN
        END

C       *****************************************************************
C       THIS PROGRAM CALCULATES THE PRESSURE DROP FOR THE SHELL SIDE OF
C       A DOUBLE PIPE HEAT EXCHANGER
C       *****************************************************************

        SUBROUTINE PDROP (FRICT, TLEN, NP, G, DEN, EQDIA, DROP)

        DROP = (4*FRICT*TLEN*NP*(G/3600.0)**2)/(64.4*DEN*EQDIA)

        RETURN
        END

C       *******************************************************************
C       THIS PROGRAM PRINTS THE RESULTS OF THE DOUBLE PIPE HEAT EXCHANGERS
C       *******************************************************************

        SUBROUTINE RESULTS

        CHARACTER*30 FLUIDT, FLUIDS, FLUIDF, TUBE, FTTUBE, FTSHELL

        REAL IDTF, IDSF, IDFF, ODTF, ODSF, ODFF
        REAL IDT, ODT, KT
        REAL IDS, ODS, KS, KST
        REAL IDF, ODF, KF, KFT
        REAL LMTD

        COMMON TUBE
        COMMON/DATA/FTTUBE, FTSHELL, TDEN, SDEN
        COMMON/DATA1/FLUIDT,IDT,ODT,WT,CPT,VIST,KT,TT1,TT2,FOLT,TL,NTP
        COMMON/DATA2/FLUIDS,IDS,ODS,WS,CPS,VISS,KS,TS1,TS2,FOLS,KST,NSP
        COMMON/DATA3/FLUIDF,IDF,ODF,WF,CPF,VISF,KF,TF1,TF2,FOLF,
     *             FHT,FTHICK,NF,KFT,NFP
        COMMON/DATA4/PI
        COMMON/DATA5/IDTF,IDSF,IDFF,ODTF,ODSF,ODFF

        COMMON/RES1/VELT,RET,PRT,FRICTT,DROPT,HTFT,HIFTU
        COMMON/RES2/VELS,RES,PRS,FRICTS,DROPS,HTFS,HIFS
        COMMON/RES3/VELF,REF,PRF,FRICTF,DROPF,HTFF,HIFF,X,FE,ESEF,HIFD,
     *UO
        COMMON/RES4/LMTD,AREA,Q

        WRITE (1, 120)
```

```
120    FORMAT (/,18X,'DOUBLE PIPE HEAT EXCHANGER RATING',/,18X,
     *         'USING BARE-TUBES/LONGITUDINAL FINNED TUBES'/,18X,
     *         'FORCED CONVECTION WITH NO CHANGE OF PHASE')

       WRITE (1, 130)
130    FORMAT (1H ,78(1H*))

       WRITE (1, 140)
140    FORMAT (45X,'TUBE SIDE', 10X, 'SHELL SIDE')

       WRITE (1, 150)
150    FORMAT (78(1H-))

       WRITE (1, 160) FTTUBE, FTSHELL
160    FORMAT (2X,'FLUID NAME:', T50, A15, T65, A15)

       IF (TUBE .EQ. 'FINS' .OR. TUBE .EQ. 'fins') THEN

       WRITE (1, 170) FLUIDT, FLUIDF
170    FORMAT (2X,'TYPE OF PHASE FLOW:', T50, A15, T65, A15)

       WRITE (1, 180) WT, WF
180    FORMAT (2X,'FLUID FLOW RATE, lb/hr.:', T45, F10.0, T60, F10.0)

       WRITE (1, 190) CPT, CPF
190    FORMAT (2X,'SPECIFIC HEAT CAPACITY, Btu/Ib.oF:', T45, F8.3,
     *         T60, F8.3)

       WRITE (1, 200) TDEN, SDEN
200    FORMAT (2X,'FLUID DENSITY, lb/ft^3.:', T45, F8.3, T60, F8.3)

       WRITE (1, 210) VIST, VISF
210    FORMAT (2X,'FLUID VISCOSITY, cP:', T45, F8.3, T60, F8.3)

       WRITE (1, 220) KT, KF
220    FORMAT (2X,'FLUID THERMAL COND., Btu/Ib.oF:', T45, F8.3,
     *         T60, F8.3)

       WRITE (1, 230) TT1, TF1
230    FORMAT (2X,'FLUID INLET TEMPERATURE, oF:', T45, F8.3,
     *         T60, F8.3)

       WRITE (1, 240) TT2, TF2
240    FORMAT (2X,'FLUID OUTLET TEMPERATURE, oF:', T45, F8.3,
     *         T60, F8.3)

       WRITE (1, 250) IDT, IDF
250    FORMAT (2X,'INSIDE DIAMETER, inch:', T45, F8.3, T60, F8.3)

       WRITE (1, 260) ODT, ODF
260    FORMAT (2X,'OUTSIDE DIAMETER, inch:', T45, F8.3, T60, F8.3)

       WRITE (1, 270) FOLT, FOLF
270    FORMAT (2X,'FOULING FACTOR:', T45, F8.3, T60, F8.3)

       WRITE (1, 280) TL, NTP
280    FORMAT (2X,'TUBE LENGTH, ft.:', T45, F8.3,/,
     *         2X,'NUMBER OF TUBE PASSES:', T45, I2)
```

```
      WRITE (1, 290) NF, FHT, FTHICK
290   FORMAT (2X, 'NUMBER OF FINS:', T45, I2,/,
     *        2X,'FIN HEIGHT, inch:', T45, F8.3,/,
     *        2X,'FIN THICKNESS, inch:', T45, F8.3)

      WRITE (1, 300) KFT
300   FORMAT (2X,'THERMAL COND. TUBE MATERIAL, Btu/hr.ft.oF:',
     *        T45,F8.3)

      WRITE (1, 310) VELT, VELF
310   FORMAT (2X,'FLUID VELOCITY, ft/sec.:', T45, F8.3, T60, F8.3)

      WRITE (1, 320) RET, REF
320   FORMAT (2X,'REYNOLDS NUMBER:', T45, F9.0, T60, F9.0)

      WRITE (1, 330) PRT, PRF
330   FORMAT (2X,'PRANDTL NUMBER:', T45, F8.4, T60, F8.3)

      WRITE (1, 340) FRICTT, FRICTF
340   FORMAT (2X,'FRICTION FACTOR (ft^2/in^2):', T45, F8.6, T60, F8.6)

      WRITE (1, 350) DROPT, DROPF
350   FORMAT (2X,'PRESSURE DROP, psi.:', T45, F8.4, T60, F8.4)

      WRITE (1, 360) X, FE, ESEF
360   FORMAT (2X,'FIN MODULUS:', T45, F8.3,/,
     *        2X,'FIN EFFICIENCY, %:', T45, F8.3,/,
     *        2X,'EFFECTIVE SURFACE EFFICIENCY, %:', T45, F8.3)

      WRITE (1, 370) LMTD
370   FORMAT (2X,'LOG MEAN TEMP. DIFF., oF:', T45, F8.2)

      WRITE (1, 380) HIFTU, HIFF
380   FORMAT (2X,'HEAT TRANSFER FILM COEFF. CORRECTED',/,2X,
     *        'FOR FOULING:, Btu/hr.ft^2.oF:', T45, F9.2, T60, F9.2)

      WRITE (1, 390) UO
390   FORMAT (2X,'OVERALL HEAT TRANSFER COEFF., Btu/hr.ft^2.oF:',
     *        T45, F9.2)

      WRITE (1, 400) Q, AREA
400   FORMAT (2X,'HEAT LOAD ON UNIT, Btu/hr.:', T45, F12.1,/,
     *        2X,'HEAT TRANSFER SURFACE ft^2.:', T45, F8.3)

      ELSEIF (TUBE .EQ. 'BARE-TUBE' .OR. TUBE .EQ. 'bare-tube') THEN

      WRITE (1, 410) FLUIDT, FLUIDS
410   FORMAT (2X,'TYPE OF PHASE FLOW:', T45, A15, T60, A15)

      WRITE (1, 420) WT, WS
420   FORMAT (2X,'FLUID FLOWRATE:, lb/hr.:', T45, F10.0, T60, F10.0)

      WRITE (1, 430) CPT, CPS
430   FORMAT (2X,'SPECIFIC HEAT CAPACITY, Btu/lb.oF:', T45, F8.3,T60,
     *        F8.3)

      WRITE (1, 440) TDEN, SDEN
440   FORMAT (2X,'FLUID DENSITY, lb/ft^3:', T45, F8.3, T60, F8.3)

      WRITE (1, 450) VIST, VISS
```

```
 450    FORMAT (2X,'FLUID VISCOSITY, cP:', T45, F8.3, T60, F8.3)

        WRITE (1, 460) KT, KS
 460    FORMAT (2X,'FLUID THERMAL COND., Btu/Ib.oF:', T45, F8.3,
     *          T60, F8.3)

        WRITE (1, 470) TT1, TS1
 470    FORMAT (2X,'FLUID INLET TEMPERATURE, oF:',T45, F8.3, T60, F8.3)

        WRITE (1, 480) TT2, TS2
 480    FORMAT (2X,'FLUID OUTLET TEMPERATURE, oF:',T40, F8.3,T60,F8.3)

        WRITE (1, 490) IDT, IDS
 490    FORMAT (2X,'INSIDE DIAMETER, inch:',T45, F8.3, T60, F8.3)

        WRITE (1, 500) ODT, ODS
 500    FORMAT (2X,'OUTSIDE DIAMETER, inch:', T45, F8.3, T60, F8.3)

        WRITE (1, 510) FOLT, FOLS
 510    FORMAT (2X,'FOULING FACTOR:', T45, F8.3, T60, F8.3)

        WRITE (1, 520) KFT
 520    FORMAT (2X,'THERMAL COND. TUBE MATERIAL, Btu/hr.ft.oF:',
     *          T45, F8.3)

        WRITE (1, 530) VELT, VELS
 530    FORMAT (2X,'FLUID VELOCITY, ft/sec.:', T45, F8.3, T60, F8.3)

        WRITE (1, 540) RET, RES
 540    FORMAT (2X,'REYNOLDS NUMBER:', T45, F9.0, T60, F9.0)

        WRITE (1, 550) PRT, PRS
 550    FORMAT (2X,'PRANDTL NUMBER:', T45, F8.3, T60, F8.3)

        WRITE (1, 560) FRICTT, FRICTS
 560    FORMAT (2X,' FRICTION FACTOR (ft^2/in^2):', T45, F8.5,T60,F8.5)

        WRITE (1, 570) DROPT, DROPS
 570    FORMAT (2X,'PRESSURE DROP, psi:', T45, F8.4, T60, F8.4)

        WRITE (1, 580) LMTD
 580    FORMAT (2X,'LOG MEAN TEMP. DIFF., oF:', T45, F8.2)

        WRITE (1, 590) HIFTU, HIFS
 590    FORMAT (2X,'HEAT TRANSFER FILM COEFF. CORRECTED',/,2X,
     *          'FOR FOULING:, Btu/hr.ft^2.oF:', T45, F9.2, T60, F9.2)

        WRITE (1, 600) UO
 600    FORMAT (2X,'OVERALL HEAT TRANSFER FILM COEFF., Btu/hr.ft^2.oF:',
     *          T45, F9.2)

        WRITE (1, 610) Q, AREA
 610    FORMAT (2X,'HEAT LOAD ON UNIT , Btu/hr.:', T45, F12.1,/,
     *          2X,'HEAT TRANSFER SURFACE, ft^2.:', T45, F8.3)

        ENDIF

        WRITE (1, 620)
 620    FORMAT (1H ,78(1H-))

C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        RETURN
        END
```

```
      PROGRAM PROG84

C     ******************************************************************
C     *  THE SIZING OF AIR-COOLED HEAT EXCHANGERS.
C     *  THE PROGRAM PERFORMS PRELIMINARY AIR-COOLER DESIGN CALCULATIONS
C     *  WITH A RANGE OF INPUT DATA.
C     *
C     *  THE PROGRAM CALCULATES:
C     *  1.  THE NUMBER OF TUBE ROWS (TUBE BUNDLE DEPTH).
C     *  2.  OUTLET AIR TEMPERATURE.
C     *  3.  LOG MEAN TEMPERATURE DIFFERENCE.
C     *  4.  TOTAL BARE-TUBE SURFACE AREA (BASED ON 1 inch OD TUBING
C     *      ON 2 3/8 inch TRIANGULAR SPACING.).
C     *  5.  COOLER FACE AREA (plan area).
C     *  6.  AIR VELOCITY ACROSS TUBES.
C     *  7.  TOTAL AIR FLOW.
C     *  8.  FAN HORSEPOWER (bhp = brake horsepower).
C     *  9.  TOTAL BUNDLE WEIGHT.
C     * 10.  TUBE BUNDLE WIDTH FOR A GIVEN TUBE LENGTH.
C
C     *  THIS PROGRAM IS BASED ON CORRELATIONS PRESENTED IN ARTICLES BY
C     *  E.C. Smith AND R. Brown.  THE CORRELATIONS PRESENTED BY GRAPHS
C     *  AND TABLES IN THE ORIGINAL ARTICLES AND FITTED TO A SERIES OF
C     *  EQUATION BY W.W. Blackwell ARE USED IN THIS PROGRAM.
C     **********************************************************************
C     *
C     *  R    = NUMBER OF TUBE ROWS.
C     *  TPI  = INLET PROCESS FLUID TEMPERATURE, oF.
C     *  TAI  = INLET AIR TEMPERATURE, oF.
C     *  BTSA = BARE-TUBE SURFACE AREA BASED ON TUBE OD, ft^2.
C     *  FA   = FACE AREA OF BUNDLE, ft^2.
C     *  FV   = FACE VELOCITY OF AIR,ft^2.
C     *  TAO1 = ESTIMATED AIR OUTLET TEMPERATURE, oF.
C     *  U    = OVERALL HEAT-TRANSFER COEFFICIENT
C              (BASED ON BARE-TUBE OD) Btu/hr.ft^2oF.
C     *  TPO  = OUTLET PROCESS FLUID TEMPERATURE, oF.
C     *  LMTD = EFFECTIVE LOG MEAN TEMPERATURE DIFFERENCE, oF.
C     *  Q    = HEAT LOAD, Btu/hr.
C     *  TAO  = CALCULATED OUTLET AIR TEMPERATURE, oF.
C     *  F    = AIR FLOW OVER TUBES, std ft^3/min.
C     *  BHP  = FAN HORSEPOWER, brake horsepower.
C     *  WT   = AIR-COOLER WEIGHT, lb.
C     *  W    = TUBE BUNDLE, WIDTH, ft.
C     *  TL   = TUBE LENGTH, ft.
C     *  C1,C2,C3,C4,C5,C6,C7,C8,C9,C10 = CONSTANTS
C     ***************************************************************

      REAL  LMTD

      OPEN (UNIT=3, FILE='DATA84.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT =1, FILE='PRN')


C     CONSTANTS USED IN THE PROGRAM


      C1 = 3.1679
      C2 = 3.7948
```

```
        C3 = 1.2557
        C4 = 1.0031
        C5 = 720.8542
        C6 = 0.9530
        C7 = 7.4212
        C8 = 12.5342
        C9 = 36.4
        C10 = 9.35

C

C       READ THE INLET PROCESS FLUID TEMPERATURE, oF: TPI
C       READ THE OUTLET PROCESS FLUID TEMPERATURE, oF: TPO
C       READ THE INLET AIR TEMPERATURE, oF: TAI
C       READ THE OVERALL HEAT-TRANSFER COEFFICIENT, Btu/hr.ft^2.oF: U
C       READ THE HEAT LOAD, Btu/hr.: Q
C       READ THE TUBE LENGTH, ft.: TL


        READ (3, *, ERR=19) TPI, TPO, TAI
        READ (3, *, ERR=19) U, Q, TL
        GO TO 20

 18     WRITE (*, 100)
 100    FORMAT (6X, 'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 110)
 110    FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999



 20     WRITE (1, 120)
 120    FORMAT (///,20X,'AN AIR-COOLED HEAT EXCHANGER DESIGN',/,78(1H*))

        WRITE (1, 130) TPI, TPO, TAI
 130    FORMAT (6X,'INLET PROCESS FLUID TEMPERATURE, oF:',T60, F8.1,
     *          /,6X,'OUTLET PROCESS FLUID TEMPERATURE, oF:',T60,F8.1,
     *          /,6X,'INLET AIR TEMPERATURE, oF:',T60,F8.1)

        WRITE (1, 140) U, Q, TL
 140    FORMAT (6X,'OVERALL HEAT-TRANSFER COEFFICEINT, Btu/hr.ft^2.oF:',
     *          T60, F8.1,/,6X,'HEAT LOAD, Btu/hr.:',T60, F12.0,/,6X,
     *          'TUBE LENGTH, ft.:', T60, F8.1)

C       CALCULATE THE NUMBER OF TUBE ROWS

        R = C1 + C2*(ALOG((TPI-TAI)/U))

C       CALCULATE THE RATIO OF BARE-TUBE SURFACE AREA BASED ON THE
C       TUBE OD TO THE FACE AREA OF BUNDLE , RATIO1=BTSA/FA

        RATIO1 = C3*(R**C4)

C       CALCULATE THE FACE VELOCITY OF AIR, ft/min.

        FV = C5*(C6**R)
```

```
         WRITE (1, 150) R, RATIO1, FV
  150    FORMAT (6X,'NUMBER OF TUBE ROWS:',T60,F6.1,/,6X,
     *   'RATIO OF BARE-TUBE SURFACE TO FACE AREA OF BUNDLE:', T60, F6.1,
     *   /, 6X, 'FACE VELOCITY OF AIR, ft./min.:', T60, F8.3)

C        CALCULATE THE ESTIMATED AIR OUTLET TEMPERATURE, oF: TAO1

         TAO1 = (0.005*U*((TPO+TPI)/2.0-TAI)) + TAI

         WRITE (1, 160) TAO1
  160    FORMAT (6X, 'ESTIMATED AIR OUTLET TEMPERATURE, oF:',T60, F8.3)


C        CALCULATE THE LOG MEAN TEMPERATURE DIFFERENCE, oF: LMTD.

   25    VAL1 = (TPO-TAI)-(TPI-TAO1)
         VAL2 = ALOG((TPO-TAI)/(TPI-TAO1))
         LMTD = VAL1/VAL2

C        CALCULATE BARE-TUBE SURFACE AREA BASED ON TUBE, OD: ft^2: BTSA

         BTSA = Q/(U*LMTD)

C        CALCULATE THE FACE AREA OF BUNDLE, ft^2: FA

         FA = BTSA/RATIO1

         WRITE (1, 170) LMTD, BTSA, FA
  170    FORMAT (6X,'EFFECTIVE LOG MEAN TEMPERATURE DIFFERENCE, oF:',T60,
     *      F8.3, /, 6X,'BARE-TUBE SURFACE AREA BASED ON TUBE OD, ft^2:',
     *      T60, F8.1, /, 6X,'FACE AREA OF BUNDLE, ft^2:',T60,F8.1)

C        CALCULATED OUTLET AIR TEMPERATURE, oF: TAO

         TAO = (Q/(FA*FV*1.08)) + TAI

         WRITE (1, 180) TAO
  180    FORMAT (6X,'CALCULATED OUTLET AIR TEMPERATURE, oF:', T60, F8.3)

C        A NECESSARY CONDITION FOR SIZING AN AIR-COOLED EXCHANGER.
C        CHECK WHETHER THE DIFFERENCE BETWEEN THE CALCULATED AIR OUTLET
C        TEMPERATURE AND THE ESTIMATED AIR OUTLET TEMPERATURE IS GREATER
C        THAN/OR EQUAL TO 0.5 (i.e. (TAO-TAO1) .GE. 0.5))

C        IF THE DIFFERENCE IS GREATER THAN OR EQUAL TO 0.5, THEN SET THE
C        ESTIMATED AIR OUTLET TEMPERATURE EQUAL TO THE CALCULATED AIR
C        OUTLET TEMPERATURE AND REPEAT THE CALCULATION FROM THE LOG MEAN
C        TEMPERATURE DIFFERENCE.

         IF ((TAO-TAO1) .GE. 0.5) THEN

         WRITE (1, 190)
  190    FORMAT (6X,'THE DIFFERENCE BETWEEN THE CALCULATED AIR', /, 6X,
     *   'OUTLET TEMPERATURE AND THE ESTIMATED AIR OUTLET', /, 6X,
     *   'TEMPERATURE IS GREATER THAN 0.5',T60,'TAO-TAO1 >0.5')

         TAO1 = TAO
         GO TO 25
         ELSE
         ENDIF
```

```
      WRITE (1, 200) BTSA,FA
 200  FORMAT (6X,'CALCULATED BARE-TUBE SURFACE AREA', /, 6X,
     *       'BASED ON TUBE OUTSIDE DIAMETER, ft^2:', T60, F8.1,
     *       /,6X,'FACE AREA OF BUNDLE, ft^2:', T60, F8.1)

C     CALCULATE AIR FLOW OVER TUBES, std ft^3/min.: F

      F = FA*FV

C     CALCULATE FAN HORSEPOWER: BHP

      BHP = BTSA/(C7+(C8*R))

C     CALCULATE AIR-COOLER WEIGHT, lb: WT.

      WT = FA*(C9+(C10*R))

C     CALCULATE TUBE BUNDLE WIDTH, ft: W

      W = FA/TL
C
      WRITE (1, 210) F, BHP
 210  FORMAT (6X,'AIR FLOW OVER TUBES, std.ft^3/min.:', T60, F9.0,
     * /, 6X, 'FAN HORSEPOWER, bhp:', T60, F8.1)

      WRITE (1, 220) WT, W
 220  FORMAT (6X,'AIR-COOLER WEIGHT, lb:', T60, F9.1, /, 6X,
     *        'TUBE BUNDLE WIDTH, ft.:',T60,F8.1)

      WRITE (1, 230)
 230  FORMAT (1H ,78(1H-))

C     FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

      WRITE (1, *) CHAR(12)

      CLOSE (3, STATUS='KEEP')
      CLOSE (1)
  999 STOP
      END
```

```
        PROGRAM PROG85

C       HEAT-TRACER REQUIREMENTS FOR PIPELINES.
C       THE PROGRAM CALCULATES THE HEAT LOSS AND TRACING REQUIREMENTS
C       FOR ANY GIVEN PIPELINE USING HOT OIL OR SOME OTHER HOT FLUID
C       MEDIUM AS THE HEAT SOURCE.  IT ALSO CALCULATES THE HEAT LOSS
C       FROM AN INSULATED PIPELINE WITHOUT A HEAT TRACER.

C       THIS PROGRAM WILL CALCULATE:
C       1.  SURFACE TEMPERATURE OF INSULATED TRACED PIPE.
C       2.  TOTAL HEAT TRANSFERRED PER 100 ft. OF PIPE.
C       3.  TOTAL HEAT TRANSFERRED FOR ENTIRE PIPELINE.
C       4.  FLOW RATE FOR HOT MEDIA.
C       5.  TOTAL NUMBER OF HEAT TRACERS REQUIRED WITH AND WITHOUT
C           TRANSFER CEMENT.


C       HEAT TRANSFERRED THROUGH AN INSULATED PIPE ENCOUNTERS FOUR
C       RESISTANCES:

C       1.  FILM RESISTANCE ON THE INSIDE WALL OF THE PIPE.
C       2.  HEAT RESISTANCE THROUGH THE PIPE WALL.
C       3.  HEAT RESISTANCE THROUGH THE INSULATION.
C       4.  AIR-FILM RESISTANCE ON THE OUTSIDE OF THE INSULATION.
C
C       HOWEVER, THE FIRST TWO RESISTANCES, 1. AND 2. ARE NORMALLY
C       VERY SMALL AND ARE THEREFORE NEGLIGIBLE IN THIS PROGRAM.
C       ***************************************************************
C       TMEDAV  = AVERAGE TEMPERATURE OF HOT MEDIUM, oF.
C       TMI     = HOT-MEDIUM INLET TEMPERATURE, oF.
C       TMO     = HOT-MEDIUM OUTLET TEMPERATURE, oF.
C       TAVG    = AVERAGE TEMPERATURE OF PIPE AND TRACER, oF.
C       DI      = INSIDE DIAMETER OF INSULATION, in.
C       OD      = OUTSIDE DIAMETER OF PIPE, in.
C       TAL     = ALLOWANCE FOR TRACER DIAMETER, in.
C       DOS     = OUTSIDE DIAMETER OF INSULATION, in.
C       TK      = INSULATION THICKNESS, in.
C       Q       = HEAT LOSS PER FOOT OF PIPE, Btu/hr.ft.
C       KINS    = THERMAL CONDUCTIVITY OF INSULATION, Btu/hr.ft^2.(oF/ft).
C       TS      = OUTSIDE SURFACE TEMPERATURE OF INSULATION, oF.
C       HA      = FILM HEAT-TRANSFER COEFFICIENT TO AIR CORRECTED
C                 FOR THE WIND, Btu/hr.ft^2.oF.
C       TAIR    = AIR TEMPERATURE, oF.
C       HCOMB   = HC+HR: COMBINED CONVECTIVE AND RADIATIVE HEAT TRANSFER
C                 CO-EFFICIENT, Btu/hr.ft^2.oF.
C       WF      = WIND FACTOR.
C       QT      = TOTAL HEAT LOSS FROM PIPELINE, Btu/hr.
C       W       = FLOW RATE OF HOT MEDIUM, lb/hr.
C       TOTL    = TOTAL PIPELINE LENGTH, ft.
C       CP      = SPECIFIC HEAT OF HOT MEDIUM, Btu/lb.oF.
C       TWOC    = NUMBER OF TRACERS REQUIRED WITHOUT HEAT-TRANSFER CEMENT.
C       TCA     = THERMAL CONDUCTANCE, TRACER TO PIPE
C                 WITHOUT CEMENT, Btu/hr.oF(ft of pipe).
C       TWC     = NUMBER OF TRACERS REQUIRED WITH HEAT TRANSFER CEMENT.
C       TCB     = THERMAL CONDUCTANCE, TRACER TO PIPE
C                 WITH CEMENT, Btu/hr.oF(ft of pipe).
C       TP      = TEMPERATURE IN THE PIPE, oF.
C       ***************************************************************
```

```
      REAL OD, KINS

      OPEN (UNIT=3, FILE ='DATA85.DAT', STATUS='OLD', ERR=18)
      OPEN (UNIT=1, FILE ='PRN')

      PI = 3.1415927

C     READ THE TOTAL LENGTH OF PIPE, ft.: TOTL
C     READ THE TEMPERATURE IN THE PIPE, oF: TP
C     READ THE HOT-MEDIUM INLET TEMPERATURE, oF: TMI
C     READ THE HOT-MEDIUM OUTLET TEMPERATURE, oF: TMO
C     READ THE AIR TEMPERATURE, oF: TAIR
C     READ THE OUTSIDE DIAMETER OF PIPE, inch.: OD
C     READ THE ALLOWANCE FOR THE TRACER DIAMETER, inch.: TAL
C     READ THE INSULATION THICKNESS, inch.: TK
C     READ THE THERMAL CONDUCTIVITY OF INSULATION, Btu/hr.ft^2(oF/ft): KINS
C     READ THE SPECIFIC HEAT CAPACITY OF THE HOT MEDIUM, Btu/lb.oF: CP
C     READ THE FILM HEAT TRANSFER COEFFICIENT TO AIR CORRECTED
C     FOR THE WIND, Btu/hr.ft^2.oF: HA
C     READ THE THERMAL CONDUCTANCE, TRACER TO PIPE
C     WITHOUT CEMENT, Btu/hr.oF (ft. of pipe).: TCA
C     READ THE THERMAL CONDUCTANCE, TRACER TO PIPE
C     WITH CEMENT, Btu/hr.oF (ft. of pipe).: TCB


      READ (3, *, ERR=19) TOTL, TP, TMI
      READ (3, *, ERR=19) TMO, TAIR, OD
      READ (3, *, ERR=19) TAL, TK, KINS
      READ (3, *, ERR=19) CP, HA, TCA, TCB

      GO TO 20

 18   WRITE (*, 100)
 100  FORMAT (6X, 'DATA FILE DOES NOT EXIST')
      GO TO 999

 19   WRITE (*, 110)
 110  FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
      GO TO 999


 20   WRITE (1, 120)
 120  FORMAT (///, 10X, 'HEAT TRACER REQUIREMENTS FOR PIPELINES AND ',
     * /, 10X, 'HEAT LOSS FROM AN INSULATED PIPELINE WITH TRACING', /,
     *        78(1H*))

      WRITE ( 1, 130) TOTL, TP, TMI
 130  FORMAT (6X, 'TOTAL PIPELINE LENGTH, ft.:',T60,F9.1,/,
     *        6X, 'TEMPERATURE IN PIPE, oF:',T60,F9.1,/,
     *        6X, 'HOT-MEDIUM INLET TEMPERATURE, oF:',T60,F9.1)

      WRITE (1, 140) TMO, TAIR, OD
 140  FORMAT (6X, 'HOT MEDIUM OUTLET TEMPERATURE, oF:',T60, F9.1,/,
     *        6X, 'AIR TEMPERATURE, oF:',T60,F9.1,/,
     *        6X, 'OUTSIDE DIAMETER OF PIPE, in.:',T60,F9.3)

      WRITE (1, 150) TAL, TK, KINS
 150  FORMAT (6X, 'ALLOWANCE FOR TRACER DIAMETER, in.:', T60, F9.2,/,
     *        6X, 'INSULATION THICKNESS, in.:', T60, F9.2, /, 6X,
     * 'THERMAL CONDUCTIVITY OF INSULATION, Btu/hr.ft^2(oF/ft):', T60,
```

```
      *  F9.3)

         WRITE (1, 160) CP, HA, TCA, TCB
 160     FORMAT (6X,'SPECIFIC HEAT OF HOT MEDIUM, Btu/Ib.oF:',T60,F9.3,
      *  /,6X,'FILM HEAT TRANSFER COEFFICIENT TO AIR',
      *  /,6X,'CORRECTED FOR WIND, Btu/ft^2.hr.oF:',T60,F9.3,
      *  /,6X,'THERMAL CONDUCTANCE TRACER TO PIPE',
      *  /,6X,'WITHOUT CEMENT, Btu/hr.oF.ft of pipe:',T60,F9.3
      *  /,6X,'THERMAL CONDUCTANCE TRACER TO PIPE',
      *  /,6X,'WITH CEMENT, Btu/hr.oF.ft of pipe:',T60,F9.3)

C        CALCULATE THE AVERAGE TEMPERATURE OF HOT MEDIUM, oF

         CONTRL = 0.0

 30      TMEDAV = 0.5*(TMI+TMO)
         TA = 0.5*(TMEDAV+TP)
         DI = OD+TAL
         DO = DI+2.0*TK
         HA1 = HA

 40      X = (ALOG(DO/DI)*HA1*DO)/(24.0*KINS)
         TS = (TA+X*TAIR)/(1.0+X)

         WRITE (1, 170) TS
 170     FORMAT (6X, 'OUTSIDE SURFACE TEMPERATURE OF INSULATION, oF:',
      *          T60,F9.3)


C        CALCULATE THE COMBINED CONVECTIVE AND RADIATIVE HEAT TRANSFER
C        COEFFICIENT.

         HCOMB = 564.0/((DO**0.19)*(273.0-(TS-TAIR)))

         WRITE (1, 180) HCOMB
 180     FORMAT (6X,'THE COMBINED CONVECTIVE AND RADIATIVE', /, 6X,
      *  'HEAT TRANSFER COEFFICIENT, Btu/h.oF.ft^2:', T60, F9.3)


C        CONSTANTS FOR THE WIND FACTOR

         C0 = 2.814
         C1 = -0.00038857
         C2 = -0.0000012857

         WF = C0+(C1*(TS-TAIR))+(C2*((TS-TAIR)**2))

C        CALCULATED FILM HEAT-TRANSFER COEFFICIENT TO AIR CORRECTED FOR
C        THE WIND, HA2: Btu/hr.ft^2.oF

         HA2 = HCOMB*WF

         IF ((HA2-HA1) .GE. 0.01) THEN
         HA1 = HA2
         GO TO 40
         ELSE

C        CALCULATE THE HEAT FLOW THROUGH THE INSULATION Btu/hr.(lin ft).

         QINS = (2.0*PI*KINS*(TA-TS))/(ALOG(DO/DI))
```

```
C       CALCULATE THE HEAT FLOW BY RADIATION AND CONVECTION TO AIR

        QRC = (HA1*PI*DO*(TS-TAIR))/12.0
        ENDIF

        WRITE (1, 190) WF, HA2
 190    FORMAT (6X,'WIND FACTOR:',T60, F9.3, /, 6X,
     *  'HEAT TRANSFER COEFFICIENT TO AIR', /, 6X,
     *  'CORRECTED FOR THE WIND, Btu/hr.ft^2.oF:', T60, F9.3)

C       CALCULATE THE TOTAL HEAT LOST FROM PIPELINE ,Btu/hr.

        QT = QINS*TOTL

        WRITE (1, 200) QINS, QT
 200    FORMAT (6X,'HEAT LOSS PER FOOT OF PIPE, Btu/hr.ft:', T60,F9.3,/,
     *  6X,'TOTAL HEAT LOSS FROM PIPELINE, Btu/hr.:', T60, F9.3)

        IF (CONTRL .EQ. 1.0) THEN
        GO TO 999
        ELSE

C       CALCULATE THE FLOW RATE OF HOT MEDIUM, lb/h

        W = QT/(CP*(TMI-TMO))

        WRITE (1, 210) W
 210    FORMAT (6X,'FLOW RATE OF HOT MEDIUM, lb/hr.:', T60, F9.3)

C       CALCULATE THE NUMBER OF TRACERS REQUIRED WITHOUT
C       HEAT-TRANSFER CEMENT.

        TWOC = QINS/(TCA*(TMEDAV-TP))

C       CALCULATE THE NUMBER OF TRACERS REQUIRED WITH
C       HEAT-TRANSFER CEMENT.

        TWC = QINS/(TCB*(TMEDAV-TP))
        ENDIF


        WRITE (1, 220) TWOC, TWC
 220    FORMAT(6X,'THE NUMBER OF TRACERS WITHOUT HEAT TRANSFER CEMENT:',
     *  T60, F9.2,/,6X,
     *  'THE NUMBER OF TRACERS WITH HEAT TRANSFER CEMENT:',T60, F9.2)

        WRITE (1, 230)
 230    FORMAT (1H ,78(1H-))

C       ***************************************************************

C       CALCULATION OF HEAT LOSS FROM AN INSULATED PIPE WITHOUT
C       TRACING, WHERE TMI=TMO=TP, AND TA=0.0

        WRITE (1, 240)
 240    FORMAT (//, 6X,'HEAT LOSS FROM AN INSULATED PIPE',\)

        WRITE (1, 250)
 250    FORMAT (' WITHOUT TRACING', /1H ,78(1H*))
```

```
C        TO CALCULATE THE HEAT LOSS FROM AN INSULATED PIPE, CONTRL=1.0

         TMI = TP
         TMO = TP
         TAL = 0.0
         CONTRL = CONTRL + 1.0
         GO TO 30

         CLOSE (3, STATUS='KEEP')
         CLOSE (1)

  999    STOP
         END
```

CHAPTER 9

Engineering Economics

INTRODUCTION

Project evaluation enables the technical and economic feasibility of a chemical process to be assessed using preliminary process design and economic evaluations. Once a process flowsheet is available, these evaluations can be classified into several steps: material balance calculations, equipment sizing, equipment cost determination, utilities requirements, investment cost estimation, sales volume forecasting, manufacturing cost estimation, and finally profitability and sensitivity analysis.

The results of an economic evaluation are reviewed together with other relevant aspects, such as, competition and likely product life in arriving at project investment decisions. The decisions are essential in order to both plan and allocate the long-term use of available resources. The objectives of an economic appraisal are:

- To ensure that the expected future benefits justify the expenditure of resources.
- To choose the best project from among alternatives to achieve future benefits.
- To use all available resources.

These objectives ensure that the right project is undertaken and is likely to attain the desired profitability.

In the chemical process industries, an investment project may arise from any of a range of activities. It may be a minor modification to an existing plant, a major plant expansion or revamping, a completely new plant (on an existing or greenfield site) or the development of an entirely new process or product. For a major or a new plant, economic assessment with increasing degrees of accuracy may be carried out at different stages as the plant progresses. This may be based on an initial research and development (R&D), through various stages of the project (e.g., pilot plants, material evaluation, preliminary plant design), which leads to the decision whether or not to proceed with investment in a full scale plant for the process. Table 9-1 lists examples of the use of engineering economics. The approach used for economic evaluation depends on the quality of the information, that is, the stage in the project at which it is undertaken.

Table 9-1
Use of Chemical Engineering Economics

Production or Plant Technical Services

A. Plant equipment continuously needs repair, replacement, or modernization. The responsible engineer should know roughly what the comparative performance, costs, and payout periods are, even if there is a plant engineering group to do that type of analysis, or a firm price quotation will be obtained later.

B. Plant changes, such as those initiated by the ever increasing costs of energy and environmental requirements, necessitate that many energy saving, pollution, and hazardous waste control possibilities must be considered. To make intelligent recommendations, the responsible engineer should personally conduct design and cost estimates, pay-back, and economic calculations on the alternatives before making even preliminary recommendations.

C. Competitors' processing methods, as well as R&D, sales, or management suggested changes must be continuously examined. Supervisors or other groups may be responsible, but the staff engineer can help a great deal by making preliminary cost estimates and economic analyses of the changes to guide his or her own thinking (and hopefully the group's position).

D. All engineers should have a feel for their company's business, products, and economics. This requires occasional economic reading, and a basic understanding of the company's annual reports and general industry economic news.

Research and Development

A. In the process of being creative, one thinks of many novel ideas. During the analytical phase of creative thinking many of the ideas will require a quick cost estimation and economic analysis to provide a better idea of their merit. Even though supervisors or others may be assigned to do this work, the chances of conceiving good ideas and having them accepted increases immensely if some economic screening can be done by the originator.

B. While conducting R&D studies, there are always many stumbling points or alternative directions that may be taken to solve problems. Often brief cost estimates and economic analyses will help the engineer in deciding which are the most promising directions to pursue.

C. After an early or intermediate stage of an R&D program has been successful, new funding requests usually are required to continue the study. These requests can always benefit from having potential preliminary economic analyses. Later, in the final stages of a successful project, the engineer may be part of a team assigned to provide a more definitive preliminary economic projection and analysis.

D. In dealing with production, sales, or management personnel, one can usually gain more respect, and be considered more practical and less "theoretical," by having a reasonable knowledge of the costs and economics of the projects under study, and general industry economics.

Sales

A. A general knowledge of company costs, profits, and competition are very helpful for more effective salesmanship.

B. Salesmen often recommend new products, improvements, or pricing ideas to their management. A cost and economic estimate for these ideas should be helpful in the proposal report.

C. Salesmen sometimes perform market surveys. Again, a general economic knowledge of the industries and companies surveyed may be essential, and is always useful.

D. Salesmen may move into management, where economic knowledge is a major part of the job.

Engineering

A. Because of the extreme specialization of most engineering companies and many company engineering departments, cost estimating and economics may not be directly required in many engineering company or department jobs. However, other jobs will deal exclusively with cost estimating and economic analysis, and all will benefit from a good, fluent knowledge of the basic economic procedures. Engineering departments or companies usually have well developed in-house methods and data that must be used, but the basics are still applicable.

General

A. All chemical engineers are assumed to know the rudiments of cost estimating, economic evaluation, and the economics of their industry. A high percentage will find this knowledge useful or necessary throughout their careers.

(table continued on next page)

Table 9-1
(continued)

B. All work situations are more or less competitive, and one means of maintaining the highest advancement potential with most jobs is to convince superiors of your knowledge and interest in management, business, and economics. Associated with this is the demonstration of ability, an interest in accepting responsibility, and ability to communicate. Many companies promote people whom they think can "manage," such as those with MBA (master of business administration) degrees or with perceived equivalent capabilities, ahead of people with a better performance record. Basically, a confidence that you can learn managerial skills as you need them and a knowledge of economics should make most chemical engineers equal or preferred candidates for advancement.

Source: Garrett [10], Courtesy of Chapman and Hall

Project Evaluation

Investment decisions are often based upon several criteria, such as annual return on investment (ROI), payback period (PBP), net present value (NPV), the average rate of return (ARR), present value ratio (PVR), or the internal rate of return (IRR). Discounted cash flow rate on return (DCFRR) is another popular means of evaluating the economic viability of a proposed project. Horwitz [1] recommended the DCFRR as the best means to determine the return on investment, because it accounts for the time value of money. The internal rate of return as an investment criterion gives the possibility that given cash flows may result in more than one internal rate of return. Cannaday *et al.* [2] developed a method for determining the relevance of an internal rate of return. They inferred that an internal rate of return is relevant, if its derivative with respect to each of the cash flows is positive.

Powell [3] reviewed the basics of various discounted cash flow techniques for project evaluation. Discounting is a method that accounts for the time value of money to provide either for the capital or to convert the cash flows to a common point in time so that they are summed. Ward [4] proposed a new concept known as the net return rate (NRR) that provides a better indication of a project's profitability. Techniques and criteria for economic evaluation of projects are widely available in the literature and texts [5,6,7,8,9,10]. A summary of the conventional decision criteria is given here.

Cash Flows

Return On Investment (ROI)

In engineering economic evaluation, rate of return on investment is the percentage ratio of average yearly profit (net cash flow) over the productive life of the project, divided by the total initial investment. This is calculated after income taxes have been deducted from the gross or pre-tax income. The remainder or net income may be used either for paying dividends, reinvestment, or can be spent for other means. ROI is defined by

$$\text{ROI} = \frac{\text{Annual return}}{\text{Investment}} \times 100 \tag{9-1}$$

The annual return may be the gross income, net pre-tax income, net after-tax income, cash flow, or profit. These may be calculated for one particular year or as an average over the project life. Investment may be the original total investment, depreciated book-value investment, lifetime average investment, fixed capital investment, or equity investment. The investment includes working capital and sometimes capitalized expenses such as interest on capital during construction.

Payback Period (PBP)

Payback period is widely used when long-term cash flows are difficult to forecast, because no information is required beyond the break-even point. It may be used for preliminary evaluation or as a project screening device for high risk projects in times of uncertainty. Payback period is usually measured as the time from the start of production to recovery of the capital investment. The payback period is the time taken for the cumulative net cash flow from start-up of the plant to equal the depreciable fixed capital investment ($C_{FC} - S$). It is the value of t that satisfies the equation

$$\sum_{t=0}^{t=(\text{PBP})} C_{CF} = (C_{FC} - S) \tag{9-2}$$

where C_{CF} = net annual cash flow

C_{FC} = fixed capital cost

S = salvage value

Figure 9-1 shows the cumulative cash flow diagram for a project. The PBP is the time that elapses from the start of the project, A, to the

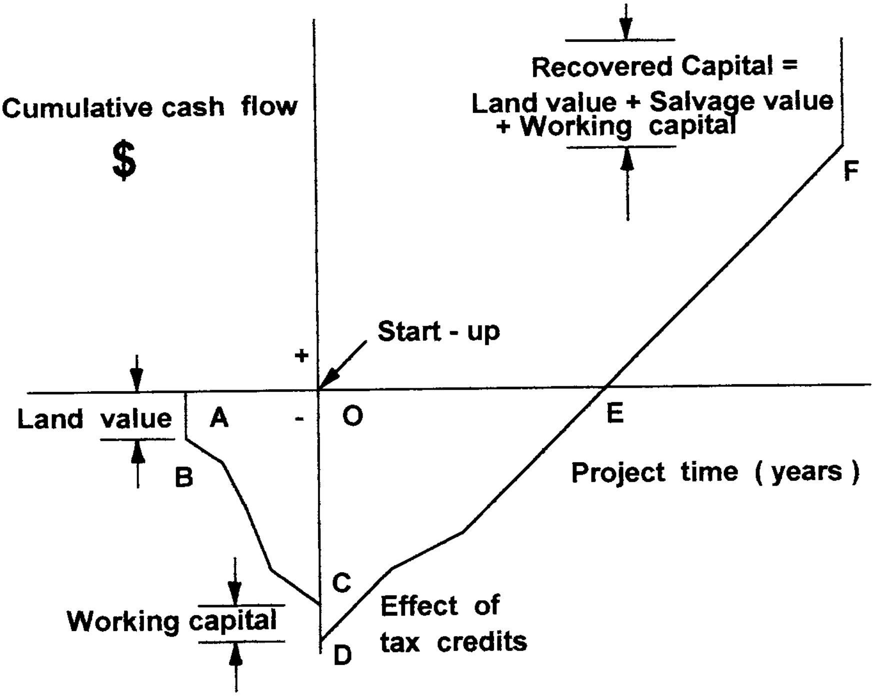

Figure 9-1. Cumulative cash flow diagram.

break-even point, E, where the rising part of the curve passes the zero cash position line. The PBP thus measures the time required for the cumulative project investment and other expenditure to be balanced by the cumulative income.

Present Worth (Or Present Value)

In an economic evaluation of a project, it is often necessary to evaluate the present value of funds that will be received at some definite time in the future. The present value (PV) of a future amount can be considered as the present principal at a given rate and compounded to give the actual amount received at a future date. The relationship between the indicated future amount and the present value is determined by a discount factor. Discounting evaluates each year's flow on an equal basis. It does this by means of the discount, or present value factor, and the reciprocal of the compound interest factor $(1 + i)^n$ with

i = interest rate

n = the year in which the interest is compounded

$$\text{The discount factor} = \frac{1}{(1+i)^n} \tag{9-3}$$

If C_n represents the amount available after n interest periods, P is the initial principal and the discreet compound interest rate is i. The present value, PV, can be expressed as:

$$PV = P = \frac{C_n}{(1+i)^n} \tag{9-4}$$

Net Present Value (NPV)

The net present value of a project is the cumulative sum of the discounted cash flows including the investment. The NPV corresponds to the total discounted net return, above and beyond the cost of capital and the recovery of the investment. The NPV represents a discounted return or profit, but is not a measure of the profitability. Each cash flow is evaluated by computing its present value. This is done by taking a cash flow of year n and multiplying it by the discount factor for the nth year.

$$\text{Present value of } p_n = C_n\left[\frac{1}{(1+i)^n}\right] \tag{9-5}$$

The present value, p, at year 0 of a cash flow, C_t, in year t at an annual discount rate of i is

$$p = \frac{C_t}{(1+i)^t} \tag{9-6}$$

For a complete project, the earlier cash flows are usually negative and the later ones positive. The net present value, NPV, is the sum of the individual present values of the yearly cash flows. This is expressed as:

$$NPV = C_0 + \frac{C_1}{(1+i)} + \frac{C_2}{(1+i)^2} + \ldots + \frac{C_n}{(1+i)^n} \tag{9-7}$$

Equation 9-7 can be expressed as:

$$NPV = \sum p = \sum_{t=0}^{t=n} \frac{C_t}{(1+t)^t} \tag{9-8}$$

The life of the project n years must be specified together with the estimated cash flows in each year up to n.

NPV = net present value

C_0 = Initial investment

C_n = cash flow

n = year n

i = interest rate of return (ROI/100)

If a project includes a series of identical yearly cash flows, such as the net inflow for several years, their present values can be obtained in one calculation instead of singly. For yearly cash flows, C, from year m to year n, then the sum of their present values is:

$$P = \frac{C}{i(1+i)^{m-1}}\left[1 - \frac{1}{(1+i)^{n-m+1}}\right] \tag{9-9}$$

Figure 9-2 shows the cumulative net present values stages in a project. Tables 9-2 through 9-5 are the discount factors for computing the net present value.

Assuming that the investment is made in year 0 (C_0 = I), and the cash flows over the project life are constant, then Equation 9-7 is simplified to give

$$NPV = \left[C\sum_{n=1}^{n}\left(\frac{1}{1+i}\right)^{n}\right] - I \tag{9-10}$$

The term 1/(1+i) is a geometric progression whose sum can be expressed as the single term

$$\sum_{n=1}^{n}\frac{1}{(1+i)^n} = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{9-11}$$

where Equation 9-11 becomes the present value of an annuity. Equation 9-7 can thus be expressed as:

$$NPV = \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] - I \tag{9-12}$$

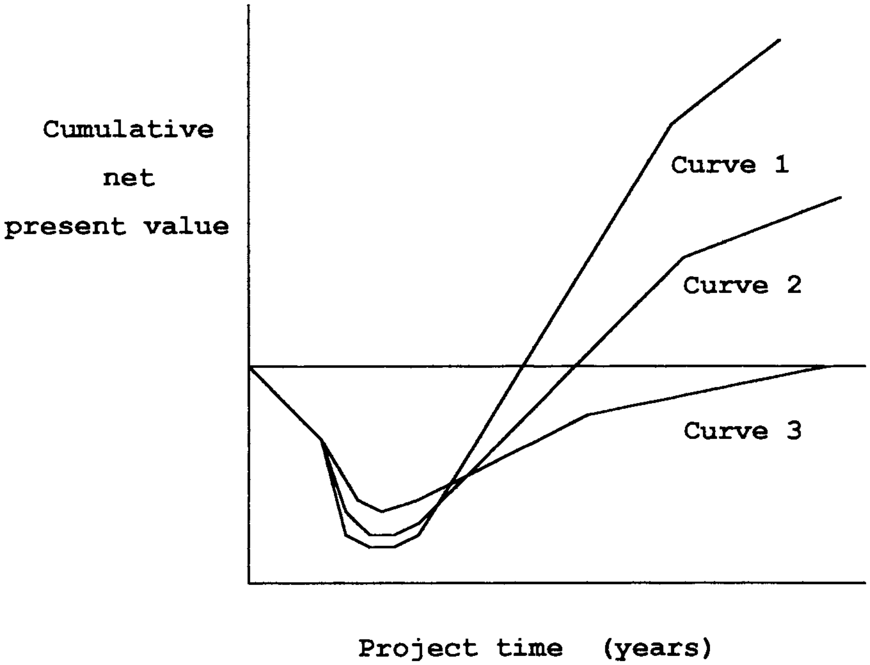

Figure 9-2. Net present value (NVP) of a project.

The internal rate of return (IRR) is that value of i that makes NPV equal to 0. Therefore, if NPV is set to 0, the IRR that makes the future cash flows equal to the investment (the "break-even" point) can be estimated. Equation 9-12 then becomes:

$$\frac{I}{C} = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{9-13}$$

where I = investment
C = cash flow for each year
i = rate of return (IRR/100)
n = years of project life

Equation 9-13 is defined as the annuity with I, the present value, and C, the equal payments, over n, years at interest, i. The I/C term is referred to as the payback period. If I and C are evaluated and the life of the project is known, i can be computed by trial and error. The value of i can be determined from Figure 9-3.

(text continued on page 735)

Table 9-2

Discount Factors. This Table Shows the Present Value of Unity Discounted for Different Numbers of Years and at Different Rates of Discount

Rate of discount	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Year										
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1	0.9901	0.9804	0.9709	0.9615	0.9524	0.9434	0.9346	0.9259	0.9174	0.9091
2	0.9803	0.9612	0.9426	0.9246	0.9070	0.8900	0.8734	0.8573	0.8417	0.8264
3	0.9706	0.9423	0.9151	0.8890	0.8638	0.8396	0.8163	0.7938	0.7722	0.7513
4	0.9610	0.9238	0.8885	0.8548	0.8227	0.7921	0.7629	0.7350	0.7084	0.6830
5	0.9515	0.9057	0.8626	0.8219	0.7835	0.7473	0.7130	0.6806	0.6499	0.6209
6	0.9420	0.8880	0.8375	0.7903	0.7462	0.7050	0.6663	0.6302	0.5963	0.5645
7	0.9327	0.8706	0.8131	0.7599	0.7107	0.6651	0.6227	0.5835	0.5470	0.5132
8	0.9235	0.8535	0.7894	0.7307	0.6768	0.6274	0.5820	0.5403	0.5019	0.4665
9	0.9143	0.8368	0.7664	0.7026	0.6446	0.5919	0.5439	0.5002	0.4604	0.4241
10	0.9053	0.8203	0.7441	0.6756	0.6139	0.5584	0.5083	0.4632	0.4224	0.3855
11	0.8963	0.8043	0.7224	0.6496	0.5847	0.5268	0.4751	0.4289	0.3875	0.3505
12	0.8874	0.7885	0.7014	0.6246	0.5568	0.4970	0.4440	0.3971	0.3555	0.3186
13	0.8787	0.7730	0.6810	0.6006	0.5303	0.4688	0.4150	0.3677	0.3262	0.2897
14	0.8700	0.7579	0.6611	0.5775	0.5051	0.4423	0.3878	0.3405	0.2992	0.2633
15	0.8613	0.7430	0.6419	0.5553	0.4810	0.4173	0.3624	0.3152	0.2745	0.2394
16	0.8528	0.7284	0.6232	0.5339	0.4581	0.3936	0.3387	0.2919	0.2519	0.2176
17	0.8444	0.7142	0.6050	0.5134	0.4363	0.3714	0.3166	0.2703	0.2311	0.1978
18	0.8360	0.7002	0.5874	0.4936	0.4155	0.3503	0.2959	0.2502	0.2120	0.1799
19	0.8277	0.6864	0.5703	0.4746	0.3957	0.3305	0.2765	0.2317	0.1945	0.1635
20	0.8195	0.6730	0.5537	0.4564	0.3769	0.3118	0.2584	0.2145	0.1784	0.1486

Table 9-3
Discount Factors. This Table Shows the Present Value of Unity Discounted for Different Numbers of Years and at Different Rates of Discount

Rate of discount	11%	12%	13%	14%	15%	16%	17%	18%	19%	20%
Year										
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1	0.9009	0.8929	0.8850	0.8772	0.8696	0.8621	0.8547	0.8475	0.8403	0.8333
2	0.8116	0.7972	0.7831	0.7695	0.7561	0.7432	0.7305	0.7182	0.7062	0.6944
3	0.7312	0.7118	0.6931	0.6750	0.6575	0.6407	0.6244	0.6086	0.5934	0.5787
4	0.6587	0.6355	0.6133	0.5921	0.5718	0.5523	0.5337	0.5158	0.4987	0.4823
5	0.5935	0.5674	0.5428	0.5194	0.4972	0.4761	0.4561	0.4371	0.4190	0.4019
6	0.5346	0.5066	0.4803	0.4556	0.4323	0.4104	0.3898	0.3704	0.3521	0.3349
7	0.4817	0.4523	0.4251	0.3996	0.3759	0.3538	0.3332	0.3139	0.2959	0.2791
8	0.4339	0.4039	0.3762	0.3506	0.3269	0.3050	0.2848	0.2660	0.2487	0.2326
9	0.3909	0.3606	0.3329	0.3075	0.2843	0.2630	0.2434	0.2255	0.2090	0.1938
10	0.3522	0.3220	0.2946	0.2697	0.2472	0.2267	0.2080	0.1911	0.1756	0.1615
11	0.3173	0.2875	0.2607	0.2366	0.2149	0.1954	0.1778	0.1619	0.1476	0.1346
12	0.2858	0.2567	0.2307	0.2076	0.1869	0.1685	0.1520	0.1372	0.1240	0.1122
13	0.2575	0.2292	0.2042	0.1821	0.1625	0.1452	0.1299	0.1163	0.1042	0.0935
14	0.2320	0.2046	0.1807	0.1597	0.1413	0.1252	0.1110	0.0985	0.0876	0.0779
15	0.2090	0.1827	0.1599	0.1401	0.1229	0.1079	0.0949	0.0835	0.0736	0.0649
16	0.1883	0.1631	0.1415	0.1229	0.1069	0.0930	0.0811	0.0708	0.0618	0.0541
17	0.1696	0.1456	0.1252	0.1078	0.0929	0.0802	0.0693	0.0600	0.0520	0.0451
18	0.1528	0.1300	0.1108	0.0946	0.0808	0.0691	0.0592	0.0508	0.0437	0.0376
19	0.1377	0.1161	0.0981	0.0829	0.0703	0.0596	0.0506	0.0431	0.0367	0.0313
20	0.1240	0.1037	0.0868	0.0728	0.0611	0.0514	0.0433	0.0365	0.0308	0.0261

Table 9-4

Discount Factors. This Table Shows the Present Value of Unity Discounted for Different Numbers of Years and at Different Rates of Discount

Rate of discount	21%	22%	23%	24%	25%	26%	27%	28%	29%	30%
Year										
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1	0.8264	0.8197	0.8130	0.8065	0.8000	0.7937	0.7874	0.7813	0.7752	0.7692
2	0.6830	0.6719	0.6610	0.6504	0.6400	0.6299	0.6200	0.6104	0.6009	0.5917
3	0.5645	0.5507	0.5374	0.5245	0.5120	0.4999	0.4882	0.4768	0.4658	0.4552
4	0.4665	0.4514	0.4369	0.4230	0.4096	0.3968	0.3844	0.3725	0.3611	0.3501
5	0.3855	0.3700	0.3552	0.3411	0.3277	0.3149	0.3027	0.2910	0.2799	0.2693
6	0.3186	0.3033	0.2888	0.2751	0.2621	0.2499	0.2383	0.2274	0.2170	0.2072
7	0.2633	0.2486	0.2348	0.2218	0.2097	0.1983	0.1877	0.1776	0.1682	0.1594
8	0.2176	0.2038	0.1909	0.1789	0.1678	0.1574	0.1478	0.1388	0.1304	0.1226
9	0.1799	0.1670	0.1552	0.1443	0.1342	0.1249	0.1164	0.1084	0.1011	0.0943
10	0.1486	0.1369	0.1262	0.1164	0.1074	0.0992	0.0916	0.0847	0.0784	0.0725
11	0.1228	0.1122	0.1026	0.0938	0.0859	0.0787	0.0721	0.0662	0.0607	0.0558
12	0.1015	0.0920	0.0834	0.0757	0.0687	0.0625	0.0568	0.0517	0.0471	0.0429
13	0.0839	0.0754	0.0678	0.0610	0.0550	0.0496	0.0447	0.0404	0.0365	0.0330
14	0.0693	0.0618	0.0551	0.0492	0.0440	0.0393	0.0352	0.0316	0.0283	0.0254
15	0.0573	0.0507	0.0448	0.0397	0.0352	0.0312	0.0277	0.0247	0.0219	0.0195
16	0.0474	0.0415	0.0364	0.0320	0.0281	0.0248	0.0218	0.0193	0.0170	0.0150
17	0.0391	0.0340	0.0296	0.0258	0.0225	0.0197	0.0172	0.0150	0.0132	0.0116
18	0.0323	0.0279	0.0241	0.0208	0.0180	0.0156	0.0135	0.0118	0.0102	0.0089
19	0.0267	0.0229	0.0196	0.0168	0.0144	0.0124	0.0107	0.0092	0.0079	0.0068
20	0.0221	0.0187	0.0159	0.0135	0.0115	0.0098	0.0084	0.0072	0.0061	0.0053

Table 9-5
Discount Factors. This Table Shows the Present Value of Unity Discounted for Different Numbers of Years and at Different Rates of Discount

Rate of discount	31%	32%	33%	34%	35%	36%	37%	38%	39%	40%
Year										
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1	0.7634	0.7576	0.7519	0.7463	0.7407	0.7353	0.7299	0.7246	0.7194	0.7143
2	0.5827	0.5739	0.5653	0.5569	0.5487	0.5407	0.5328	0.5251	0.5176	0.5102
3	0.4448	0.4348	0.4251	0.4156	0.4064	0.3975	0.3889	0.3805	0.3724	0.3644
4	0.3396	0.3294	0.3196	0.3102	0.3011	0.2923	0.2839	0.2757	0.2679	0.2603
5	0.2592	0.2495	0.2403	0.2315	0.2230	0.2149	0.2072	0.1998	0.1927	0.1859
6	0.1979	0.1890	0.1807	0.1727	0.1652	0.1580	0.1512	0.1448	0.1386	0.1328
7	0.1510	0.1432	0.1358	0.1289	0.1224	0.1162	0.1104	0.1049	0.0997	0.0949
8	0.1153	0.1085	0.1021	0.0962	0.0906	0.0854	0.0806	0.0760	0.0718	0.0678
9	0.0880	0.0822	0.0768	0.0718	0.0671	0.0628	0.0588	0.0551	0.0516	0.0484
10	0.0672	0.0623	0.0577	0.0536	0.0497	0.0462	0.0429	0.0399	0.0371	0.0346
11	0.0513	0.0472	0.0434	0.0400	0.0368	0.0340	0.0313	0.0289	0.0267	0.0247
12	0.0392	0.0357	0.0326	0.0298	0.0273	0.0250	0.0229	0.0210	0.0192	0.0176
13	0.0299	0.0271	0.0245	0.0223	0.0202	0.0184	0.0167	0.0152	0.0138	0.0126
14	0.0228	0.0205	0.0185	0.0166	0.0150	0.0135	0.0122	0.0110	0.0099	0.0090
15	0.0174	0.0155	0.0139	0.0124	0.0111	0.0099	0.0089	0.0080	0.0072	0.0064
16	0.0133	0.0118	0.0104	0.0093	0.0082	0.0073	0.0065	0.0058	0.0051	0.0046
17	0.0101	0.0089	0.0078	0.0069	0.0061	0.0054	0.0047	0.0042	0.0037	0.0033
18	0.0077	0.0068	0.0059	0.0052	0.0045	0.0039	0.0035	0.0030	0.0027	0.0023
19	0.0059	0.0051	0.0044	0.0038	0.0033	0.0029	0.0025	0.0022	0.0019	0.0017
20	0.0045	0.0039	0.0033	0.0029	0.0025	0.0021	0.0018	0.0016	0.0014	0.0012

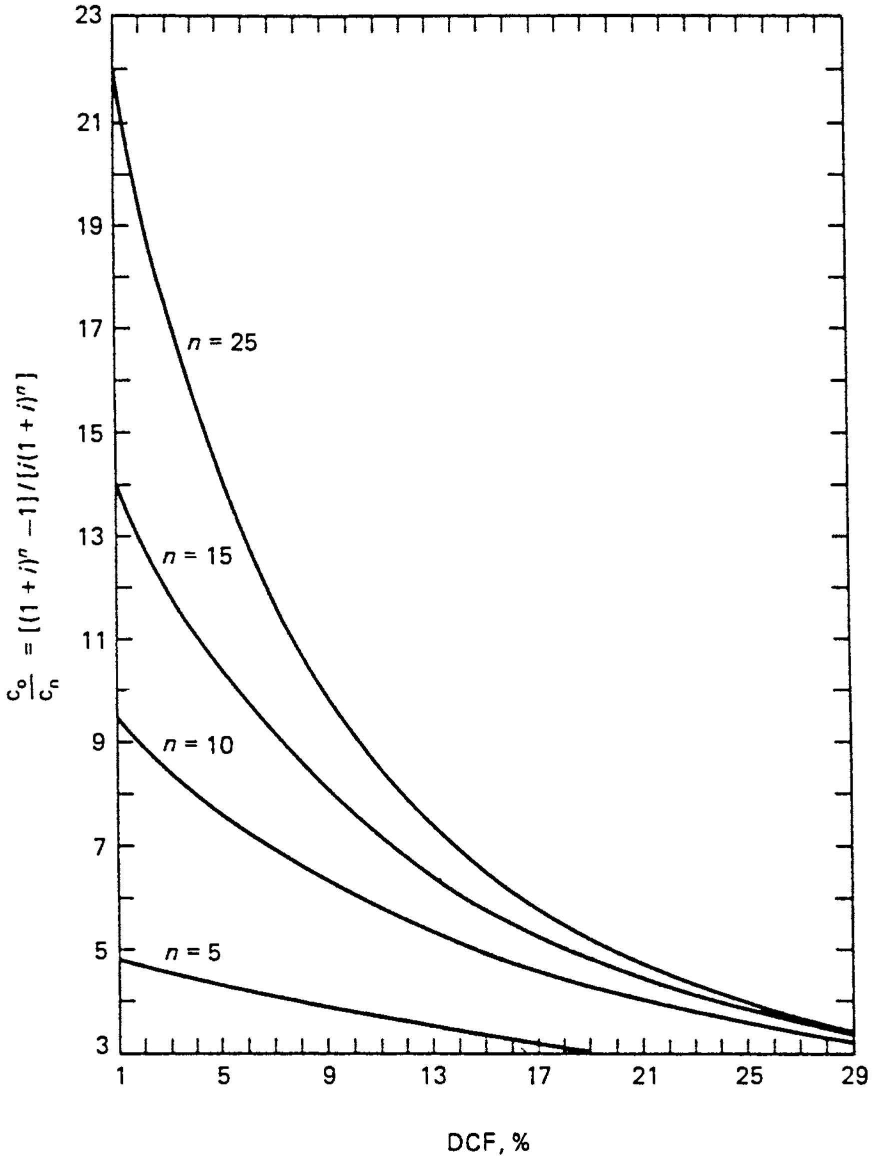

Figure 9-3. Graphical solution for simplified DCF calculation. (Constant cash flow, compounded annually, no salvage or working capital return.) Source: Horwitz [1].

(text continued from page 729)

The NPV measures the direct incentive to invest in a given proposal as a bonus or premium over the amount an investor could otherwise earn by investing the same money in a safe alternative, which would yield a return calculated at the rate, i. The resulting NPV from a project's cash flow is a measure of the cash profit that the project will produce after recovering the initial investment and meeting all costs, including the cost of capital. The more positive the NPV is, the more attractive the proposition. If NPV is 0, the viability of the project is marginal; if it is negative, the proposal is unattractive.

Discounted Cash Flow Rate of Return (DCFRR)

The discounted cash flow rate of return is known by other terms, for example, the profitability index, the true rate of return, the investor's rate of return, and the internal rate of return. It is defined as the discount rate, i, which makes the NPV of a project equal to zero. This can be expressed mathematically by

$$\mathrm{NVP} = \sum p = \sum_{t=0}^{t=n} \frac{C_t}{(1 + t)^t} = 0 \qquad (9\text{-}14)$$

The main advantage of DCFRR over NPV is that it is independent of the zero or base year that is chosen. In contrast, the value of NPV varies acccording to the zero year chosen. In calculating the NPV, the cost of capital has to be explicitly included as i in the discounting calculations. In computing the DCFRR, the cost of capital is not included. Instead the value calculated for i is compared with the cost of capital to see whether the project is profitable. The DCFRR for a project is the rate of return on investment. It measures the efficiency of the capital and determines the earning power of the project investment. Therefore, a DCFRR of say 20 percent implies that 20 percent per year will be earned on the investment, in addition to which the project generates sufficient money to repay the original investment plus any interest payable on borrowed capital plus all taxes and expenses.

Net Return Rate (NRR)

The net return rate is analogous to the rate of return and is the net average discounted "return" on the investment over and above the cost of capital. This is defined by:

$$\mathrm{NRR} = \frac{\mathrm{NPV}}{\begin{pmatrix}\text{Discounted}\\ \text{investment}\end{pmatrix}\begin{pmatrix}\text{Project}\\ \text{life}\end{pmatrix}} \times 100 \qquad (9\text{-}15)$$

where the investment is discounted to the same point as the NPV. Holland *et al.* [7] introduced the NPV/investment ratio as a normalized measure of the total discounted return over the life of the investment. Ward [4] showed that the NPV can be divided by the number of cash flow increments (venture lifetime) so that the NRR corresponds to the average discounted net return on investment. The cost of capital is already accounted for by the discount rate in the NPV computation, and therefore the NRR is the true return rate.

Depreciation

Estimation of depreciation charges may be based on:

1. cost of operation
2. tax allowance
3. means of building up a fund to finance plant replacement
4. measure of falling value

The annual depreciation charge can be calculated using "straight line" depreciation, and is expressed as:

$$D = \frac{C_{FC} - S}{n} \qquad (9\text{-}16)$$

where D = annual depreciation
C_{FC} = initial fixed capital cost
n = n years of projected life
S = salvage value

Assuming that C_{FC} is the initial fixed capital investment, and S is the projected salvage value at the end of n years of projected life, then the depreciated rate, d_j, for any particular year, j, is:

$$D_j = (C_{FC} - S)d_j \qquad (9\text{-}17)$$

where D_j = annual depreciation charge

With the straight line calculation procedure, where d_j is constant, combining Equation 9-16 and Equation 9-17 gives:

$$d = \frac{1}{n} \tag{9-18}$$

The various components of a plant such as equipment, buildings, and improvements are characterized by projected lifetimes. During this period, each item depreciates from its initial investment cost, C_{FC}, to a salvage value, S, over the period of n years of its projected lifetime. At the end of any particular year, k, the depreciated value or book value, V_k, is:

$$V_k = C_{FC} - \sum_{1}^{k} D_j \tag{9-19}$$

where D_j is the annual depreciation charge for year j. Substituting Equation 9-17 into Equation 9-19 gives

$$\begin{aligned} V_k &= C_{FC} - \sum_{1}^{k} (C_{FC} - S)d_j \\ &= C_{FC} - (C_{FC} - S)\sum_{1}^{k} d_j \end{aligned} \tag{9-20}$$

For the straight line depreciation procedure,

$$\sum_{1}^{k} d_j = \sum_{1}^{k} d = kd = \frac{1}{n} \tag{9-21}$$

and

$$V_k = C_{FC} - \frac{k}{n}(C_{FC} - S) \tag{9-22}$$

Double Declining Balance (DDB) Depreciation

Equipment and complete plants depreciate and lose value more rapidly in the early stages of life. The depreciation based upon the declining book value balance can be expressed as:

$$D_j = d_j . V_{j-1} \tag{9-23}$$

The rate of depreciation, d_j, is the same for each year, j; however, the depreciation charges decrease each year because the book value decreases each year. For a declining balance method, the depreciation rate of decline is up to twice, but no more than twice the straight line rate. This is given by:

$$d_j = d = \frac{2}{n} \tag{9-24}$$

Capitalized Cost

The capitalized cost, C_K, of a piece of equipment of a fixed capital cost, C_{FC}, having a finite life of n years and an annual interest rate, i, is defined by

$$(C_K - C_{FC})(1 + i)^n = C_K - S \tag{9-25}$$

where S = salvage or scrap value

C_K is in excess of C_{FC} by an amount, which, when compounded at an annual interest rate, i, for n years, will have a future worth of C_K less the salvage or scrap value, S. If the renewal cost of the equipment and the interest rate are constants at $(C_{FC} - S)$ and i, then C_K is the amount of the capital required to replace the equipment in perpetuity.

Rearranging Equation 9-25 gives

$$C_K = \left[C_{FC} - \frac{S}{(1 + i)^n}\right]\left[\frac{(1 + i)^n}{(1 + i)^n - 1}\right] \tag{9-26}$$

or

$$C_K = (C_{FC} - S.f_d)f_K \tag{9-27}$$

where f_d = discount factor

f_K = the capitalized cost factor = $(1 + i)^n/[(1 + i)^n - 1]$

The Average Rate Of Return (ARR)

The average rate of return (ARR) method averages out the cash flow over the life of the project. This is defined by

$$\text{ARR} = \frac{\text{average cash flow}}{\text{original investment}} \times 100 \tag{9-28}$$

The higher the percentage value of the ARR, the better the profitability of the project.

Present Value Ratio (Present Worth Ratio)

A commonly used profitability index in conjunction with the NPV method shows how closely a project has met the criterion of economic performance. This index is known as the present value ratio (PVR) or present worth ratio (PWR), and is defined as

$$\text{Present value} = \frac{\text{present value of all positive cash flows}}{\text{present value of all negative cash flows}} \qquad (9\text{-}29)$$

The present value ratio (PVR) gives an indication of how much the project makes relative to the investment. A ratio of 1.0 shows that the income just matches the expected income from capital invested for a given interest rate. A ratio of less than 1.0 indicates that the income does not come up to the minimum expectations. A ratio of more than 1.0 means that the project exceeds the minimum expectations.

Profitability

A project is profitable if its earnings are greater than the cost of capital. In addition, the larger the additional earnings, the more profitable the venture, and the greater the justification for putting the capital at risk. Therefore, a profitability estimate attempts to quantify the risk taken. The methods used to assess profitability are:

1. return on investment (ROI)
2. payback period (PB)
3. net present value (NPV)
4. discounted cash flow rate of return (DCFRR)
5. net return rate (NRR)
6. equivalent maximum investment period (EMIP)
7. interest recovery period (IRP)
8. rate of return on depreciated investment
9. rate of return on average investment
10. capitalized cost
11. average rate of return (ARR)
12. present value ratio (PVR)

Abrams [11] has listed other methods for assessing a project's profitability.

Economic Analysis

Computer programs have been developed to estimate the net present value (NPV), present value ratio (PVR), net return rate (NRR), average rate of return (ARR), payback period (PBP) and discounted cash flow rate of return (DCFRR). These analyses are done for a given cash flow over the operating life of a project. These programs can be incorporated as subroutines into larger programs, if required. In addition, a detailed computer program has been developed to review an economic project using Kirkpatrick's [12] input data. These data are defined as follows:

Annual Revenue, $. The money received (sales minus the cost of sales) for one-year production from the plant. This is assumed as being constant for life of the project.

Annual Operating Cost, $. The cost of raw materials, labor, utilities, administration, insurance, and royalties, etc., but does not include debt service payments.

Depreciating Base, $. The capitalized cost of the facility and less non-depreciable items, such as land and inventory. No salvage is subtracted because double declining balance depreciation is used.

Project Life, Years. The length of time for which the facility is to be operated. It is also the term of the loan and the depreciation time.

Initial Loan, $. The capitalized cost minus owner equity.

Payments/Year. The number of payments on the loan per year: 1-annually, 2-biannually, 4-quarterly, and 12-monthly.

Periodic Interest Rate. The annual interest rate divided by the payments per year. For a 10 percent annual interest rate and monthly repayments, this is 0.10/12.

Investment Tax Credit, $. The percentage of the initial investment allowed as a tax credit in the year the investment is made.

Tax Rate. The percentage tax that must be paid on the project's pre-tax income. This rate is assumed to remain constant during the life of the project.

Debt Service/Period, $. The amount of each loan payment, that is:

$$\frac{(\text{Loan})\left[\dfrac{\text{Annual interest}}{\text{Payments per year}}\right]}{1-\left[1+\dfrac{\text{Annual interest}}{\text{Payments per year}}\right]^{-\left(\text{years}\times\frac{\text{Payments}}{\text{year}}\right)}}$$

The Salvage Value (or Scrap Value). The projected salvage value of equipment at the end of the project lifetime is that portion of the fixed capital that cannot be depreciated.

Land Value. Land is not considered depreciable. It can be used indefinitely for succeeding projects on a specific site, or it can be sold.

Working capital. The capital invested in various necessary inventoried items, which are completely recoverable at any time.

The calculations for every year of the project life are:

1. Calculate the depreciation as double declining (that is, twice the depreciation based divided by project life), and subtract it from the depreciation base.
2. Calculate the yearly interest and principal of the debt service payments.
3. Subtract from the revenue, the operating cost, annual depreciation, and interest.
4. Subtract from positive pre-tax income, until no negative pre-tax income remains, if the pre-tax income is negative or has been negative in a prior year.
5. Calculate the income tax due at the given rate, and apply the investment tax credit against the income tax due until the credit is exhausted, if after Step 4, the pre-tax income is still positive.
6. Deduct the income tax remaining after Step 5 from the pre-tax income, leaving the after-tax income.
7. Add the after-tax income to the depreciation for the year, yielding the cash flow.
8. Determine the loan balance at the end of the year.
9. Determine the amount of unused depreciation after the last year of the project's life. Because double declining depreciation does not totally exhaust the depreciation account, the unused depreciaton should be added to the cash flow of the last year as salvage value recovered at the termination of the project under consideration.

10. Calculate the net present value, NPV, for a known discount rate.
11. Determine the present value ratio, PVR.
12. Calculate the net return rate, NRR.
13. Calculate the average rate of return, ARR.
14. Estimate the payback period, PBP.

For a given discount rate, calculate the discount factor during the operating life of the project. Multiply the discount factor by the cash flow and obtain the net present value and the net return rate. Valle-Riesta [8] has listed alternative methods of calculating cash flow, as shown in Table 9-6.

Methods 1 and 2 in Table 9-6 give identical results.

Table 9-6
Method of Computing Cash Flow from Project

Method 1	Method 2
1. Cost of Manufacture (COM) includes depreciation	1. Cost of Manufacture (COM) includes depreciation
2. General expenses	2. Depreciation
3. Total operating expense (3) = (1) + (2)	3. COM less depreciation (3) + (1) – (2)
4. Total sales	4. General expenses
5. Profit before taxes	5. Out of pocket expenditure
6. Income taxes (6) ≈ 1/2 (5)	6. Total sales
7. Profit after tax (7) = (5) – (6) ≈ 1/2 (5)	7. Cash flow before taxes (7) = (6) – (5)
8. Depreciation	8. Profit before taxes (8) = (7) – (2)
9. Continuous cash flow from project (9) = (7) + (8)	9. Income tax (9) ≈ 1/2 (8)
	10. Profit after tax (10) = (8) – (9) ≈ 1/2 (8)
	11. Continuous cash flow from project (11) = (10) + (2)

Source: Valle-Riesta [8]

Cash flows into a project can be time-dependent, in which the cash flows occur in a continuous process rather than on a one-time basis. Figure 9-4 illustrates a continuous cash flow diagram. Continuous cash flows into the project are from sales revenues, and cash flows out are for out-of-pocket expenses. The difference between the incoming and outgoing cash flow is the net cash flow generated by the project. The combined net cash flow generated by all the company's projects is reduced by the income tax payment to yield the net continuous cash flow. Expressing the definition of profit with the continuous cash flow results in the following:

Profit before taxes = continuous cash flow – depreciation before taxes

Profit after taxes = continuous cash flow – depreciation after taxes

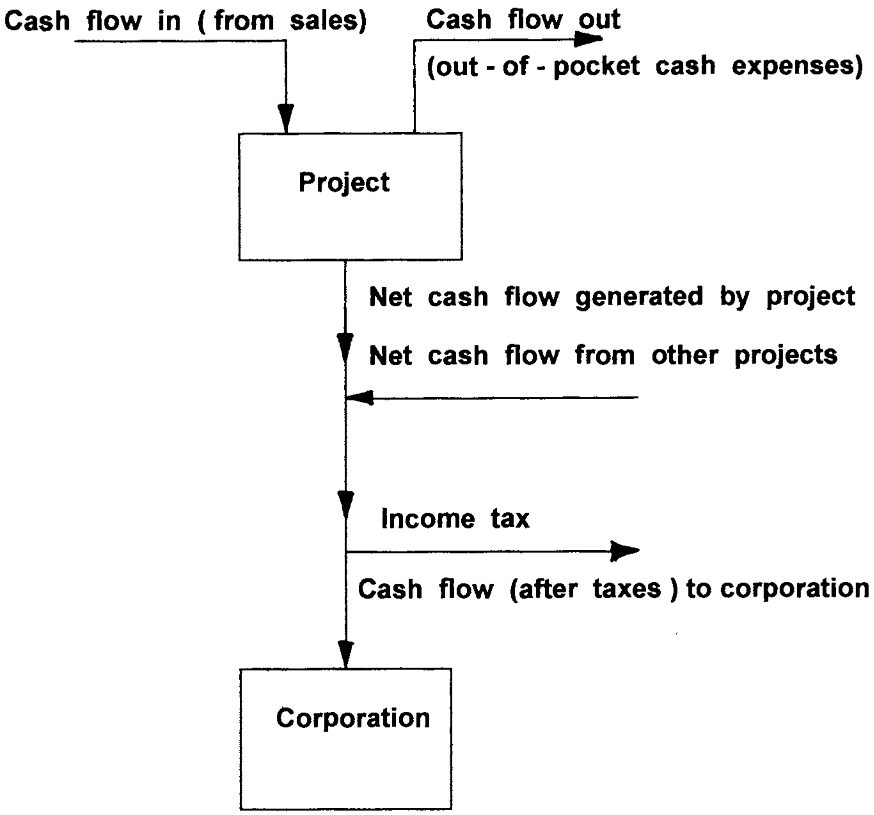

Figure 9-4. A continuous cash flow diagram. Source: Valle-Riestra [8].

It is useful to keep in mind that:

Cash flow ≠ profit

Allen [9] has provided a systematic procedure for assessing investment proposals for new plant and equipment, exploiting new technology, and replacing uneconomic, inefficient, and obsolete plants, process, and equipment.

Inflation

A decrease in the average purchasing value of currency is referred to as inflation. An inflation rate of 15 percent, for example, means that the average cost of goods and services will increase 15 percent in one year. The result is that commencing construction one year early will reduce the amount of money expended by 15 percent. Since the 1980s, inflation has been considered in most economic project evaluations.

When inflation is used in economic evaluations, all items except interest on a loan and depreciation are considered to increase in value at the same rate as inflation. Generally, interest is set at the time a loan is negotiated and does not change with inflation. In addition, depreciation depends on the method (for example, straight line or double declining balance) used and the capital charges incurred before start-up are not affected by the inflation rate after start-up. Determining the profitability of a project (for example, NPV), the interest rate is assumed to be greater than the inflation rate. Money may be lost on the project while the net present value indicates the opposite, if the inflation rate is greater than the interest rate. There are cases in which the interest rate is set at the expected inflation rate plus a real expected interest rate. The real expected interest rate is the interest rate that is used to calculate the net present value when there is no inflation. Alternatively, the present value is calculated using the inflation rate as the interest rate, the net present value is then determined using the real expected interest rate.

CAPITAL COST ESTIMATION

Capital cost estimation is an essential part of investment appraisal. Many types of capital cost estimates are made, ranging from the order of magnitude to detailed estimates requiring the collection of accurate technical data. The American Association of Cost Engineers defined five types of cost estimates as follows:

Order-of-magnitude estimate (ratio estimate). Approximate method based on cost data for previous similar types of plant. Probable error within 10 to 50 percent.

Study estimate (factored estimate). Better than order-of-magnitude but requires knowledge of major items of equipment. Used for feasibility surveys. Probable error up to 30 percent.

Preliminary estimate (budget authorization estimate). More detailed information required than for study estimate. Probable error up to 20 percent.

Definitive estimate (project control estimate). Based on considerable data obtained before preparing completed drawings and specifications. Probable error within 10 percent.

Detailed estimate (firm or contractor's estimate). Requires completed drawings and specifications. Probable error within 10 percent.

Process plant designs start from preliminary designs based on approximate technical data, calculations, and cost data to final designs that require detailed and accurate data, calculations, and quotations. Cost estimates of a proposed plant are continuously carried out during the development of a process from the laboratory to construction.

The total capital cost, C_{TC}, of a project consists of the fixed capital cost, C_{FC}, plus the working capital, C_{WC}, plus the cost of land and any other non-depreciable assets, C_L. This is given by

$$C_{TC} = C_{FC} + C_{WC} + C_L \qquad (9\text{-}30)$$

The fixed capital cost, C_{FC}, is the capital required to provide all the depreciable facilities. C_{FC} may be divided into two classes known as the battery limits and auxiliary facilities. The boundary of battery limits includes all manufacturing and processing equipment. The auxiliary facilities are the storage areas, administration offices, utilities and other essential and non-essential supporting facilities.

Equipment Cost Estimations By Capacity Ratio Exponents

It is often necessary to calculate the cost of a piece of equipment when there are no available cost data for the particular size of capacity. If the cost of a piece of equipment or plant size or capacity, Q_1, is C_1, the cost C_2 of a similar piece of equipment or plant size or capacity, Q_2, can be calculated from the equation

$$C_2 = C_1\left(\frac{Q_2}{Q_1}\right)^m \tag{9-31}$$

where

the value, m, depends on the type of equipment or plant. The value of the index, m, is generally taken as 0.6 [13], the well known six-tenths rule. This value can be used to get a rough estimate of the capital cost, if there are insufficient data to calculate the index for the particular size of equipment required. Table 9-7 lists values of m for various types of equipment. Cost indexes should be used to bring the cost data to a desired year. A cost index is a value for a given point in time showing the cost at that time relative to a certain base time. If the cost at some time in the past is known, the equipment cost at the present time can be determined from the equation

$$\text{Present cost} = \text{previous cost}\left(\frac{\text{present index}}{\text{previous index}}\right) \tag{9-32}$$

Cost indexes are used to give a general estimate, but no index can account for all the factors. Many different types of cost indexes are

Table 9-7
Typical Exponents for Equipment Cost vs Capacity

Equipment	Exponent (m)
Reciprocating compressor	0.75
Turboblowers compressor	0.5
Electric motors	0.8
Evaporators	0.5
Heat exchangers	0.65 to 0.95
Piping	0.7 to 0.9
Pumps	0.7 to 0.9
Rectangular tanks	0.5
Spherical tanks	0.7
Towers, constant diameter	0.7
Towers, constant height	1.0

Source: Institution of Chemical Engineers [15].

published in magazines such as the *Chemical Engineering Plant* cost index, *Engineering News-Records* construction index, the *Oil & Gas Journal,* and *Process Engineering.* Table 9-8 shows the international plant cost indexes from March 1992 to February 1993.

Factored Cost Estimate

The purchased cost of an item of equipment, free on board (FOB) is quoted by a supplier, and may be multiplied by a factor of 1.1 to give the approximate delivered cost. The factorial methods for estimating the total installed cost of a process plant are based on a combination of materials, labor, and overhead cost components. The fixed capital cost, C_{CF}, of a plant based on design can be estimated using the Lang Factor method [14] given by the equation

$$C_{FC} = f_L \sum C_{EQ} \tag{9-33}$$

where $f_L = 3.10$ for solids processing
$f_L = 3.63$ for mixed solids-fluid processing
$f_L = 4.74$ for fluid processing

ΣC_{EQ} is the sum of the delivered costs of all the major items of process equipment. The major advantage of the Lang method is that the cost of equipment is available.

Other methods for estimating capital investment consider the fixed-capital investment required as a separate unit. These are known as the functional-unit estimates, the process step scoring method, and the modular estimate.

The functional unit may be characterized as a unit operation, unit process, or separation method that involves energy transfer, moving parts, or a high level of internals. The unit includes all process streams together with side or recycle streams. Bridgwater [16] proposed seven functional units, namely, compressor, reactor, absorber, solvent extractor, solvent recovery column, main distillation column, and furnace and waste heat boiler. Taylor [17] developed the step counting method, based on a system in which a complexity score accounting for factors such as throughput, corrosion problems, and reaction time is estimated for each process step. The modular estimate considers individual modules in the total system with each module consisting of a group of similar items. For the modular estimate, all heat exchangers are classified in one module, all furnaces in another, all vertical process vessels in another,

Table 9-8
International Plant Cost Indexes
Mar 1992–Feb 1993 Base Date Jan 1990 = 100

COUNTRY	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Australia	107.7	107.9	107.9	108.2	108.4	108.6	108.7	108.8	108.8	109.0	109.3	109.4
Belgium	108.6	109.2	109.3	109.2	110.4	110.8^{R}	110.8	111.4	111.2	111.2	111.2	111.2
Canada	107.0	107.0	106.9	106.3	105.7	106.3	106.9	107.5	107.5	108.7	108.8	108.8
Denmark	107.0	108.4	108.5	109.3	110.4	108.0	108.5	108.9	108.5	110.4	110.7	-
France	106.5	106.9	107.0	107.1	107.5	107.5	108.1	108.3	108.5	108.6	109.2	109.5
Germany	113.8	114.0	114.0	114.9	115.0	115.0	115.4	115.4	115.4^{F}	116.2	116.3	116.4
Italy	109.5	109.6	109.6	109.9	110.1	110.0	110.2	110.5	110.5	110.7	-	-
Japan	103.0	102.8	102.8	110.4	102.7	101.3	103.1	103.3	103.4	102.5	100.3	103.0
Netherlands	106.8	108.0	108.1	108.1	108.8	108.8	108.8	108.7	108.7	108.7	109.5	109.5
New Zealand	103.9	104.4	104.4	104.4	105.0	105.0	105.0	105.3	105.4	105.4	-	-
Spain	111.1	113.2	113.2	113.3	114.4	114.4	114.4	114.7	114.8	114.8	-	-
Sweden	106.2	107.9	108.8	109.2	109.6	107.9	108.4	109.0	109.5	111.3	-	-
USA	101.7	101.1	101.6	101.4	100.4	100.8	100.7	100.9	100.5	100.7	100.7	100.7
UK	117.2	115.0	115.1	117.0	116.8	117.1	118.2	116.2	114.4	114.6	114.9	115.8

R = revised value, P = provisional value, F = forecast value

SOURCE: PROCESS ENGINEERING JUNE 1993

etc. The total cost estimate is considered under six general groupings. These are chemical processing, solids handling, site development, industrial buildings, offsite facilities, and project indirects [18].

Nomenclature

ARR = average rate of return
C = cash flow for each year
C_{CF} = net annual cash flow
C_{FC} = fixed capital cost
C_K = capitalized cost
C_L = land cost
C_0 = initial investment cost
C_n = cash flow
C_{TC} = total capital cost
C_{WC} = working capital cost
C_1 = capital cost of the designed plant
C_2 = capital cost of the existing plant
D = annual depreciation
DCFRR = discounted cash flow rate of return
D_j = annual depreciation charge
d_j = depreciation rate
EMIP = equivalent maximum investment period
f_d = discount factor
f_K = capitalized cost factor
I = investment cost
IRP = interest recovery period
IRR = internal rate of return
i = interest rate of return (ROI/100)
m = exponential power for cost capacity relationships
NPV = net present value
NRR = net return rate
n = years of project life
PBP = payback period
PV = present value
PVR = present value ratio
PWR = present worth ratio
Q_1 = capacity of the designed plant
Q_2 = capacity of existing plant
ROI = return of investment
S = salvage value

PROBLEMS AND SOLUTIONS

Problem 9-1

Consider a plant costing \$1,000,000 to build that produces a product A. For the same capital outlay a different plant can be erected to produce an alternative product B. Conditions are such that each plant will only be in operation for eight years and then both will be scrapped. The cash flows in each of the eight years obtained by selling A and B are shown in Table 9-9. A choice is being made about which plant is more profitable.

Solution

The computer program PROG91 calculates the net present value and the net return rate at discount rates of 5, 10, 15, 20, 25, 30, 35, and 40%. Tables 9-10 and 9-11 give both the input data and computer outputs for products A and B. Figure 9-5 shows a plot of the cumulative cash flows against the project life, and Figure 9-6 gives a plot of the NPV against the discount rate. Figure 9-5 gives the payback period of product A between 3 and 4 years and product B is about 2 years. The results show

Table 9-9
Annual Cash Flows and Cumulative Cash Flows

Year	Product A Cash Flows \$	Product A Cumulative Cash Flows \$	Product B Cash Flows \$	Product B Cumulative Cash Flows \$
	–1,000,000	–1,000,000	–1,000,000	–1,000,000
1	100,000	–900,000	800,000	–200,000
2	200,000	–700,000	700,000	500,000
3	300,000	–400,000	600,000	1,100,000
4	400,000	0	500,000	1,600,000
5	500,000	500,000	400,000	2,000,000
6	600,000	1,100,000	300,000	2,300,000
7	700,000	1,800,000	200,000	2,500,000
8	800,000	2,600,000	100,000	2,600,000

Table 9-10
Input Data and Computer Output for the Net Present Value of Product A at 10 Percent Discount Rate

```
DATA91.DAT
-------------
8
10
-1000000
100000
200000
300000
400000
500000
600000
700000
800000

                         NET PRESENT VALUE CALCULATION
******************************************************************************

                       9   YEARLY CASH FLOWS INCLUDING YEAR 0

                       10.00   PERCENTAGE ANNUAL DISCOUNT RATE
------------------------------------------------------------------------------

      YEAR      CASH FLOWS ($)     CUMULATIVE           DISCOUNT         PRESENT
                                   CASH FLOWS ($)       FACTOR           VALUE ($)
------------------------------------------------------------------------------
      0         -1000000.00        -1000000.00          1.0000         -1000000.00
      1           100000.00         -900000.00           .9091           90909.09
      2           200000.00         -700000.00           .8264          165289.25
      3           300000.00         -400000.00           .7513          225394.43
      4           400000.00                .00           .6830          273205.36
      5           500000.00          500000.00           .6209          310460.63
      6           600000.00         1100000.00           .5645          338684.31
      7           700000.00         1800000.00           .5132          359210.63
      8           800000.00         2600000.00           .4665          373205.84
------------------------------------------------------------------------------

      THE NET PRESENT VALUE ($):          1136359.53

      PRESENT VALUE RATIO:               2.136

      THE NET RETURN RATE:               14.20    %

      THE AVERAGE RATE OF RETURN:        45.00    %

      THE PAYBACK PERIOD IS BETWEEN:        3   AND    4    YEARS
```

that product B gives greater present value ratios than product A. In addition, product B gives greater net present values at different discount rates than product A. These show that product B is more promising than product A. Further profitability indexes (ARR, NRR, PBP) suggest that product B is a better choice than product A.

Problem 9-2

Using the cash flows of products A and B in Problem 9-1, determine the discount cash flow rate of return (DCFRR).

Table 9-11
Input Data and Computer Output for the Net Present Value of Product B at 10 Percent Discount Rate

```
DATA91.DAT
-------------
8
10
-1000000
800000
700000
600000
500000
400000
300000
200000
100000


                          NET PRESENT VALUE CALCULATION
*******************************************************************************

                        9   YEARLY CASH FLOWS INCLUDING YEAR 0

                       10.00   PERCENTAGE ANNUAL DISCOUNT RATE
-------------------------------------------------------------------------------

      YEAR      CASH FLOWS ($)    CUMULATIVE          DISCOUNT         PRESENT
                                  CASH FLOWS ($)      FACTOR           VALUE ($)
-------------------------------------------------------------------------------
      0       -1000000.00          -1000000.00        1.0000         -1000000.00
      1         800000.00           -200000.00         .9091           727272.71
      2         700000.00            500000.00         .8264           578512.37
      3         600000.00           1100000.00         .7513           450788.85
      4         500000.00           1600000.00         .6830           341506.70
      5         400000.00           2000000.00         .6209           248368.50
      6         300000.00           2300000.00         .5645           169342.16
      7         200000.00           2500000.00         .5132           102631.61
      8         100000.00           2600000.00         .4665            46650.73
-------------------------------------------------------------------------------

      THE NET PRESENT VALUE ($):           1665073.63

      PRESENT VALUE RATIO:                2.665

      THE NET RETURN RATE:                20.81    %

      THE AVERAGE RATE OF RETURN:         45.00    %

      THE PAYBACK PERIOD IS BETWEEN:        1   AND   2    YEARS
```

Solution

The computer program PROG92 determines the discounted cash flow rate of return (DCFRR). Tables 9-12 and 9-13 illustrate both the input data and computer outputs for products A and B. The DCFRR of product A is 28.264%, and that of product B is 64.863%. The results further confirm that product B is more promising than product A.

Problem 9-3

Calculate the yearly return of investment on the following financing data as shown in Table 9-14.

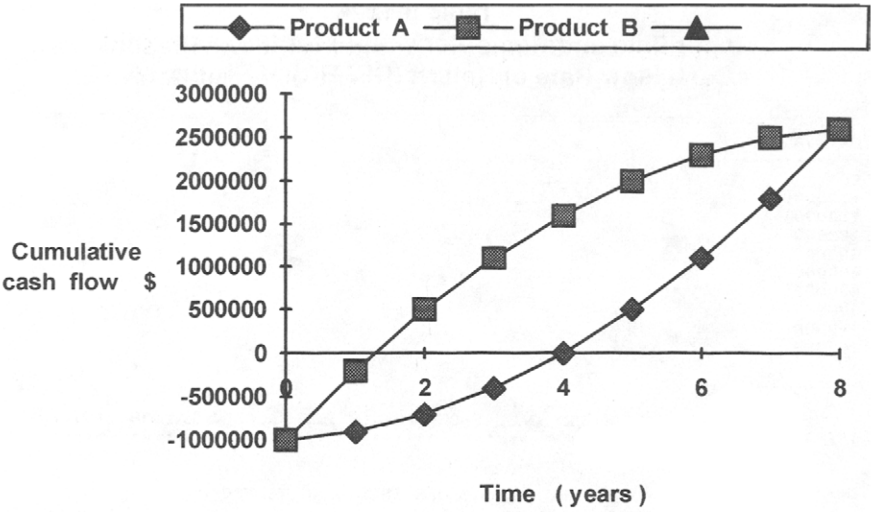

Figure 9-5. Cumulative cash flow diagram.

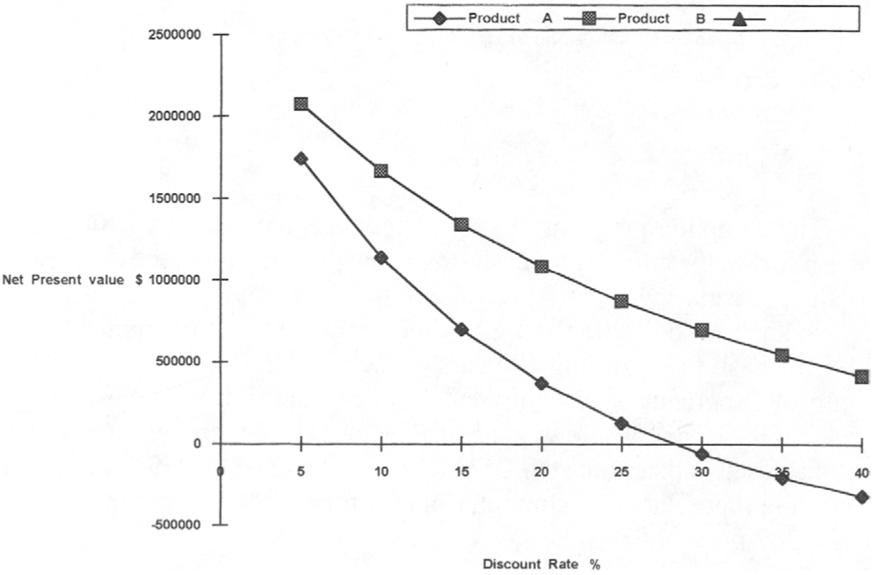

Figure 9-6. Net present value vs. discount rate.

Table 9-12
Input Data and Computer Output for the Discount Cash Flow Rate of Return (DCFRR) of Product A

```
DATA92.DAT
----------
9
-1000000
100000
200000
300000
400000
500000
600000
700000
800000


                      DISCOUNT CASH FLOW RATE OF RETURN CALCULATION
***************************************************************************


                      9   YEARLY CASH FLOWS INCLUDING YEAR 0

                   YEAR             CASH FLOW ($)
***************************************************************************
                   0              -1000000.00
                   1                100000.00
                   2                200000.00
                   3                300000.00
                   4                400000.00
                   5                500000.00
                   6                60000O.00
                   7                700000.00
                   8                800000.00
---------------------------------------------------------------------------

      THE DISCOUNT CASH FLOW RATE OF RETURN (%):  28.264
```

Solution

The computer program PROG93 computes the following: the yearly cash flows, the cumulative cash flows, the present value, the net present value, present value ratio, average return rate, net return rate, and the payback period. Table 9-15 gives the input data and computer output for the cash flows during 10 years of the project life, and at a discount rate of 5 percent. The computed salvage value of the investment is \$4,294,967. The cash flows generated by the computer program PROG93 is then used to determine the DCFRR from program PROG92. Table 9-16 lists the input data and computer output for DCFRR of the investment as 6.347 percent.

(text continued on page 761)

Table 9-13
Input Data and Computer Output for the Discount Cash Flow Rate of Return (DCFRR) of Product B

```
DATA92.DAT
-----------
9
-1000000
800000
700000
600000
500000
400000
300000
200000
100000


                         DISCOUNT CASH FLOW RATE OF RETURN CALCULATION
*****************************************************************************


                        9   YEARLY CASH FLOWS INCLUDING YEAR 0


                     YEAR           CASH FLOW ($)
*****************************************************************************
                     0             -1000000.00
                     1               800000.00
                     2               700000.00
                     3               600000.00
                     4               500000.00
                     5               400000.00
                     6               300000.00
                     7               200000.00
                     8               100000.00
-----------------------------------------------------------------------------

      THE DISCOUNT CASH FLOW RATE OF RETURN (%):  64.863
```

Table 9-14
Financing Data

1.	Annual revenue, $	9,000,000
2.	Annual operating cost $	1,200,000
3.	Depreciating base, $	40,000,000
4.	Project life, years	10
5.	Initial loan, $	30,000,000
6.	Number of payment per year	12
7.	Annual interest, %	10
8.	Investment credit, %	10
9.	Tax rate, %	50
10.	Rate of return, %	5

Table 9-15
Input Data and Computer Output for the Economic Project Evaluation at 5 Percent Discount Rate

```
DATA93.DAT
-----------
9000000
1200000
40000000
10
30000000
12
10
10
50
5
```

```
                     ECONOMIC EVALUATION OF A PROJECT
****************************************************************************

      1      ANNUAL REVENUE  $:                          9000000.00

      2      ANNUAL OPERATING COST  $:                   1200000.00

      3      DEPRECIATION BASE  $:                      40000000.00

      4      PROJECT LIFE, YEARS:                    10.

      5      INITIAL LOAN  $:                           30000000.00

      6      NUMBER OF PAYMENTS PER YEAR:             12.

      7      ANNUAL INTEREST,  %:                     10.

      8      INVESTMENT CREDIT, %:                    10.

      9      TAX RATE,  %:                            50.

     10      DISCOUNT RATE  %:                         5.00
----------------------------------------------------------------------------


                                YEAR   1
****************************************************************************

     REVENUE  $:                                         9000000.00

     OPERATING COST  $:                                  1200000.00

     DEPRECIATION  $:                                    8000000.00

     INTEREST  $:                                        2917171.30

     PRE-TAX INCOME  $:                                 -3117171.30

     TAX AT 50.%,  $:                                           .00

     AFTER TAX INCOME  $:                               -3117171.30

     CASH FLOW  $:                                       4882828.70
****************************************************************************
```

Table 9-15
(continued)

```
                                YEAR   2
****************************************************************************

      REVENUE  $:                                        9000000.00

      OPERATING COST  $:                                 1200000.00

      DEPRECIATION  $:                                   6400000.00

      INTEREST  $:                                       2724472.52

      PRE-TAX INCOME  $:                                -1324472.52

      TAX AT 50.%,  $:                                          .00

      AFTER TAX INCOME  $:                              -1324472.52

      CASH FLOW  $:                                      5075527.48
****************************************************************************


                                YEAR   3
****************************************************************************

      REVENUE  $:                                        9000000.00

      OPERATING COST  $:                                 1200000.00

      DEPRECIATION  $:                                   5120000.00

      INTEREST  $:                                       2511595.66

      PRE-TAX INCOME  $:                                  168404.34

      TAX AT 50.%,  $:                                          .00

      AFTER TAX INCOME  $:                                168404.34

      CASH FLOW  $:                                      5288404.34
****************************************************************************


                                YEAR   4
****************************************************************************

      REVENUE  $:                                        9000000.00

      OPERATING COST  $:                                 1200000.00

      DEPRECIATION  $:                                   4096000.00

      INTEREST  $:                                       2276427.81

      PRE-TAX INCOME  $:                                 1427572.19

      TAX AT 50.%,  $:                                          .00

      AFTER TAX INCOME  $:                               1427572.19

      CASH FLOW  $:                                      5523572.19
****************************************************************************
```

(table continued on next page)

Table 9-15
(continued)

```
                                  YEAR    5
*******************************************************************************

      REVENUE  $:                                                 9000000.00

      OPERATING COST  $:                                          1200000.00

      DEPRECIATION  $:                                            3276800.00

      INTEREST  $:                                                2016634.81

      PRE-TAX INCOME  $:                                          2506565.19

      TAX AT 50.%,  $:                                                   .00

      AFTER TAX INCOME  $:                                        2506565.19

      CASH FLOW  $:                                               5783365.19
*******************************************************************************


                                  YEAR    6
*******************************************************************************

      REVENUE  $:                                                 9000000.00

      OPERATING COST  $:                                          1200000.00

      DEPRECIATION  $:                                            2621440.00

      INTEREST  $:                                                1729638.09

      PRE-TAX INCOME  $:                                          3109819.75

      TAX AT 50.%,  $:                                                   .00

      AFTER TAX INCOME  $:                                        3109819.75

      CASH FLOW  $:                                               5731259.75
*******************************************************************************


                                  YEAR    7
*******************************************************************************

      REVENUE  $:                                                 9000000.00

      OPERATING COST  $:                                          1200000.00

      DEPRECIATION  $:                                            2097152.00

      INTEREST  $:                                                1412589.07

      PRE-TAX INCOME  $:                                          4290259.00

      TAX AT 50.%,  $:                                                   .00

      AFTER TAX INCOME  $:                                        4290259.00

      CASH FLOW  $:                                               6387411.00
*******************************************************************************
```

Table 9-15
(continued)

```
                                YEAR   8
*****************************************************************************

      REVENUE  $:                                         9000000.00

      OPERATING COST  $:                                  1200000.00

      DEPRECIATION  $:                                    1677722.00

      INTEREST  $:                                        1062340.87

      PRE-TAX INCOME  $:                                  5059937.50

      TAX AT 50.%,  $:                                    2230008.00

      AFTER TAX INCOME  $:                                2829929.50

      CASH FLOW  $:                                       4507651.13
*****************************************************************************


                                YEAR   9
*****************************************************************************

      REVENUE  $:                                         9000000.00

      OPERATING COST  $:                                  1200000.00

      DEPRECIATION  $:                                    1342177.00

      INTEREST  $:                                         675417.10

      PRE-TAX INCOME  $:                                  5782405.50

      TAX AT 50.%,  $:                                    2891202.75

      AFTER TAX INCOME  $:                                2891202.75

      CASH FLOW  $:                                       4233380.00
*****************************************************************************


                                YEAR  10
*****************************************************************************

      REVENUE  $:                                         9000000.00

      OPERATING COST  $:                                  1200000.00

      DEPRECIATION  $:                                    1073742.00

      INTEREST  $:                                         247977.37

      PRE-TAX INCOME  $:                                  6478281.00

      TAX AT 50.%,  $:                                    3239140.50

      AFTER TAX INCOME  $:                                3239140.50

      CASH FLOW  $:                                       4312882.38
*****************************************************************************

      SALVAGE VALUE  $:                                   4294967.30
```

(table continued on next page)

Table 9-15
(continued)

```
                     ECONOMIC PROJECT EVALUATION
                NET PRESENT VALUE AT A GIVEN DISCOUNT RATE
***************************************************************************


                 11   YEARLY CASH FLOWS INCLUDING YEAR 0

                  5.00   PERCENTAGE ANNUAL DISCOUNT RATE
----------------------------------------------------------------------------


             YEARLY CASH FLOWS ($)
----------------------------------------------------------------------------

     YEAR      CASH FLOWS ($)   CUMULATIVE          DISCOUNT        PRESENT
                                CASH FLOWS ($)      FACTOR          VALUE ($)
----------------------------------------------------------------------------
    0       -40000000.00       -40000000.00        1.0000       -40000000.00
    1         4882828.70       -35117171.30         .9524         4650313.26
    2         5075527.48       -30041643.82         .9070         4603653.46
    3         5288404.34       -24753239.47         .8638         4568323.13
    4         5523572.19       -19229667.28         .8227         4544257.34
    5         5783365.19       -13446302.09         .7835         4531418.98
    6         5731259.75        -7715042.34         .7462         4276755.43
    7         6387411.00        -1327631.34         .7107         4539415.19
    8         4507651.13         3180019.78         .6768         3050956.82
    9         4233380.00         7413399.78         .6446         2728875.61
   10         8607849.67        16021249.45         .6139         5284472.96
---------------------------------------------------------------------------

    THE NET PRESENT VALUE ($):          42778442.19

    PRESENT VALUE RATIO:                1.069

    THE NET RETURN RATE:               10.695    %

    THE AVERAGE RATE OF RETURN:        14.005    %

    THE PAYBACK PERIOD IS BETWEEN:         7   AND    8   YEARS
```

Table 9-16
Input Data and Computer Output for the Discount Cash Flow Rate of Retern (DCFRR) the the Economic Project Evaluation

```
DATA92.DAT
------------
11
-40000000.0
4882828.70
5075527.48
5288404.34
5523572.19
5783365.19
5731259.75
6387411.00
4507651.13
4233380.00
8607849.67


                    DISCOUNT CASH FLOW RATE OF RETURN CALCULATION
*******************************************************************************


                 11   YEARLY CASH FLOWS INCLUDING YEAR 0


                YEAR             CASH FLOW ($)
*******************************************************************************
                 0              -40000000.00
                 1                4882829.00
                 2                5075528.00
                 3                5288405.00
                 4                5523572.00
                 5                5783365.00
                 6                5731260.00
                 7                6387411.00
                 8                4507651.00
                 9                4233380.00
                10                8607850.00
-------------------------------------------------------------------------------


      THE DISCOUNT CASH FLOW RATE OF RETURN (%):    6.347
```

(text continued from page 754)

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```
        PROGRAM PROG91


C       ******************************************************************
C       *  THIS PROGRAM CALCULATES THE YEARLY CASH FLOWS, THE CUMULATIVE *
C       *  CASH FLOWS, DISCOUNT FACTORS AT A GIVEN RATE AND PRESENT      *
C       *  VALUES. THE PROGRAM FURTHER CALCULATES THE NET PRESENT VALUE, *
C       *  PRESENT VALUE RATIO, THE AVERAGE RATE OF RETURN, THE NET      *
C       *  RETURN RATE, AND THE PAYBACK PERIOD.                          *
C       ******************************************************************
C       ARR     =   AVERAGE RATE OF RETURN
C       YCF     =   YEARLY CASH FLOW
C       DF      =   DISCOUNT FACTOR
C       CUCF    =   CUMULATIVE CASH FLOW
C       NPV     =   NET PRESENT VALUE
C       NOCF    =   NUMBER OF PROJECT LIFE EXCLUDING YEAR 0
C       NRR     =   NET RETURN RATE
C       PV      =   PRESENT VALUE
C       PVR     =   PRESENT VALUE RATIO
C       TIME    =   PAYBACK PERIOD
C       *******************************************************************


        REAL*8 YCF, DF, PV, NPV, CUCF
        EXTERNAL XNPV
        REAL  NRR

        INTEGER TIME, TIME1

        DIMENSION YCF(0:100), DF(0:100), PV(0:100), CUCF(0:100)
C

        OPEN (UNIT = 3, FILE = 'DATA91.DAT', STATUS ='OLD', ERR=18)
        OPEN (UNIT = 1, FILE = 'PRN')


C       READ THE NUMBER OF YEARLY CASH FLOWS EXCLUDING YEAR 0: NOCF


        READ (3, *, ERR=19) NOCF

C       READ THE ANNUAL DISCOUNT RATE IN PERCENTAGE: DISC
C       READ THE YEARLY CASH FLOW: YCF


        READ (3, *, ERR=19) DISC
        READ (3, *, ERR=19) (YCF(K), K = 0, NOCF)

        GO TO 10

 18     WRITE (*, 21)
 21     FORMAT (6X,'DATA FILE DOES NOT EXIST')
        GO TO 999

 19     WRITE (*, 23)
 23     FORMAT(6X,'ERROR MESSAGE IN THE DATA VALUE')
        GO TO 999
```

```
 10     WRITE (1, 100)
 100    FORMAT (//,25X,'NET PRESENT VALUE CALCULATION',/1H ,78(1H*))

        NOCF1 = NOCF + 1

        WRITE (1, 110) NOCF1
 110    FORMAT(/,20X,I4,3X,'YEARLY CASH FLOWS INCLUDING YEAR 0')

        WRITE (1, 120) DISC
 120    FORMAT (/,20X,F8.2,3X,'PERCENTAGE ANNUAL DISCOUNT RATE',/,
     *  1H ,78(1H-))

        WRITE (1, 130)
 130    FORMAT (/,7X,'YEAR',5X,'CASH FLOWS ($)',4X,'CUMULATIVE',\)

        WRITE (1, 140)
 140    FORMAT (10X, 'DISCOUNT', 8X, 'PRESENT')

        WRITE (1, 150)
 150    FORMAT (34X,'CASH FLOWS ($)', 6X, 'FACTOR', 10X, 'VALUE ($)',
     *          /1H ,78(1H-))

C       CALCULATE THE CUMULATIVE CASH FLOW


        CUCF(0) = YCF(0)
        DO I = 1, NOCF
        CUCF(I) = CUCF(I-1) + YCF(I)
        END DO


        R1 = DISC/100.0
        PV(0) = YCF(0)*1.0

        DO 15 I1 = 0, 0
        IF (I1 .EQ. 0) THEN
        R1 = 0.0
        DF(I1) = 1.0/((1.0+R1)**I1)
        PV(I1) = YCF(I1)*DF(I1)
        ELSE
        ENDIF
 15     CONTINUE

        R1 = DISC/100.0

        DO 20 I1 = 1, NOCF
        DF(I1) =  1.0/((1.0+R1)**I1)
        PV(I1) =  YCF(I1)*DF(I1)
  20    CONTINUE


        DO  K = 0, NOCF
        WRITE (1, 160) K, YCF(K), CUCF(K), DF(K), PV(K)
 160    FORMAT (5X,I3,5X,F14.2,5X,F14.2,5X,F9.4,5X,F14.2)
        END DO

        WRITE (1, 170)
 170    FORMAT (78(1H-))
```

```
C       CALCULATE THE NET PRESENT VALUE FROM THE PRESENT VALUE


        NPV = 0.0
        DO J = 0, NOCF
        NPV = NPV + PV(J)
        END DO


        WRITE (1, 180) NPV
 180    FORMAT (1H0, 6X,'THE NET PRESENT VALUE ($):', 3X, T40, F14.2)


C       CALCULATE THE PRESENT VALUE RATIO, PVR
C       PVR = PRESENT VALUE OF ALL POSITIVE CASH FLOWS/
C             PRESENT VALUE OF ALL NEGATIVE CASH FLOWS

        SUM1 = 0.0
        DO K = 1, NOCF
        SUM1 = SUM1 + PV(K)
        END DO

        PVR = SUM1 /ABS(YCF(0))

        WRITE (1, 190) PVR
 190    FORMAT (1H0, 6X, 'PRESENT VALUE RATIO:', 3X, T40, F8.3)


C       CALCULATE THE NET RETURN RATE (NRR) i.e. THE NET PRESENT VALUE
C       DIVIDED BY THE PRODUCT OF INITIAL INVESTMENT AND THE PROJECT LIFE
C       (EXCLUDING YEAR 0).


        NRR = ABS(NPV /(ABS(PV(0))*NOCF))*100

        WRITE (1, 200) NRR
 200    FORMAT (1H0, 6X, 'THE NET RETURN RATE:', 3X,T40, F8.2,3X,'%')


C       CALCULATE THE AVERAGE RATE OF RETURN (ARR) i.e. THE AVERAGE
C       CASH FLOW DURING THE LIFE OF THE PROJECT (EXCLUDING YEAR 0).

        SUM = 0.0
        DO I = 1, NOCF
        SUM = SUM + YCF(I)
        END DO

        AVSUM = SUM/(NOCF)
        ARR = (AVSUM/ABS(YCF(0)))*100.0

        WRITE (1, 210) ARR
 210    FORMAT (1H0,6X,'THE AVERAGE RATE OF RETURN:',3X,T40,F8.2,
     *         3X,'%')


C       CALCULATE THE PAYBACK TIME FROM THE CUMULATIVE CASH FLOW, TIME: YEARS


        DO I = 0, NOCF
        IF ( CUCF(I+1) .GT. CUCF(I) .AND. CUCF(I+1) .GE. 0.0) THEN
```

```
        TEMP = CUCF(I+1)
        CUCF(I+1) = CUCF(I)
        CUCF(I) =  TEMP
        TIME = I
        TIME1 = TIME + 1
        GO TO 40
        ELSE
        ENDIF
        END DO

  40    WRITE (1, 220) TIME, TIME1
 220    FORMAT (1H0,6X,'THE PAYBACK PERIOD IS BETWEEN:',
     *           3X,T45,I2,2X,'AND',2X,I2,3X,'YEARS')


C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE (3, STATUS = 'KEEP')
        CLOSE (1)

  999   STOP
        END
```

```
      PROGRAM PROG92


C     ***************************************************************
C     *  THIS PROGRAM CALCULATES THE DISCOUNT CASH FLOW RATE OF     *
C     *  RETURN FROM A SET OF YEARLY CASH FLOWS                     *
C     ***************************************************************
C     YCF      =   YEARLY CASH FLOW
C     DCFRR    =   DISCOUNT CASH FLOW RATE OF RETURN
C     NOCF     =   THE NUMBER OF YEARLY CASH FLOW INCLUDING YEAR 0
C     ***************************************************************


      EXTERNAL DCFRR

      DIMENSION YCF (1:100)


      OPEN (UNIT = 3, FILE = 'DATA92.DAT', STATUS = 'OLD', ERR = 18)
      OPEN (UNIT = 1, FILE = 'PRN')


C     READ THE NUMBER OF YEARLY CASH FLOWS INCLUDING YEAR 0: NOCF

      READ (3, *, ERR=19) NOCF

C     READ THE YEARLY CASH FLOWS: YCF

      READ (3, *, ERR=19) (YCF(K), K = 1, NOCF)


      GO TO 10

 18   WRITE (*, 21)
 21   FORMAT (6X, 'DATA FILE DOES NOT EXIST')
      GO TO 999

 19   WRITE (*, 23)
 23   FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')
      GO TO 999

 10   WRITE (1, 100)
 100  FORMAT (///,20X,'DISCOUNT CASH FLOW RATE OF RETURN CALCULATION',
     *        /1H ,78(1H*))

      WRITE (1, 110) NOCF
 110  FORMAT (/,1H0,15X,I4,3X,'YEARLY CASH FLOWS INCLUDING YEAR 0')

      WRITE (1, 120)
 120  FORMAT (//, 17X,'YEAR', 12X, 'CASH FLOW ($)', /1H ,78(1H*))

      DO 20 K = 1, NOCF
      L = K - 1
      WRITE (1, 130) L, YCF(K)
 130  FORMAT (15X, I3, 11X, F14.2)
 20   CONTINUE

      WRITE (1, 140)
```

```
 140    FORMAT (78(1H-))

        DCF = DCFRR (YCF, NOCF)

        WRITE (1, 150) DCF
 150    FORMAT (/,1H0,6X,'THE DISCOUNT CASH FLOW RATE OF RETURN (%):',
     *          3X, T50, F8.3)


C       FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

        WRITE (1, *) CHAR(12)

        CLOSE (3, STATUS = 'KEEP')
        CLOSE (1)

 999    STOP
        END
C
C       ****************************************************************
C       THIS PROGRAM CALCULATES THE DISCOUNT CASH FLOW RETURN OF A SET
C       OF YEARLY CASH FLOWS
C       ****************************************************************

        FUNCTION DCFRR (CF, IYRS)
        DIMENSION CF (1:100)

        XIF = 1.
        M = 1

 10     PV = CF(IYRS)

        IF (M .GT. 100) THEN
        GO TO 20
        ELSE
        DO 30 J = 1, IYRS - 1
        PV = PV*XIF + CF(IYRS-J)
 30     CONTINUE
        ENDIF

        DPV = (IYRS-1)*CF(IYRS)

        DO 40 J = 1, IYRS - 2
        DPV = DPV*XIF + (IYRS-J-1)*CF(IYRS-J)
 40     CONTINUE

        P = PV/DPV

        IF ((ABS(P)-1.E-4) .GT. 0.0) THEN
        GO TO 50
        ELSE
        X1 = 1/XIF - 1.
        DCFRR = 100 * X1

        GO TO 60
        ENDIF

 50     XIF = XIF - P
        M = M + 1
        GO TO 10

 20     WRITE (1, 160)
 160    FORMAT (//,1H0,3X,'DCFRR CONVERGENCE OF NEXT CASH FLOW DOES ,
     *  OCCUR AFTER 100 TRIES',/)

 60     RETURN
        END
```

```
      PROGRAM PROG93

C     ****************************************************************
C     *  ECONOMIC EVALUATION OF PROJECTS                             *
C     *  THE PROGRAM CALCULATES YEARLY RETURN OF INVESTMENT AND THE  *
C     *  PRESENT VALUE AT A GIVEN DISCOUNT RATE.                     *
C     *  THE PROGRAM ALSO CALCULATES THE NET PRESENT VALUE, THE      *
C     *  AVERAGE RATE OF RETURN, THE NET RETURN RATE AND THE PAYBACK *
C     *  TIME                                                        *
C     ****************************************************************
C
C     X(1)     =  ANNUAL REVENUE, $.
C     X(2)     =  ANNUAL OPERATING COST, $.
C     X(3)     =  DEPRECIATION BASE, $.
C     X(4)     =  PROJECT LIFE, YEARS.
C     X(5)     =  INITIAL LOAN, $.
C     X(6)     =  NUMBER OF PAYMENTS PER YEAR
C     X(7)     =  ANNUAL INTEREST, %.
C     X(8)     =  INVESTMENT CREDIT, %.
C     X(9)     =  TAX RATE, %.
C     ARR      =  AVERAGE RATE OF RETURN
C     CF       =  CASH FLOW, $.
C     CUCF     =  CUMULATIVE CASH FLOW, $.
C     DF       =  DISCOUNT FACTOR
C     N        =  NUMBER OF YEARS
C     NRR      =  THE NET RETURN RATE
C     NPV      =  THE NET PRESENT VALUE, $.
C     PV       =  PRESENT VALUE
C     PVR      =  PRESENT VALUE RATIO
C     R        =  RATE OF RETURN
C     ***************************************************************
C
C

      REAL*8, B, E, S1, BT, X, CF, CUCF, DF, PV, NPV

      DIMENSION X(1:100), CF(0:100), CUCF(0:100), DF(0:100), PV(0:100)

      EXTERNAL FUN

      INTEGER A, FL, N, TIME, TIME1
      REAL NRR

      OPEN (UNIT = 3, FILE = 'DATA93.DAT', STATUS = 'OLD', ERR = 18)
      OPEN (UNIT = 1, FILE = 'PRN')

      READ (3, *, ERR=19)(X(I),I=1,9)
      READ (3, *, ERR=19)R

      WRITE (1, 100)
100   FORMAT (///, 22X,'ECONOMIC EVALUATION OF A PROJECT',
     *        /1H ,78(1H*))

      I = 1

      WRITE (1, 110) I, X(I)
110   FORMAT (1H0, 6X, I2, 6X,'ANNUAL REVENUE  $:',T55, F14.2)
```

```
        I = I+1

        WRITE (1, 120) I, X(I)
120     FORMAT (1H0, 6X, I2, 6X, 'ANNUAL OPERATING COST  $:',T55, F14.2)

        I = I + 1

        WRITE (1, 130) I, X(I)
130     FORMAT (1H0, 6X, I2, 6X, 'DEPRECIATION BASE  $:',T55, F14.2)

        I = I + 1

        WRITE (1, 140) I, X(I)
140     FORMAT (1H0, 6X, I2, 6X, 'PROJECT LIFE, YEARS:',T55, F3.0)

        I = I + 1

        WRITE (1, 150) I, X(I)
150     FORMAT (1H0, 6X, I2, 6X, 'INITIAL LOAN  $:',T55, F14.2)

        I = I + 1

        WRITE (1, 160) I, X(I)
160     FORMAT (1H0,6X,I2,6X,'NUMBER OF PAYMENTS PER YEAR:',T55,F4.0)

        I = I + 1

        WRITE (1, 170) I, X(I)
170     FORMAT (1H0, 6X, I2, 6X, 'ANNUAL INTEREST,  %:',T55, F4.0)

        I = I + 1

        WRITE (1, 180) I, X(I)
180     FORMAT (1H0, 6X, I2, 6X, 'INVESTMENT CREDIT, %:',T55, F4.0)

        I = I + 1

        WRITE (1, 190) I, X(I)
190     FORMAT (1H0, 6X, I2, 6X, 'TAX RATE,  %:',T55, F4.0)

        I = I + 1

        WRITE (1, 200) I, R
200     FORMAT (1H0, 6X, I2, 6X, 'DISCOUNT RATE  %:',T55, F6.2)

        WRITE (1, 210)
210     FORMAT (78(1H-))


        GO TO 20

18      WRITE (*, 220)
220     FORMAT (6X, 'DATA FILE DOES NOT EXIST')

        GO TO 999

19      WRITE (*, 230)
230     FORMAT (6X, 'ERROR MESSAGE IN THE DATA VALUE')

        GO TO 999
```

```
20     A = 0
       FL = 0
22     IF (FL .EQ. 1) THEN
       GO TO 60
       ELSE

       Q7 = X(3)
       Q5 = X(5)
       Q2 = X(7)
       X(7) = X(7)/(100.0*X(6))
       Q1 = X(8)
       X(8) = (X(8)*X(3))/100.0
       P3 = (X(5)*X(7))/(1.0-(1.0+X(7))**(-X(4)*X(6)))
       ENDIF

21     A = A + 1
       D = (2.0*X(3))/X(4)
       X(3) = X(3) - D
       I = X(6)
25     B = B + (X(5)*X(7))
       VAL1 = Q5 + (X(5)*X(7)) - P3

       IF (VAL1 .GT. 0.0) THEN
       GO TO 30
       ELSE

       WRITE (1, 240)
240    FORMAT (1H0, 6X, 'ERROR IN THE DATA VALUE')

       WRITE (1, 250)
250    FORMAT (1H0,6X,'I.E. THE TOTAL LOAN PLUS THE INTEREST PER',/1H ,
    *        6X,'PERIOD IS LESS THAN THE PAYMENTS')
       ENDIF

       GO TO 999


30     X(5) = X(5) + (X(5)*X(7)) - P3

       I = I - 1

       IF (I .LT. 0 .OR. I .GT. 0) THEN
       GO TO 25
       ELSE

       WRITE (1, 260) A
260    FORMAT (/, 1H1, 32X, 'YEAR', 2X, I2, /1H , 78(1H*))

       WRITE (1, 270) X(1)
270    FORMAT (1H0, 6X, 'REVENUE  $:', T55, F14.2)

       WRITE (1, 280) X(2)
280    FORMAT (1H0, 6X, 'OPERATING COST  $:', T55, F14.2)

       WRITE (1, 290) D
290    FORMAT (1H0, 6X, 'DEPRECIATION  $:', T55, F14.2)

       WRITE (1, 300) B
300    FORMAT (1H0, 6X, 'INTEREST  $:', T55, F14.2)
```

```
        ENDIF


        E = X(1) - X(2) - D - B
        X1 = E
        IF (X1 .LT. 0.0) THEN
        GO TO 40
        ELSE
        X1 = E - PO
        ENDIF
        IF (X1 .LT. 0.0) THEN
        GO TO 50
        ELSE
        E = X1
        PO = 0.0
        S1 = (E*X(9))/100.0
        X1 = S1 - X(8)
        ENDIF
        IF (X1 .EQ. 0.0 .OR. X1 .GT. 0.0) THEN
        GO TO 55
        ELSE
        X(8) = X(8) - S1
        S1 = 0.0
        ENDIF

70      WRITE (1, 310) E
310     FORMAT (1H0, 6X, 'PRE-TAX INCOME  $:', T55, F14.2)

        WRITE (1, 320) X(9), S1
320     FORMAT (1H0, 6X, 'TAX AT',F4.0,'%,  $:', T55, F14.2)

        BT = E - S1

        WRITE (1, 330) BT
330     FORMAT (1H0, 6X, 'AFTER TAX INCOME  $:', T55, F14.2)

        CF(A) = BT + D

        WRITE (1, 340) CF(A)
340     FORMAT (1H0, 6X, 'CASH FLOW  $:', T55, F14.2)

        WRITE (1, 350)
350     FORMAT ( 78(1H*))

        B = 0.0

        IF ((A-X(4)) .LT. 0.0) THEN

        GO TO 21
        ELSE

        WRITE (1, 360) X(3)
360     FORMAT (1H0, 6X, 'SALVAGE VALUE  $:', T55, F14.2)
        ENDIF


        GO TO 60

  40    PO = PO - X1
        S1 = 0.0
```

```
        GO TO 70
   50   PO = -X1
        X1 = 0.0
        GO TO 40
   55   S1 = X1
        X(8) = 0.0
        GO TO 70
        FL = 1

        GO TO 22


C      CALCULATE THE NET PRESENT VALUE OF INVESTMENT


 60     WRITE (1, 370)
 370    FORMAT (1H1,30X,'ECONOMIC PROJECT EVALUATION',/1H ,20X,
     *          'NET PRESENT VALUE AT A GIVEN DISCOUNT RATE',/,78(1H*))

        NOCF = X(4) + 1
        N = X(4)

        WRITE (1, 380) NOCF
 380    FORMAT (/,1H0, 22X,I3,3X,'YEARLY CASH FLOWS INCLUDING YEAR 0')

        WRITE (1, 390) R
 390    FORMAT (/,1H0,20X,F8.2,3X,'PERCENTAGE ANNUAL DISCOUNT RATE',/,
     *      1H , 78(1H-))

        WRITE (1, 400)
 400    FORMAT (/, 1H0, 15X,'YEARLY CASH FLOWS ($)',/1H ,78(1H-),/1H0,
     *  7X, 'YEAR', 5X, 'CASH FLOWS ($)', 3X, 'CUMULATIVE',\)

        WRITE (1, 410)
 410    FORMAT (10X, 'DISCOUNT', 8X, 'PRESENT')

        WRITE (1, 420)
 420    FORMAT (34X, 'CASH FLOWS ($)', 6X, 'FACTOR', 10X, 'VALUE ($)',
     *          /1H , 78(1H-))

C       CALCULATIVE THE CUMULATIVE CASH FLOW

        CUCF(0) = -Q7

        DO I = 1, N-1
        CUCF (I) = CUCF(I-1) + CF(I)
        END DO

        CF(N) = CF(N) + X(3)

        CUCF(N) = CUCF(N-1) + CF(N)

        R1 = R/100.0
        CF(0) = -Q7
        PV(0) = CF(0)*1.0


C       CALCULATE THE PRESENT VALUE FOR YEAR 0
```

```
      DO 75 I1 = 0, 0
      IF (I1 .EQ. 0) THEN
      R1 = 0.0
      DF (I1) = 1.0/((1.0+R1)**I1)

      PV(I1) = CF(I1)*DF(I1)

      ELSE
      ENDIF
 75   CONTINUE


C     CALCULATE THE PRESENT VALUE FOR SUBSEQUENT YEARS


      R1 = R/100

      DO 80 I1 = 1, N-1
C     I2 = I1-1
      DF (I1)= 1.0/((1.0+R1)**I1)
      PV(I1) = CF(I1)*DF(I1)

 80   CONTINUE

C     CALCULATE THE PRESENT VALUE FOR THE FINAL YEAR PLUS
C     THE SALVAGE VALUE


      DF(N) = 1/((1+R1)**N)
      PV(N) = CF(N)* DF(N)

      DO 90 K=0, N


C     PRINT THE VALUES OF THE YEARLY CASH FLOWS, CUMULATIVE CASH FLOWS
C     DISCOUNT FACTORS AND THE PRESENT VALUES

      WRITE (1, 430) K, CF(K), CUCF(K), DF(K), PV(K)
 430  FORMAT (5X, I3, 5X, F14.2, 5X, F14.2, 5X, F9.4, 5X, F14.2)

 90   CONTINUE

      WRITE (1, 440)
 440  FORMAT (78(1H-))

C     CALCULATE THE NET PRESENT VALUE

      NPV = 0.0
      DO J = 1, NOCF
      NPV = NPV + PV(J)
      END DO

      WRITE (1, 450) NPV
 450  FORMAT (1H0, 6X, 'THE NET PRESENT VALUE ($):',3X,T40,F14.2)


C     CALCULATE THE PRESENT VALUE RATIO, PVR
C     PVR = PRESENT VALUE OF ALL POSITIVE CASH FLOWS/
C         = PRESENT VALUE OF ALL NEGATIVE CASH FLOWS
```

```
        SUM = 0.0
        DO K = 1, N
        SUM = SUM + PV(K)
        END DO

        PVR = SUM/ABS(CF(0))

        WRITE (1, 460) PVR
 460    FORMAT (1H0, 6X, 'PRESENT VALUE RATIO:', 3X, T40, F8.3)


C       CALCULATE THE NET RETURN RATE (NRR) i.e. THE NET PRESENT VALUE
C       DIVIDED BY THE PRODUCT OF INITIAL INVESTMENT AND THE PROJECT LIFE
C       (EXCLUDING YEAR 0).

        NRR = ABS (NPV/(ABS(CF(0))*N))*100

        WRITE (1, 470) NRR
 470    FORMAT (1H0,6X,'THE NET RETURN RATE:',3X,T40,F8.3,3X,'%')

C       CALCULATE THE AVERAGE RATE OF RETURN (ARR) i.e. THE AVERAGE
C       CASH FLOW DURING THE LIFE OF THE PROJECT (EXCLUDING YEAR 0).

        SUM1 = 0.0

        DO I = 1, N
        SUM1 = SUM1 +CF(I)
        END DO


        AVSUM = SUM1/N
        ARR = (AVSUM/ABS(CF(0)))*100.0


        WRITE (1, 480) ARR
480     FORMAT (1H0, 6X, 'THE AVERAGE RATE OF RETURN:',3X,T40,F8.3,
     *         3X,'%')


C       CALCULATE THE PAYBACK TIME FROM THE CUMULATIVE CASH FLOW
C       TIME: Years


        DO I = 0, N
        IF (CUCF(I+1) .GT. CUCF(I) .AND. CUCF(I+1) .GE. 0.0) THEN
        TEMP = CUCF (I+1)
        CUCF (I+1) = CUCF (I)
        CUCF (I) = TEMP
        TIME = I
        TIME1 = TIME +1
        GO TO 44
        ELSE
        ENDIF
        END DO


 44     WRITE (1, 490) TIME, TIME1
 490    FORMAT (1H0,6X,'THE PAYBACK PERIOD IS BETWEEN:',
     *        3X,T45,I2,2X,'AND',2X,I2,2X,'YEARS')
```

```
C        FORM FEED THE PRINTING PAPER TO TOP OF THE NEXT PAGE.

         WRITE (1, *) CHAR(12)

         CLOSE (3, STATUS = 'KEEP')
         CLOSE (1)

  999    STOP
         END
```

CHAPTER 10

The International System of Units (SI) and Conversion Tables

The International System of Units, or the SI units, are derived from Systeme International d'Unites and are evolved from the mass-length-time-temperature system. This is derived from the seven base units of length, mass, time, temperature, amount of substance, electric current, and luminous intensity. Also, two supplementary units of plane angle and solid angle are required to describe the physical and chemical properties. Table 10-1 lists the supplementary units and their symbols.

All other units in SI are derived from the nine base and supplementary units. Table 10-2 gives approved derived units with names, formulas, and their symbols. Lists of derived SI units that do not have approved names but are widely used in chemical engineering are given in Table 10-3. The wide range in magnitude of the units used in normal practice requires the use of different sized units, rather than a powers-of-ten numerical multiplier. SI provides prefixes for decimal multiples and submultiples of the base supplementary and approved derived units. Table 10-4 shows these prefixes by name, symbol, and magnitude. In addition to learning the new units and symbols, conversion is required when numerical values are reported in imperial or the c.g.s units. The conversion of units is mainly handled through the use of conversion tables as listed in Table 10-5.

Table 10-1
SI and Supplementary Units

Type	Quantity and Symbol	Unit	Unit Symbol
base	Length, L	meter	m
base	mass, m	kilogram	kg
base	time, t	second	s
base	temperature, T	Kelvin	K
base	amount of substance, n	mole	mol
base	electric current, I	ampere	A
base	luminous intensity, I	candela	cd
Supplementary	plane angle, θ	radian	rad
Supplementary	solid angle, ω	steradian	sr

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Table 10-2
SI Derived Units with Special Names

Quantity and symbol	Unit	Unit symbol	Formula
frequency, f	hertz	Hz	s^{-1}
force, F	newton	N	kg.m/s^2
pressure, stress p, τ	pascal	Pa	N/m^2, kg/m.s^2
energy, work, quantity of heat, E, W, Q	joule	J	N/m, kg.m^2/s^2
power, radiant flux, P	watt	W	J/s, kg.m^2/s^3
quantity of electricity, electric charge, Q	coulomb	C	A.s
electric potential, potential difference, electromotive force, E	volt	V	W/A, kg/A.s^3
capacitance, C	farad	F	C/V, A^2.s^4/kg.m^2
electric resistance, R	ohm	Ω	V/A, m^2.kg/A^2.s^3
conductance, G	siemens	S	A/V, A^2.s^3/kg.m^2
magnetic flux, ϕ	weber	Wb	V.s, m^2.kg/A.s^2
magnetic flux density, B	tesla	T	Wb/m^2, kg/A.s^2
inductance, L	henry	H	Wb/A, m^2.kg/A.s
luminous flux, F	lumen	lm	cd.sr
illuminance, B	lux	lx	cd.sr/m^2
radioactivity, λ	becquerel	Bq	s^{-1}
absorbed dose, D	gray	Gy	J/kg

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Table 10-3
Some Derived SI Units

Property	Common Symbol	SI units formula
thermal conductivity	k	W/m.K
heat transfer rate	q	W
heat transfer coefficient	h	$W/m^2.K$
specific enthalpy	H	J/kg
heat capacity	C_p	J/kg.K
Newtonian viscosity	μ	Pa.s, kg/m.s
kinematic viscosity	ν	m^2/s
thermal diffusivity	α	m^2s
volumetric flow rate	q	m^3/s
power	P	W
enthropy	S	J/K
density	ρ	kg/m^3
mass velocity	G	$kg/s.m^2$
concentration	c	kg/m^3
concentration	c	mol/m^3
velocity	u	m/s
acceleration	a,g	m/s^2
mass transfer coefficient	k_c	m/s
mass diffusivity	D	m^2/s
moment	I	N.m
thermal flux	q/A	W/m^2
mass flux (molar)	N_a/A	$mol/m^2.s$
momentum flux	τ_y/A	Pa
mass transfer rate	N_a	mol/s
mass flow rate	w	kg/s
surface tension	γ	N/m
gas constant	R	Pa.m3/mol.K, J/mol.K

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Table 10-4
Magnitude Prefixes for SI Units

Name	Symbol	Magnitude
atto	a	10^{-18}
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
deka	da	10^{1}
hecto	h	10^{2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}
peta	P	10^{15}
exa	E	10^{18}

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Table 10-5
Conversion of Units

Length

in	ft	mm	cm	m	km	mile
1	0.083333	25.4	2.54	0.0254		
12	1	304.8	30.48	0.3048	3.048×10^{-4}	1.894×10^{-4}
0.03937	3.2808×10^{-3}	1	0.1	10^{-3}		
0.3937	0.032808	10	1	0.01		
39.3701	3.28084	1000	100	1	10^{-3}	6.214×10^{-4}
39370.1	3280.84	10^{6}	100000	1000	1	0.621371
63360	5280	1.60934×10^{6}	160934	1609.34	1.60934	1

Area

in^2	ft^2	mm^2	cm^2	m^2	km^2
1	6.944×10^{-3}	645.16	6.4516	6.452×10^{-4}	
144	1	92903	929	0.0929	
1.55×10^{-3}	1.076×10^{-5}	1	0.01	10^{-6}	
0.155	1.076×10^{-3}	100	1	10^{-4}	
1550	10.764	10^6	10000	1	
	1.0764×10^7			10^6	1

(table continued on next page)

Table 10-5
(continued)

Volume

in^3	ft^3	mm^3	ml	l	m^3	US gal
1	5.787×10^{-4}	16387	16.39	0.01639	1.639×10^{-5}	4.329×10^{-3}
1728	1	2.832×10^{7}	2.832×10^{4}	28.32	0.02832	7.4805
6.1024×10^{-5}	3.531×10^{-8}	1	1×10^{-3}	10^{-6}	10^{-9}	2.642×10^{-7}
0.061026	3.532×10^{-5}	1000	1	10^{-3}	10^{-6}	2.642×10^{-4}
61.026	0.03532	1×10^{6}	1000	1	1×10^{-3}	0.2642
61024	35.31	10^{9}	1×10^{6}	1000	1	264.2
231.0	0.1337	3.785×10^{6}	3785	3.785	3.785×10^{-3}	1

1 US barrel = 42 US gal = 34.97 UK gal
1 US gal = 0.832674 UK gal

Mass

lb	g	kg	t (tonne)	US ton (short ton)
1	453.592	0.453592	4.5359×10^{-4}	5.0×10^{-4}
2.2046×10^{-3}	1	10^{-3}		
2.20462	10^{3}	1	10^{-3}	1.1023×10^{-3}
2204.62	10^{6}	1000	1	1.10231
2000	907185	907.185	0.907185	1

(table continued on next page)

Table 10-5
(continued)

Density

lb/in^3	lb/ft^3	g/cm^3	kg/m^3
1	1728	27.6799	27679.9
5.787×10^{-4}	1	0.0160185	16.0185
0.036127	62.428	1	1000
3.6046×10^{-5}	0.062428	10^{-3}	1

Velocity

ft/s	ft/min	mm/s	cm/s	m/s	km/s	km/h
1	60	304.8	30.48	0.3048	3.048×10^{-4}	1.09728
0.016667	1	5.08	0.508	5.08×10^{-3}	5.08×10^{-6}	0.018288
3.281×10^{-3}	0.19685	1	0.1	10^{-3}	10^{-6}	3.6×10^{-3}
0.032808	1.9685	10	1	0.01	10^{-5}	0.036
3.28084	196.85	1000	100	1	10^{-3}	3.6
3280.84	196850	10^{6}	100000	10^{3}	1	3600
0.911344	54.6806	277.778	27.7778	0.277778	2.778×10^{-4}	1

(table continued on next page)

Table 10-5
(continued)

Temperature

Kelvin, K	$T = \theta + 273.15 = \frac{5}{9}(t + 459.67) = \frac{5}{9}(r)$
degree Celsius, °C	$t = T - 273.15 = \frac{5}{9}(t - 32) = \frac{5}{9}(r - 491.67)$
degree Fahrenheit, °F	$t = \frac{9}{5}(T) - 459.67 = \frac{9}{5}(\theta) + 32 = r - 459.67$
degree Rankine, °R	$r = \frac{9}{5}(T) = \frac{9}{5}(\theta) + 491.67 = t + 459.67$

where T = Kelvin, θ = °C, t = °F, r = °R

Mass Flow Rate (mass/time)

lb/s	lb/min	lb/h	g/s	kg/s	kg/h	tonne/d
1	60	3600	453.6	0.4536	1633	39.19
1.667×10^{-2}	1	60	7.560	7.56×10^{-3}	27.216	0.653
2.778×10^{-4}	0.01667	1	0.1260	1.26×10^{-4}	0.4536	0.01089
2.205×10^{-3}	0.1323	7.937	1	1×10^{-3}	3.60	0.08640
2.205	132.3	7937	1000	1	3600	86.40
6.124×10^{-4}	0.03674	2.205	0.2778	2.778×10^{-4}	1	0.02400
0.02551	1.531	91.86	11.57	0.01157	41.67	1

(table continued on next page)

Table 10-5
(continued)

Volumetric Flow Rate (volume/time)

ft^3/s	ft^3/min	US gal/min	ml/s	l/s	l/min	m^3/s	m^3/h
1	60	448.83104	2.832×10^4	28.32	1699	0.02832	101.9
0.01667	1	7.480717	471.9	0.4719	28.31	4.719×10^{-4}	1.699
2.228×10^{-3}	0.133644	1	63.0917	0.063092	3.78534	6.3092×10^{-5}	0.22715
3.532×10^{-5}	2.119×10^{-3}	0.158503	1	1×10^{-3}	0.06	1×10^{-6}	3.6×10^{-3}
0.03531	2.119	15.85026	1000	1	60	1×10^{-3}	3.6
5.886×10^{-4}	0.03531	0.264172	16.67	0.01667	1	1.667×10^{-5}	0.0600
35.31	2119	1.585×10^4	1×10^6	1000	6×10^4	1	3600
9.81×10^{-3}	0.5886	4.40286	277.8	0.2778	16.67	2.778×10^{-4}	1

1 US gal/min = 0.832674 U.K. gal/min
1 UK gal/min = 1.20095 US gal/min

Dynamic Viscosity

pdls/ft2	lb/ft.h	cP	P	kg/m.h	Ns/m2
1	3600	1488	14.88	5358	1.488
2.776×10^{-4}	1	0.4134	4.134×10^{-3}	1.488	4.134×10^{-4}
6.720×10^{-4}	2.419	1	0.01	3.6	10^{-3}
0.0672	241.9	100	1	360	0.100
1.866×10^{-4}	0.6720	0.2778	2.778×10^{-3}	1	2.788×10^{-4}
0.6720	2419	1000	10	3600	1

(table continued on next page)

Table 10-5
(continued)

Force

poundal pdl	pound-force lbf	kilogram-force kgf	newton N	KN
1	0.0311	0.0141	0.1383	1.383×10^{-4}
32.174	1	0.4536	4.448	4.448×10^{-3}
70.93	2.2046	1	9.807	9.807×10^{-3}
7.233	0.2248	0.1020	1	10^{-3}
7233	224.8	102.0	1000	1

Energy, Work, Heat

Foot pound-force ft lbf	British thermal unit Btu	calorie cal	horsepower hour hph	kilowatt hour kWh	Joule J	kilojoule kJ
1	1.285×10^{-3}	0.3238	5.051×10^{-7}	3.766×10^{-7}	1.3558	1.356×10^{-3}
778.17	1	252	3.930×10^{-4}	2.931×10^{-4}	1055.1	1.0551
3.0880	3.968×10^{-3}	1	1.560×10^{-6}	1.163×10^{-6}	4.1868	4.187×10^{-3}
1.98×10^{6}	2544.4	641186	1	0.7457	2.6845×10^{6}	2684.5
2.65522×10^{6}	3412.1	859845	1.3410	1	3.600×10^{6}	3600
0.7376	9.478×10^{-4}	0.2388	3.725×10^{-7}	2.778×10^{-7}	1	10^{-3}
737.56	0.9478	238.85	3.725×10^{-4}	2.778×10^{-4}	1000	1

(table continued on next page)

Table 10-5
(continued)

Pressure

lb_f/in^2	lb_f/ft^2	in H_2O	mm Hg	atm	Pascal, Pa N/m^2	kN/m^2	bar
1	144	27.68	51.71	0.06805	6895	6.895	0.06895
6.944×10^{-3}	1	0.1922	0.3591	4.726×10^{-4}	47.88	0.04788	4.788×10^{-4}
0.03613	5.202	1	1.868	2.458×10^{-3}	249.1	0.2491	2.491×10^{-3}
0.01934	2.785	0.5352	1	1.316×10^{-3}	133.3	0.1333	1.333×10^{-3}
14.70	2116	406.8	760.0	1	1.013×10^{5}	101.3	1.013
1.450×10^{-4}	0.02089	4.015×10^{-3}	7.501×10^{-3}	9.869×10^{-6}	1	1×10^{-3}	1×10^{-5}
0.1450	20.89	4.015	7.501	9.869×10^{-3}	1000	1	0.0100
14.50	2089	401.5	750.1	0.9869	1×10^{5}	100	1

Specific Heat Capacity (heat/mass × degree temperature)

ft lb_f/lb°F	Btu/lb°F	kcal/kg.K	kgf m/kgK	J/kg.K	kJ/kg.K
1	1.28507×10^{-3}	1.28507×10^{-3}	0.54864	5.38032	5.380×10^{-3}
778.169	1	1	426.935	4186.8	4.1868
778.169	1	1	426.935	4186.8	4.1868
1.82269	2.34228×10^{-3}	2.34228×10^{-3}	1	9.80665	9.807×10^{-3}
0.185863	0.2388×10^{-3}	0.2388×10^{-3}	0.10197	1	10^{-3}
185.863	0.2388	0.2388	101.97	1000	1

(table continued on next page)

Table 10-5
(continued)

Power, Heat Flow Rate

ft lbf/s	Btu/h	hp	kcal/h	W	kW
1	4.626	1.818×10^{-3}	1.1658	1.3558	1.356×10^{-3}
0.2162	1	3.930×10^{-4}	0.2520	0.2931	2.931×10^{-4}
550	2544	1	641.19	745.70	0.7457
0.8578	3.9683	1.560×10^{-3}	1	1.163	1.163×10^{-3}
0.7376	3.4121	1.341×10^{-3}	0.8598	1	10^{-3}
737.6	3412.1	1.3410	859.8	1000	1

Specific Energy (heat/mass) (e.g., calorific value, mass basis, specific latent heat, enthalpy)

ft lbf/lb	Btu/lb	kcal/kg	kg fm/kg	kJ/kg	MJ/kg
1	1.285×10^{-3}	7.139×10^{-4}	0.3048	2.989×10^{-3}	2.989×10^{-6}
778.2	1	0.5556	237.19	2.326	2.326×10^{-3}
1400.7	1.8	1	426.9	4.187	4.187×10^{-3}
3.281	4.216×10^{-3}	2.342×10^{-3}	1	9.807×10^{-3}	9.807×10^{-6}
334.55	0.4299	0.2388	101.97	1	10^{-3}
334553	429.9	238.8	101972	1000	1

(table continued on next page)

Table 10-5
(continued)

Heat Transfer Coefficient (Thermal Conductance) (heat/area × time × degree temperature)

Btu/ft^{2}h°F	Btu/ft^{2}s°F	cal/cm^{2}s°C	kcal/ft^{2}h°C	W/m^2°C	kW/m^2°C
1	2.778×10^{-4}	1.356×10^{-4}	0.4536	5.678	5.678×10^{-3}
3600	1	0.4882	1633	20442	20.442
7373	2.048	1	3344	41868	41.868
2.205	6.124×10^{-4}	2.990×10^{-4}	1	12.52	0.01252
0.1761	4.892×10^{-5}	2.388×10^{-5}	0.07988	1	10^{-3}
176.1	0.04892	0.02388	79.88	1000	1

Thermal Conductivity (heat × length/area × time × degree temperature)

Btu in/ft^{2}h°F	Btu/ft h°F	cal/cm s°C	kcal/m h°C	W/m°C
1	0.0833	3.445×10^{-4}	0.1240	0.1442
12	1	4.134×10^{-3}	1.488	1.731
2903	241.9	1	360	418.7
8.064	0.6720	2.778×10^{-3}	1	1.163
6.933	0.5778	2.388×10^{-3}	0.8598	1

(table continued on next page)

Table 10-5
(continued)

Stress (force/area)

dyne/cm2	N/m2	lb_f/ft^2	kN/m2	lb_f/in^2
1	0.1	2.089×10^{-3}	1×10^{-4}	1.45×10^{-5}
10	1	0.02089	1×10^{-3}	1.45×10^{-4}
478.8	47.88	1	0.04788	6.944×10^{-3}
1×10^{4}	1000	20.89	1	0.145
6.895×10^{4}	6895	144	6.895	1

1 N/mm² = 1 MN/m² = 1 MPa
1 kg_f/mm² = 9.80665 N/mm² = 9.80665 MPa

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Chemical and Engineering News. A weekly publication of the American Chemical Society. It gives the financial condition for over 100 various chemical companies, the production rates for large-volume chemicals, foreign trade statistics, and world production statistics for selected chemicals.

Chemical Engineering. A publication of McGraw-Hill having articles and news covering all aspects of process and project engineering.

Chemical Engineering Progress. A monthly publication of the American Institute of Chemical Engineers. It contains articles on engineering and technical information as well as news of the society. It also publishes a symposium series of volumes on specific topics.

Hydrocarbon Processing. A monthly publication of the Gulf Publishing Company. This covers process and project engineering of refineries and petrochemical operations. It has a flow sheet in every issue and gives over 100 processes flow sheets in its yearly handbook.

Journal of the Air and Waste Management Association (formerly *Journal of the Air Pollution Control Association.* A monthly journal of the Air Pollution Control Association that present articles on air pollution, waste management, and methods of abatement with research articles.

Journal of Chemical and Engineering Data. A quarterly publication of the American Chemical Society. It gives many specific data.

Journal of Physical and Chemical Reference Data. A quarterly publication of the American Chemical Society. It contains mainly physical and chemical property data.

Industrial and Engineering Chemistry-Research. A monthly publication of the American Chemical Society. It is mainly involved with laboratory developments. It reports research studies on various processes, unit operations, and products.

Oil and Gas Journal. A weekly publication of the PenWell Publishing Company. This reports on business and technology for the petroleum and natural gas industry. There are articles on processes, processing techniques, and costs. It gives marketing production, exploration studies, and current news.

The Chemical Engineer. A bi-weekly publication of the U.K. Institution of Chemical Engineers. It features articles on new technology as well as news of the society.

Appendix A

Table A1-1
Selected Constants for Liquid Density Equation

Compound	A	B	T_c °C
Fluorine	0.5649	0.2828	–129.0
Chlorine	0.5615	0.2720	144.0
Sulfur dioxide	0.5164	0.2554	157.6
Carbon monoxide	0.2931	0.2706	–140.1
Carbon dioxide	0.4576	0.2590	31.1
Hydrogen chloride	0.4183	0.2619	51.5
Ammonia	0.2312	0.2471	132.4
Water	0.3471	0.2740	374.2
Hydrogen peroxide	0.4375	0.2505	455.0
Hydrogen	0.0315	0.3473	–240.2
Nitrogen	0.3026	0.2763	–146.8
Oxygen	0.4227	0.2797	–118.5
Ethylene	0.2118	0.2784	9.9
Methane	0.1611	0.2877	–82.6
Ethane	0.2202	0.3041	32.3
Propane	0.2204	0.2753	96.7
Benzene	0.3051	0.2714	288.94

Table A1-1
(continued)

Toluene	0.2883	0.2624	318.8
Aniline	0.3392	0.2761	426.0
Phenol	0.4094	0.3246	420.0
Cyclopropane	0.2614	0.2826	124.9
Cyclohexane	0.2729	0.2727	280.3
1,3 Butadiene	0.2444	0.2710	152.0
Methanol	0.2928	0.2760	239.4
Chloroform	0.5165	0.2666	263.4
Carbon tetrachloride	0.5591	0.2736	283.2

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Table A1–2
Selected Constants for Liquid Viscosity Equation

Compound	A	B	$C \times 10^{-2}$	$D \times 10^{-6}$	Range °C
Fluorine	–1.576	85.63	–0.04073	–2.725	–219 to 188.1
Chlorine	–0.7681	151.4	–0.08065	0.4075	–101 to 144.0
Sulfur dioxide	–2.67	406.7	0.6141	–12.54	–72.7 to 157.6
Carbon monoxide	–2.346	105.2	0.4613	–19.64	–205 to 140.1
Carbon dioxide	–1.345	21.22	1.034	–34.05	–56.5 to 31.1
Hydrogen chloride	–1.515	194.6	0.3067	–13.76	–114.2 to 51.5
Ammonia	–8.591	876.4	2.681	–36.12	–77.74 to 132.4
Water	–10.73	1828	1.966	–14.66	0.0 to 374.2
Hydrogen peroxide	–1.615	503.8	0.03501	–1.168	–0.43 to 455.0
Hydrogen	–4.857	25.13	14.09	–2773	–259.4 to –240.2
Nitrogen	–12.14	376.1	12.00	–470.9	–209.9 to –195.8
Oxygen	–2.072	93.22	0.6031	–27.21	–218.4 to –118.5

Ethylene	–7.706	468.1	3.725	–76.33	–169.2 to 9.9
Methane	–11.67	499.3	8.125	–226.3	–182.6 to –82.6
Ethane	–4.444	290.1	1.905	–41.64	–183.2 to 32.3
Propane	–3.372	313.5	1.034	–20.26	–187.7 to 96.7
Benzene	2.003	64.66	–1.105	9.648	5.53 to 288.94
Phenol	–8.039	1889	1.055	–6.718	40.75 to 420.0
Cyclopropane	–1.335	116.2	0.01108	–0.03836	–93.88 to 238.5
Cyclohexane	–1.910	599.2	–0.06749	0.5026	6.55 to 280.3
1,3 Butadiene	–2.637	434.5	0.1937	–2.907	–108.9 to 152.0
Ethanol	–2.697	700.9	0.2682	–4.917	–105 to 243.1
Chloroform	–1.812	397.5	0.1174	–1.784	–63.2 to 263.4
Carbon tetrachloride	–5.658	994.5	1.016	–8.733	–20 to 283.2

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Table A1–3
Selected Constants for Liquid Heat Capacitity Equation.

Compound	A	B × 10^{-3}	C × 10^{-6}	D × 10^{-9}	Range °C
Fluorine	–0.288	252.8	–331.0	1464	–219 to –140.0
Chlorine	–0.1322	4.720	–20.37	28.94	–101 to 80.0
Sulfur dioxide	–0.5737	10.34	–40.28	52.85	–72.7 to 150
Carbon monoxide	0.5645	4.798	–143.7	911.95	–205 to –150
Carbon dioxide	–19.30	254.6	–1095.5	1573.3	–56.5 to 20
Hydrogen chloride	–0.1121	7.048	–35.31	66.21	–114.2 to 20
Ammonia	–1.923	31.1	–110.9	137.6	–77.4 to 100
Water	0.6741	2.825	–8.371	8.601	0 to 350
Hydrogen peroxide	0.444	1.199	–2.738	2.615	–0.43 to 425
Hydrogen	3.79	–329.8	12170.9	–2434.8	–259.4 to –245
Nitrogen	–1.064	59.47	–768.7	3357.3	–209.9 to –160
Oxygen	–0.4587	32.34	–395.1	1575.7	–218.4 to –130

Ethylene	–0.3402	6.218	–50.12	126.3	–169 to –40
Methane	1.23	–10.33	72.0	–107.3	–182.6 to 110
Ethane	0.1388	8.481	–56.54	126.1	–183.2 to 20
Propane	0.3326	2.332	–13.36	30.16	–187.7 to 80
Benzene	–1.481	15.46	–43.70	44.09	5.53 to 250
Toluene	–0.1461	4.584	–13.46	14.25	–95 to 310
Aniline	0.1407	2.467	–6.085	5.927	–6.15 to 360
Phenol	–0.6896	8.218	–18.42	14.47	40.75 to 400
Cyclopropane	–0.02618	6.913	–34.77	59.9	–127.42 to 100
Cyclohexane	–1.284	13.39	–35.1	32.27	6.55 to 260
1,3 Butadiene	0.3785	1.049	–5.761	13.74	–108.9 to 120
Methanol	0.8382	–3.231	8.296	–0.1689	–97.6 to 220
Chloroform	–0.09154	3.149	–10.64	12.4	–63.2 to 250
Carbon tetrachloride	–0.01228	2.058	–7.04	8.610	–22.9 to 260

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Table A1–4
Selected Constants for Liquid Thermal Conductivity Equation

Compound	A	$B \times 10^{-2}$	$C \times 10^{-4}$	Range °C
Fluorine	612.54	−162.29	−118.41	−219 to −140
Chlorine	559.01	−48.30	−15.24	−101 to 132
Sulfur dioxide	2140.81	−783.66	71.43	−50 to 150
Carbon monoxide	475.48	3.31	−214.26	−205 to −145
Carbon dioxide	972.06	−201.53	−22.99	−56 to 26
Hydrogen chloride	1071.70	−18.44	−65.81	−114 to 31
Ammonia	2551.30	−376.62	−29.35	−77 to 100
Water	−916.62	1254.73	−152.12	0 to 350
Hydrogen peroxide	−466.56	805.86	−87.58	0 to 400
Hydrogen	−20.14	2473.70	−5347.26	−259 to −241
Nitrogen	627.99	−368.91	−22.57	−209 to −152
Oxygen	583.79	−210.49	−48.31	−218 to −135
Ethylene	851.45	−228.94	−4.71	−169.2 to −4.0
Methane	722.72	−144.42	−76.36	182.6 to −90
Ethane	699.31	−165.88	−4.87	−183.2 to 20
Propane	623.51	−126.79	−2.12	−187.7 to 80.0
Benzene	424.26	1.14	−9.03	5.53 to 260
Toluene	485.10	−53.84	−0.59	−95 to 308
Aniline	537.55	−30.42	−1.49	−6.15 to 408
Phenol	440.93	86.70	−7.01	40.75 to 396
Cyclopropane	396.82	−42.10	−6.72	−127.42 to 117
Cyclohexane	388.26	−22.72	−3.30	6.55 to 254
1,3 Butadiene	718.26	−187.18	11.74	−108.9 to 120
Methanol	770.13	−114.28	2.79	−97.6 to 210
Chloroform	390.25	−20.58	−5.06	−63.2 to 237
Carbon tetrachloride	383.95	−45.45	−0.24	−22.9 to 224

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Table A1–5
Selected Constants for Liquid Surface Tension Equation

Compound	T_1, °C	T_c, °C	R	Range, °C
Fluorine	–200.0	–129.0	0.8811	–219.6 to –129.0
Chlorine	20.0	144.0	1.0508	–101.0 to 144.0
Sulfur dioxide	30.0	157.6	1.1768	–72.7 to 157.6
Carbon monoxide	–193.0	–140.1	1.1441	–191.5 to –140.1
Carbon dioxide	20.0	31.1	1.3015	–56.5 to 31.1
Hydrogen chloride	–93.0	51.5	1.0972	–114.2 to 51.5
Ammonia	–45.0	132.4	1.1548	–77.74 to 132.4
Water	25.0	374.2	0.8105	0 to 100.0
Water	100.0	374.2	1.1690	100.0 to 374.2
Hydrogen peroxide	18.2	455.0	0.9141	–0.43 to 455.0
Hydrogen	–256.0	–240.2	1.1012	–259 to –240.2
Nitrogen	–203.0	–146.8	1.2123	–209.9 to –146.8
Oxygen	–202.0	–118.5	1.1933	–218.4 to –118.5
Ethylene	–120.0	9.9	1.2760	–169.2 to 9.9
Methane	–168.16	–82.6	1.3941	–182.6 to –82.6
Ethane	–120.0	32.3	1.2060	–183.2 to 32.3
Propane	–90.0	96.7	1.1982	–187.7 to 96.7
Benzene	20.0	288.94	1.2243	5.53 to 288.94
Touluene	20.0	318.8	1.2364	–95.0 to 318.8
Aniline	20.0	426.0	1.1022	–6.15 to 426.0
Phenol	60.0	420.0	1.0725	40.75 to 420.0
Cyclopropane	10.0	124.9	1.3201	–127.42 to 124.9
Cyclohexane	20.0	280.3	1.4246	6.55 to 280.3
1,3 Butadiene	40.0	152.0	1.2055	–4.41 to 152.0
Methanol	20.0	239.4	0.8115	–97.6 to 239.4
Chloroform	25.0	263.4	1.1824	–63.2 to 263.4
Carbon tetrachloride	30.0	283.2	1.2278	–22.9 to 283.2

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Table A1–6
Selected Constants for Liquid Vapor Pressure Equation

Compound	A	B	C	D × 10−3	E × 10−6	Range °C
Fluorine	21.480	–516.51	–7.1218	14.355	—	–219.2 to –129.0
Chlorine	42.262	–2009.8	–13.963	9.3705	—	–100.4 to 144.1
Sulfur dioxide	46.554	–2456.3	–15.169	9.0026	—	–67.6 to 157.6
Carbon monoxide	32.863	–606.91	–12.969	27.551	—	–200.7 to –140
Carbon dioxide	47.544	–1792.2	–16.559	13.833	—	–56.0 to 31.2
Hydrogen chloride	136.05	–3047.3	–58.416	95.496	–58.507	150.8 to 51.5
Ammonia	38.44	–2066.2	–12.105	7.7768	—	–65 to 132.4
Water	16.373	–2818.6	–1.6908	–5.7546	4.0073	0.0 to 374.2
Hydrogen peroxide	44.791	–4022.7	–13.076	4.5627	—	–0.01 to 455
Hydrogen	5.2366	–46.28	–0.44809	25.290	—	–259.4 to –240.2
Nitrogen	21.623	–455.57	–7.5107	17.214	—	–210 to –146.8
Oxygen	5.6486	–411.30	1.8118	–25.042	62.612	–219.1 to –118.4

Ethylene	30.895	–1196.8	–10.153	9.9351	—	–169 to 10.1
Methane	22.573	–656.24	–7.3942	11.896	—	–182.2 to 81.9
Ethane	16.316	–1074.8	–3.1434	4.5534	10.373	–179.5 to 32.3
Propane	36.007	–1737.2	–11.666	8.5187	—	–128.9 to 96.8
Benzene	51.204	–3245.7	–16.403	7.540	—	7.6 to 289.4
Toluene	115.21	–4918.1	–43.467	38.548	–13.496	–60.0 to 320.6
Aniline	18.893	–3104.0	–3.4714	0.02743	—	77.4 to 426
Phenol	672.71	–22197.3	–266.67	226.43	–73.731	67.8 to 420
Cyclopropane	38.45	–1865.2	–12.578	8.9375	—	–90 to 125.2
Cyclohexane	64.753	–3619.2	–21.753	10.742	—	–25.4 to 280.3
1,3 Butadiene	41.401	–2181.2	–13.451	8.4524	—	–108.9 to 152
Methanol	–42.629	–1186.2	23.279	–35.082	17.578	–67.4 to 240
Chloroform	26.828	–2292.6	–7.186	3.1365	—	–42 to 263
Carbon tetrachloride	50.612	–3135.7	–16.313	7.8036	—	–69.7 to 283.2

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Table A1–7
Selected Constants for Enthalpy of Vaporization Equation

Compound	ΔH_{V1}, cal/g	T_1, °C	T_c, °C	R
Fluorine	41.1	–188.1	–129.0	0.38
Chlorine	69.6	–34.06	144.0	0.38
Sulfur dioxide	93.0	–10.0	157.6	0.38
Carbon monoxide	51.6	–191.5	–140.1	0.38
Carbon dioxide	56.1	0.0	31.1	0.38
Hydrogen chloride	105.8	–85.03	51.5	0.38
Ammonia	327.4	–33.43	132.4	0.38
Water	538.7	100.0	374.2	0.38
Hydrogen peroxide	321.9	150.2	455.0	0.38
Hydrogen	107.0	–252.8	–240.2	0.237
Nitrogen	47.5	–195.8	–146.8	0.38
Oxygen	50.9	–183.0	–118.5	0.38
Ethylene	115.4	–103.7	9.9	0.38
Methane	121.7	–161.5	–82.6	0.38
Ethane	116.7	–88.2	32.3	0.38
Propane	101.8	–42.1	96.7	0.38
Benzene	94.1	80.1	288.94	0.38
Toluene	86.1	110.6	318.8	0.38
Aniline	112.4	184.4	426.0	0.38
Phenol	116.4	181.8	420.0	0.38
Cyclopropane	113.8	–32.8	124.9	0.38
1,3 Butadiene	100.2	–4.41	152.0	0.38
Methanol	260.1	64.7	239.4	0.40
Chloroform	58.9	61.3	263.4	0.38
Carbon tetrachloride	46.55	76.7	283.2	0.38

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Table A1–8
Selected Constants for Gas Heat Capacity Equation

Compound	A	$B \times 10^{-3}$	$C \times 10^{-6}$	$D \times 10^{-9}$	Range K
Fluorine	5.89	6.94	–5.48	1.52	298–1500
Chlorine	7.00	5.05	–4.39	1.30	298–1500
Sulfur dioxide	5.85	15.40	–11.1	2.91	298–1500
Carbon monoxide	6.92	–0.65	2.80	–1.14	298–1500
Carbon dioxide	5.14	15.4	–9.94	2.42	298–1500
Hydrogen chloride	7.24	–1.76	3.07	–1.00	298–1500
Ammonia	6.07	8.23	–0.16	–0.66	298–1500
Water	8.10	–0.72	3.63	–1.16	298–1500
Hydrogen peroxide	5.52	19.80	–13.90	3.74	298–1500
Hydrogen	6.88	–0.022	0.21	0.13	298–1500
Nitrogen	7.07	–1.32	3.31	–1.26	298–1500
Oxygen	6.22	2.71	–0.37	–0.22	298–1500
Ethylene	0.934	36.9	–19.3	4.01	298–1500
Methane	5.04	9.32	8.87	–5.37	298–1500
Ethane	2.46	36.1	–7.0	–0.46	298–1500
Propane	–0.58	69.9	–32.9	6.54	298–1500
Benzene	–8.79	116.0	–76.1	18.9	298–1500
Toluene	–9.34	138.5	–87.2	20.6	298–1500
Aniline	–8.11	143.4	–107.0	30.7	298–1500
Phenol	–5.68	126.0	–85.4	20.5	298–1500
Cyclopropane	–6.28	79.8	–50.5	12.2	298–1500
1,3 Butadiene	–0.56	81.1	–53.5	13.6	298–1500
Methanol	3.62	24.9	–7.05	—	298–1500
Chloroform	7.71	34.3	–26.40	7.29	298–1500
Carbon tetrachloride	12.6	33.2	–29.3	8.58	298–1500

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Table A1–9
Selected Constants for Heat of Formation Equation

Compound	A	$B \times 10^{-3}$	$C \times 10^{-6}$	Range, K
Sulfur dioxide	–69.6	–5.29	—	298 to 717
Sulfur dioxide	–86.9	0.32	—	717 to 1500
Nitrogen dioxide	7.94	–0.188	—	298 to 1500
Carbon monoxide	–26.5	0.84	–1.05	298 to 1500
Carbon dioxide	–93.9	–0.43	—	298 to 1500
Hydrogen chloride	–21.9	–0.610	—	298 to 1500
Ammonia	–9.34	–6.20	2.36	298 to 1500
Water	–57.4	–1.79	—	298 to 1500
Hydrogen peroxide	–31.8	–3.04	1.19	298 to 1500
Methane	–15.4	–9.59	3.50	298 to 1500
Ethane	–16.4	–14.8	6.13	298 to 1500
Propane	–20.0	–19.1	8.15	298 to 1500
Benzene	23.7	–15.3	6.27	298 to 1500
Toluene	16.8	–19.0	7.84	298 to 1500
Aniline	25.2	–17.6	8.98	298 to 1500
Phenol	–19.3	–14.6	7.18	298 to 1500
Cyclopropane	16.9	–16.7	7.90	298 to 1500
Cyclohexane	–21.6	–32.0	15.80	298 to 1500
1,3 Butadiene	29.0	–10.1	4.13	298 to 1500
Methanol	–44.96	–11.9	4.98	298 to 1500
Chloroform	–24.7	0.0334	—	298 to 1500
Carbon tetrachloride	–24.0	2.42	—	298 to 1500

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Table A1–10
Selected Constants for Free Energy of Formation Equation

Compound	A	$B \times 10^{-3}$	Range, K
Sulfur dioxide	–71.9	0.25	298 to 717
Sulfur dioxide	–86.8	17.7	717 to 1500
Nitrogen dioxide	7.82	15.1	298 to 1500
Carbon monoxide	–26.5	–21.3	298 to 1500
Carbon dioxide	–94.2	–0.42	298 to 1500
Hydrogen chloride	–22.3	–1.72	298 to 1500
Ammonia	–12.3	27.2	298 to 1500
Water	–58.6	12.7	298 to 1500
Hydrogen peroxide	–33.2	26.4	298 to 1500
Methane	–20.1	24.9	298 to 1500
Ethane	–23.3	49.7	298 to 1500
Propane	–28.8	74.7	298 to 1500
Benzene	16.7	45.9	298 to 1500
Toluene	7.8	68.7	298 to 1500
Aniline	18.5	70.6	298 to 1500
Phenol	–25.0	56.5	298 to 1500
Cyclopropane	10.3	47.7	298 to 1500
Cyclohexane	–35.1	139.0	298 to 1500
1,3 Butadiene	24.2	38.6	298 to 1500
Methanol	–50.2	36.5	298 to 1500
Chloroform	–24.8	26.9	298 to 1500
Carbon tetrachloride	–22.6	32.1	298 to 1500

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Table A1–11
Selected Constants for Gas Thermal Conductivity Equation

Compound	A	B × 10^{-2}	C × 10^{-4}	D × 10^{-8}	Range °C
Fluorine	1.8654	19.79	1.24	–17.77	–130 to 525
Chlorine	3.25	5.8	0.21	–1.25	–80 to 1200
Sulfur dioxide	–19.31	15.15	–0.33	0.55	0 to 1400
Carbon monoxide	1.21	21.79	–0.8416	1.958	–160 to 1400
Carbon dioxide	–17.23	19.14	0.1308	–2.514	–90 to 1400
Hydrogen chloride	–0.26	12.67	–0.25	0.16	–150 to 1400
Ammonia	0.91	12.87	2.93	–8.68	0 to 1400
Water	17.53	–2.42	4.3	–21.73	0 to 800
Hydrogen peroxide	–21.07	16.97	0.17	–1.56	0 to 1200
Hydrogen	19.34	159.74	–9.93	37.29	–160 to 1200
Nitrogen	0.9359	23.44	–1.21	3.591	–160 to 1200
Oxygen	–0.7816	23.8	–0.8939	2.324	–160 to 1200
Ethylene	–42.04	28.65	0.7963	–3.262	–75 to 1000
Methane	–4.463	20.84	2.815	–8.631	0 to 1000
Ethane	–75.8	52.57	–4.593	39.74	0 to 750
Propane	4.438	–1.122	5.198	–20.08	0 to 1000
Benzene	–20.19	8.64	2.34	–9.69	0 to 1000
Toluene	18.14	–9.57	5.66	–22.22	0 to 1000
Aniline	–26.39	11.89	1.55	–4.30	0 to 1000
Phenol	–31.87	15.26	1.74	–4.40	0 to 1000
Cyclopropane	–20.46	9.74	3.77	–16.28	0 to 800
Cyclohexane	–20.57	4.45	4.07	–17.31	0 to 800
1,3 Butadiene	–67.92	29.96	1.74	–12.20	0 to 1000
Methanol	–18.62	9.95	2.90	–12.38	0 to 1000
Chloroform	–5.732	6.29	0.5904	–3.352	25 to 1000
Carbon tetrachloride	–0.4161	4.067	0.6115	–3.566	25 to 1000

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Table A1–12
Selected Constants for Gas Viscosity Equation

Compound	A	$B \times 10^{-2}$	$C \times 10^{-6}$	Range °C
Fluorine	22.09	76.9	−211.6	−200 to 1000
Chlorine	5.175	45.69	−88.54	−200 to 1200
Sulfur dioxide	−3.793	46.45	−72.76	−100 to 1400
Carbon monoxide	32.28	47.47	−96.48	−200 to 1400
Carbon dioxide	25.45	45.49	−86.49	−100 to 1400
Hydrogen chloride	−9.554	54.45	−96.56	−120 to 1400
Ammonia	−9.372	38.99	−44.05	−200 to 1200
Water	−31.89	41.45	−8.272	0 to 1000
Hydrogen peroxide	5.381	28.98	38.40	−80 to 1000
Hydrogen	21.87	22.2	−37.51	−160 to 1200
Nitrogen	30.43	49.89	−109.3	−160 to 1200
Oxygen	18.11	66.32	−187.9	−160 to 1000
Ethylene	3.586	35.13	−80.55	−100 to 800
Methane	15.96	34.39	−81.40	−80 to 1000
Ethane	5.576	30.64	−53.07	−80 to 1000
Propane	4.912	27.12	−38.06	−80 to 1000
Benzene	−15.76	32.45	−72.32	0 to 1000
Toluene	−8.421	27.11	−40.18	0 to 1000
Aniline	−14.98	29.03	−1.116	0 to 1000
Phenol	−16.41	32.00	0	0 to 1000
Cyclopropane	−7.787	34.78	−81.3	0 to 1000
Cyclohexane	−4.705	26.32	−44.1	0 to 1000
1,3 Butadiene	−10.67	34.32	−80.8	0 to 1000
Methanol	−5.636	34.45	−3.34	0 to 900
Chloroform	−6.688	37.26	−50.87	0 to 1000
Carbon tetrachloride	5.698	32.73	−40.28	0 to 1000

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Appendix B

Table B-1
Compressibility Factor of Natural Gas

```
******************************************************************************
        TEMPERATURE, oF            SPECIFIC GRAVITY
           60.                         .550

        PRESSURE psia.        COMPRESSIBILITY FACTOR Z
------------------------------------------------------------------------------
              100.                        .98160
              200.                        .97934
              300.                        .97263
              400.                        .96270
              500.                        .95042
              600.                        .93651
              700.                        .92156
              800.                        .90610
              900.                        .89053
             1000.                        .87520
             1100.                        .86041
             1200.                        .84636
             1300.                        .83322
             1400.                        .82110
             1500.                        .81008
             1600.                        .80021
             1700.                        .79151
             1800.                        .78399
             1900.                        .77767
             2000.                        .77253
             2100.                        .76860
             2200.                        .76586
             2300.                        .76432
             2400.                        .76395
             2500.                        .76473
```

Table B-1
(continued)

```
************************************************************************
        TEMPERATURE, oF           SPECIFIC GRAVITY
           60.                        .550

        PRESSURE psia.      COMPRESSIBILITY FACTOR Z
------------------------------------------------------------------------
           2600.                      .76663
           2700.                      .76960
           2800.                      .77354
           2900.                      .77838
           3000.                      .78401
           3100.                      .79032
           3200.                      .79718
           3300.                      .80447
           3400.                      .81208
           3500.                      .81989
           3600.                      .82780
           3700.                      .83573
           3800.                      .84363
           3900.                      .85144
           4000.                      .85916
           4100.                      .86678
           4200.                      .87436
           4300.                      .88195
           4400.                      .88966
           4500.                      .89761
           4600.                      .90597
           4700.                      .91495
           4800.                      .92478
           4900.                      .93575
           5000.                      .94817
```

Table B-2
Compressibility Factor of Natural Gas

```
***************************************************************************
        TEMPERATURE, oF           SPECIFIC GRAVITY
          70.                       .550

        PRESSURE psia.       COMPRESSIBILITY FACTOR Z
---------------------------------------------------------------------------
           100.                        .98208
           200.                        .98046
           300.                        .97453
           400.                        .96546
           500.                        .95411
           600.                        .94117
           700.                        .92721
           800.                        .91272
           900.                        .89810
          1000.                        .88369
          1100.                        .86975
          1200.                        .85649
          1300.                        .84406
          1400.                        .83257
          1500.                        .82209
          1600.                        .81267
          1700.                        .80432
          1800.                        .79706
          1900.                        .79089
          2000.                        .78583
          2100.                        .78187
          2200.                        .77903
          2300.                        .77729
          2400.                        .77665
          2500.                        .77710
          2600.                        .77859
          2700.                        .78109
          2800.                        .78452
          2900.                        .78880
          3000.                        .79383
          3100.                        .79951
          3200.                        .80572
          3300.                        .81234
          3400.                        .81926
          3500.                        .82638
          3600.                        .83360
          3700.                        .84085
          3800.                        .84806
          3900.                        .85519
          4000.                        .86223
          4100.                        .86919
          4200.                        .87610
          4300.                        .88303
          4400.                        .89006
          4500.                        .89733
          4600.                        .90499
          4700.                        .91323
          4800.                        .92228
          4900.                        .93241
          5000.                        .94392
---------------------------------------------------------------------------
```

Table B-3
Compressibility Factor of Natural Gas

```
*****************************************************************************
        TEMPERATURE, oF              SPECIFIC GRAVITY
          80.                           .550

        PRESSURE psia.          COMPRESSIBILITY FACTOR Z
-----------------------------------------------------------------------------
             100.                          .98250
             200.                          .98147
             300.                          .97625
             400.                          .96798
             500.                          .95750
             600.                          .94547
             700.                          .93243
             800.                          .91886
             900.                          .90513
            1000.                          .89158
            1100.                          .87845
            1200.                          .86594
            1300.                          .85419
            1400.                          .84330
            1500.                          .83334
            1600.                          .82434
            1700.                          .81634
            1800.                          .80933
            1900.                          .80333
            2000.                          .79834
            2100.                          .79437
            2200.                          .79143
            2300.                          .78952
            2400.                          .78864
            2500.                          .78878
            2600.                          .78990
            2700.                          .79197
            2800.                          .79492
            2900.                          .79868
            3000.                          .80317
            3100.                          .80826
            3200.                          .81387
            3300.                          .81987
            3400.                          .82616
            3500.                          .83264
            3600.                          .83922
            3700.                          .84582
            3800.                          .85239
            3900.                          .85889
            4000.                          .86531
            4100.                          .87165
            4200.                          .87794
            4300.                          .88425
            4400.                          .89066
            4500.                          .89729
            4600.                          .90429
            4700.                          .91185
            4800.                          .92017
            4900.                          .92952
            5000.                          .94017
-----------------------------------------------------------------------------
```

Table B-4
Compressibility Factor of Natural Gas

```
*****************************************************************************
         TEMPERATURE, oF            SPECIFIC GRAVITY
            90.                          .550

         PRESSURE psia.        COMPRESSIBILITY FACTOR Z
----------------------------------------------------------------------------
            100.                          .98288
            200.                          .98238
            300.                          .97781
            400.                          .97029
            500.                          .96061
            600.                          .94943
            700.                          .93726
            800.                          .92455
            900.                          .91167
           1000.                          .89893
           1100.                          .88657
           1200.                          .87476
           1300.                          .86366
           1400.                          .85334
           1500.                          .84387
           1600.                          .83529
           1700.                          .82762
           1800.                          .82085
           1900.                          .81501
           2000.                          .81010
           2100.                          .80613
           2200.                          .80311
           2300.                          .80105
           2400.                          .79995
           2500.                          .79980
           2600.                          .80058
           2700.                          .80226
           2800.                          .80477
           2900.                          .80806
           3000.                          .81203
           3100.                          .81658
           3200.                          .82163
           3300.                          .82705
           3400.                          .83275
           3500.                          .83864
           3600.                          .84462
           3700.                          .85063
           3800.                          .85661
           3900.                          .86253
           4000.                          .86836
           4100.                          .87413
           4200.                          .87984
           4300.                          .88558
           4400.                          .89141
           4500.                          .89745
           4600.                          .90385
           4700.                          .91076
           4800.                          .91841
           4900.                          .92702
           5000.                          .93688
----------------------------------------------------------------------------
```

Table B-5
Compressibility Factor of Natural Gas

```
*****************************************************************************
        TEMPERATURE, oF            SPECIFIC GRAVITY
          100.                          .550

        PRESSURE psia.       COMPRESSIBILITY FACTOR Z
-----------------------------------------------------------------------------
           100.                        .98321
           200.                        .98320
           300.                        .97923
           400.                        .97239
           500.                        .96348
           600.                        .95308
           700.                        .94173
           800.                        .92983
           900.                        .91775
          1000.                        .90577
          1100.                        .89413
          1200.                        .88300
          1300.                        .87251
          1400.                        .86274
          1500.                        .85374
          1600.                        .84556
          1700.                        .83820
          1800.                        .83167
          1900.                        .82599
          2000.                        .82116
          2100.                        .81720
          2200.                        .81411
          2300.                        .81192
          2400.                        .81062
          2500.                        .81021
          2600.                        .81067
          2700.                        .81199
          2800.                        .81410
          2900.                        .81694
          3000.                        .82043
          3100.                        .82449
          3200.                        .82901
          3300.                        .83390
          3400.                        .83905
          3500.                        .84439
          3600.                        .84982
          3700.                        .85528
          3800.                        .86071
          3900.                        .86608
          4000.                        .87137
          4100.                        .87660
          4200.                        .88179
          4300.                        .88699
          4400.                        .89228
          4500.                        .89778
          4600.                        .90360
          4700.                        .90993
          4800.                        .91694
          4900.                        .92487
          5000.                        .93398
-----------------------------------------------------------------------------
```

Table B-6
Compressibility Factor of Natural Gas

```
****************************************************************************
        TEMPERATURE, oF          SPECIFIC GRAVITY
           60.                       .600

        PRESSURE psia.      COMPRESSIBILITY FACTOR Z
----------------------------------------------------------------------------
          100.                          .96443
          200.                          .95901
          300.                          .94996
          400.                          .93810
          500.                          .92410
          600.                          .90857
          700.                          .89204
          800.                          .87496
          900.                          .85775
         1000.                          .84077
         1100.                          .82432
         1200.                          .80866
         1300.                          .79403
         1400.                          .78060
         1500.                          .76851
         1600.                          .75787
         1700.                          .74877
         1800.                          .74124
         1900.                          .73532
         2000.                          .73098
         2100.                          .72821
         2200.                          .72695
         2300.                          .72715
         2400.                          .72871
         2500.                          .73155
         2600.                          .73556
         2700.                          .74062
         2800.                          .74663
         2900.                          .75345
         3000.                          .76096
         3100.                          .76903
         3200.                          .77756
         3300.                          .78642
         3400.                          .79552
         3500.                          .80475
         3600.                          .81403
         3700.                          .82330
         3800.                          .83251
         3900.                          .84163
         4000.                          .85066
         4100.                          .85961
         4200.                          .86852
         4300.                          .87748
         4400.                          .88658
         4500.                          .89598
         4600.                          .90584
         4700.                          .91638
         4800.                          .92786
         4900.                          .94058
         5000.                          .95488
----------------------------------------------------------------------------
```

Table B-7
Compressibility Factor of Natural Gas

```
****************************************************************************
        TEMPERATURE, oF            SPECIFIC GRAVITY
          70.                        .600

        PRESSURE psia.        COMPRESSIBILITY FACTOR Z
----------------------------------------------------------------------------
             100.                         .96511
             200.                         .96051
             300.                         .95238
             400.                         .94152
             500.                         .92858
             600.                         .91413
             700.                         .89868
             800.                         .88267
             900.                         .86649
            1000.                         .85049
            1100.                         .83495
            1200.                         .82015
            1300.                         .80628
            1400.                         .79352
            1500.                         .78201
            1600.                         .77186
            1700.                         .76314
            1800.                         .75589
            1900.                         .75015
            2000.                         .74589
            2100.                         .74311
            2200.                         .74175
            2300.                         .74175
            2400.                         .74304
            2500.                         .74553
            2600.                         .74912
            2700.                         .75370
            2800.                         .75917
            2900.                         .76540
            3000.                         .77229
            3100.                         .77970
            3200.                         .78754
            3300.                         .79569
            3400.                         .80406
            3500.                         .81255
            3600.                         .82110
            3700.                         .82963
            3800.                         .83810
            3900.                         .84649
            4000.                         .85478
            4100.                         .86300
            4200.                         .87119
            4300.                         .87942
            4400.                         .88779
            4500.                         .89643
            4600.                         .90552
            4700.                         .91525
            4800.                         .92587
            4900.                         .93767
            5000.                         .95097
----------------------------------------------------------------------------
```

Table B-8
Compressibility Factor of Natural Gas

```
****************************************************************************
         TEMPERATURE, oF            SPECIFIC GRAVITY
            80.                          .600

         PRESSURE psia.        COMPRESSIBILITY FACTOR Z
----------------------------------------------------------------------------
            100.                        .96572
            200.                        .96186
            300.                        .95459
            400.                        .94466
            500.                        .93271
            600.                        .91927
            700.                        .90483
            800.                        .88983
            900.                        .87462
           1000.                        .85955
           1100.                        .84490
           1200.                        .83090
           1300.                        .81776
           1400.                        .80565
           1500.                        .79470
           1600.                        .78502
           1700.                        .77667
           1800.                        .76971
           1900.                        .76415
           2000.                        .75999
           2100.                        .75721
           2200.                        .75576
           2300.                        .75560
           2400.                        .75665
           2500.                        .75882
           2600.                        .76203
           2700.                        .76618
           2800.                        .77115
           2900.                        .77684
           3000.                        .78315
           3100.                        .78995
           3200.                        .79716
           3300.                        .80465
           3400.                        .81235
           3500.                        .82016
           3600.                        .82802
           3700.                        .83587
           3800.                        .84366
           3900.                        .85136
           4000.                        .85898
           4100.                        .86653
           4200.                        .87404
           4300.                        .88160
           4400.                        .88928
           4500.                        .89723
           4600.                        .90560
           4700.                        .91458
           4800.                        .92440
           4900.                        .93534
           5000.                        .94770
----------------------------------------------------------------------------
```

Table B-9
Compressibility Factor of Natural Gas

TEMPERATURE, oF	SPECIFIC GRAVITY
90.	.600

PRESSURE psia.	COMPRESSIBILITY FACTOR Z
100.	.96626
200.	.96308
300.	.95660
400.	.94754
500.	.93650
600.	.92401
700.	.91054
800.	.89648
900.	.88220
1000.	.86801
1100.	.85419
1200.	.84096
1300.	.82852
1400.	.81703
1500.	.80662
1600.	.79739
1700.	.78941
1800.	.78273
1900.	.77735
2000.	.77330
2100.	.77053
2200.	.76902
2300.	.76872
2400.	.76955
2500.	.77144
2600.	.77431
2700.	.77805
2800.	.78257
2900.	.78777
3000.	.79354
3100.	.79979
3200.	.80640
3300.	.81329
3400.	.82037
3500.	.82756
3600.	.83478
3700.	.84199
3800.	.84915
3900.	.85622
4000.	.86322
4100.	.87014
4200.	.87703
4300.	.88396
4400.	.89102
4500.	.89832
4600.	.90602
4700.	.91429
4800.	.92337
4900.	.93351
5000.	.94499

Table B-10
Compressibility Factor of Natural Gas

TEMPERATURE, oF	SPECIFIC GRAVITY
100.	.600

PRESSURE psia.	COMPRESSIBILITY FACTOR Z
100.	.96674
200.	.96419
300.	.95843
400.	.95018
500.	.94000
600.	.92840
700.	.91583
800.	.90266
900.	.88926
1000.	.87590
1100.	.86287
1200.	.85037
1300.	.83860
1400.	.82771
1500.	.81782
1600.	.80903
1700.	.80141
1800.	.79499
1900.	.78981
2000.	.78586
2100.	.78312
2200.	.78156
2300.	.78113
2400.	.78178
2500.	.78341
2600.	.78596
2700.	.78934
2800.	.79345
2900.	.79819
3000.	.80348
3100.	.80920
3200.	.81528
3300.	.82161
3400.	.82811
3500.	.83472
3600.	.84136
3700.	.84798
3800.	.85455
3900.	.86104
4000.	.86745
4100.	.87380
4200.	.88012
4300.	.88647
4400.	.89293
4500.	.89964
4600.	.90672
4700.	.91434
4800.	.92273
4900.	.93212
5000.	.94279

Table B-11
Compressibility Factor of Natural Gas

```
*****************************************************************************
        TEMPERATURE, oF          SPECIFIC GRAVITY
           60.                      .650

        PRESSURE psia.      COMPRESSIBILITY FACTOR Z
-----------------------------------------------------------------------------
           100.                      .94835
           200.                      .93926
           300.                      .92722
           400.                      .91276
           500.                      .89642
           600.                      .87870
           700.                      .86004
           800.                      .84088
           900.                      .82161
          1000.                      .80258
          1100.                      .78414
          1200.                      .76659
          1300.                      .75021
          1400.                      .73524
          1500.                      .72189
          1600.                      .71033
          1700.                      .70067
          1800.                      .69302
          1900.                      .68738
          2000.                      .68375
          2100.                      .68206
          2200.                      .68223
          2300.                      .68411
          2400.                      .68756
          2500.                      .69242
          2600.                      .69851
          2700.                      .70565
          2800.                      .71370
          2900.                      .72248
          3000.                      .73185
          3100.                      .74169
          3200.                      .75188
          3300.                      .76231
          3400.                      .77288
          3500.                      .78353
          3600.                      .79418
          3700.                      .80478
          3800.                      .81531
          3900.                      .82573
          4000.                      .83606
          4100.                      .84632
          4200.                      .85656
          4300.                      .86688
          4400.                      .87737
          4500.                      .88819
          4600.                      .89954
          4700.                      .91163
          4800.                      .92474
          4900.                      .93919
          5000.                      .95536
-----------------------------------------------------------------------------
```

Table B-12
Compressibility Factor of Natural Gas

```
*****************************************************************************
        TEMPERATURE, oF           SPECIFIC GRAVITY
           70.                        .650

        PRESSURE psia.       COMPRESSIBILITY FACTOR Z
-----------------------------------------------------------------------------
            100.                         .94926
            200.                         .94120
            300.                         .93025
            400.                         .91696
            500.                         .90180
            600.                         .88527
            700.                         .86780
            800.                         .84979
            900.                         .83162
           1000.                         .81365
           1100.                         .79618
           1200.                         .77953
           1300.                         .76395
           1400.                         .74969
           1500.                         .73694
           1600.                         .72588
           1700.                         .71663
           1800.                         .70926
           1900.                         .70381
           2000.                         .70027
           2100.                         .69856
           2200.                         .69861
           2300.                         .70029
           2400.                         .70345
           2500.                         .70794
           2600.                         .71358
           2700.                         .72022
           2800.                         .72769
           2900.                         .73584
           3000.                         .74455
           3100.                         .75368
           3200.                         .76313
           3300.                         .77280
           3400.                         .78259
           3500.                         .79245
           3600.                         .80230
           3700.                         .81210
           3800.                         .82183
           3900.                         .83145
           4000.                         .84098
           4100.                         .85045
           4200.                         .85990
           4300.                         .86941
           4400.                         .87910
           4500.                         .88910
           4600.                         .89959
           4700.                         .91079
           4800.                         .92296
           4900.                         .93640
           5000.                         .95147
-----------------------------------------------------------------------------
```

Table B-13
Compressibility Factor of Natural Gas

```
**************************************************************************************
          TEMPERATURE, oF           SPECIFIC GRAVITY
             80.                       .650

          PRESSURE psia.       COMPRESSIBILITY FACTOR Z
--------------------------------------------------------------------------------------
               100.                     .95008
               200.                     .94295
               300.                     .93303
               400.                     .92081
               500.                     .90677
               600.                     .89136
               700.                     .87501
               800.                     .85809
               900.                     .84098
              1000.                     .82400
              1100.                     .80747
              1200.                     .79167
              1300.                     .77687
              1400.                     .76329
              1500.                     .75114
              1600.                     .74058
              1700.                     .73172
              1800.                     .72465
              1900.                     .71940
              2000.                     .71595
              2100.                     .71426
              2200.                     .71422
              2300.                     .71573
              2400.                     .71863
              2500.                     .72279
              2600.                     .72803
              2700.                     .73420
              2800.                     .74115
              2900.                     .74874
              3000.                     .75683
              3100.                     .76531
              3200.                     .77408
              3300.                     .78305
              3400.                     .79213
              3500.                     .80125
              3600.                     .81037
              3700.                     .81943
              3800.                     .82841
              3900.                     .83730
              4000.                     .84609
              4100.                     .85482
              4200.                     .86354
              4300.                     .87231
              4400.                     .88125
              4500.                     .89049
              4600.                     .90019
              4700.                     .91056
              4800.                     .92186
              4900.                     .93435
              5000.                     .94839
--------------------------------------------------------------------------------------
```

Table B-14
Compressibility Factor of Natural Gas

TEMPERATURE, oF 90.

SPECIFIC GRAVITY .650

PRESSURE psia.	COMPRESSIBILITY FACTOR Z
100.	.95082
200.	.94455
300.	.93557
400.	.92435
500.	.91136
600.	.89701
700.	.88170
800.	.86582
900.	.84971
1000.	.83368
1100.	.81805
1200.	.80307
1300.	.78902
1400.	.77611
1500.	.76453
1600.	.75445
1700.	.74599
1800.	.73922
1900.	.73417
2000.	.73084
2100.	.72916
2200.	.72907
2300.	.73043
2400.	.73311
2500.	.73697
2600.	.74185
2700.	.74760
2800.	.75408
2900.	.76115
3000.	.76868
3100.	.77657
3200.	.78471
3300.	.79303
3400.	.80145
3500.	.80990
3600.	.81834
3700.	.82672
3800.	.83501
3900.	.84322
4000.	.85133
4100.	.85938
4200.	.86742
4300.	.87551
4400.	.88376
4500.	.89228
4600.	.90125
4700.	.91085
4800.	.92133
4900.	.93295
5000.	.94602

Table B-15
Compressibility Factor of Natural Gas

```
*************************************************************************
        TEMPERATURE, oF            SPECIFIC GRAVITY
          100.                        .650

        PRESSURE psia.        COMPRESSIBILITY FACTOR Z
-------------------------------------------------------------------------
             100.                        .95149
             200.                        .94600
             300.                        .93790
             400.                        .92761
             500.                        .91559
             600.                        .90224
             700.                        .88793
             800.                        .87303
             900.                        .85786
            1000.                        .84274
            1100.                        .82796
            1200.                        .81378
            1300.                        .80044
            1400.                        .78817
            1500.                        .77715
            1600.                        .76755
            1700.                        .75947
            1800.                        .75300
            1900.                        .74816
            2000.                        .74495
            2100.                        .74331
            2200.                        .74317
            2300.                        .74441
            2400.                        .74691
            2500.                        .75051
            2600.                        .75506
            2700.                        .76044
            2800.                        .76648
            2900.                        .77307
            3000.                        .78009
            3100.                        .78743
            3200.                        .79501
            3300.                        .80273
            3400.                        .81054
            3500.                        .81837
            3600.                        .82618
            3700.                        .83393
            3800.                        .84160
            3900.                        .84917
            4000.                        .85665
            4100.                        .86408
            4200.                        .87149
            4300.                        .87894
            4400.                        .88655
            4500.                        .89442
            4600.                        .90270
            4700.                        .91159
            4800.                        .92131
            4900.                        .93211
            5000.                        .94429
-------------------------------------------------------------------------
```

Table B-16
Compressibility Factor of Natural Gas

```
***************************************************************************
         TEMPERATURE, oF            SPECIFIC GRAVITY
           60.                        .700

         PRESSURE psia.       COMPRESSIBILITY FACTOR Z
---------------------------------------------------------------------------
            100.                         .93263
            200.                         .91942
            300.                         .90381
            400.                         .88617
            500.                         .86692
            600.                         .84646
            700.                         .82520
            800.                         .80352
            900.                         .78179
           1000.                         .76039
           1100.                         .73966
           1200.                         .71995
           1300.                         .70158
           1400.                         .68488
           1500.                         .67009
           1600.                         .65746
           1700.                         .64714
           1800.                         .63925
           1900.                         .63382
           2000.                         .63083
           2100.                         .63018
           2200.                         .63173
           2300.                         .63527
           2400.                         .64060
           2500.                         .64746
           2600.                         .65562
           2700.                         .66486
           2800.                         .67495
           2900.                         .68571
           3000.                         .69697
           3100.                         .70859
           3200.                         .72045
           3300.                         .73247
           3400.                         .74455
           3500.                         .75664
           3600.                         .76868
           3700.                         .78064
           3800.                         .79249
           3900.                         .80424
           4000.                         .81590
           4100.                         .82749
           4200.                         .83908
           4300.                         .85077
           4400.                         .86267
           4500.                         .87494
           4600.                         .88778
           4700.                         .90143
           4800.                         .91618
           4900.                         .93237
           5000.                         .95040
---------------------------------------------------------------------------
```

Table B-17
Compressibility Factor of Natural Gas

TEMPERATURE, oF	SPECIFIC GRAVITY
70.	.700

PRESSURE psia.	COMPRESSIBILITY FACTOR Z
100.	.93383
200.	.92188
300.	.90756
400.	.89125
500.	.87332
600.	.85417
700.	.83419
800.	.81374
900.	.79318
1000.	.77287
1100.	.75316
1200.	.73437
1300.	.71684
1400.	.70086
1500.	.68669
1600.	.67456
1700.	.66464
1800.	.65703
1900.	.65178
2000.	.64886
2100.	.64817
2200.	.64958
2300.	.65289
2400.	.65789
2500.	.66434
2600.	.67202
2700.	.68070
2800.	.69017
2900.	.70025
3000.	.71079
3100.	.72165
3200.	.73272
3300.	.74391
3400.	.75515
3500.	.76638
3600.	.77755
3700.	.78864
3800.	.79963
3900.	.81050
4000.	.82129
4100.	.83201
4200.	.84274
4300.	.85355
4400.	.86456
4500.	.87593
4600.	.88783
4700.	.90051
4800.	.91423
4900.	.92932
5000.	.94614

Table B-18
Compressibility Factor of Natural Gas

```
*****************************************************************************
        TEMPERATURE, oF              SPECIFIC GRAVITY
           80.                           .700

        PRESSURE psia.          COMPRESSIBILITY FACTOR Z
-----------------------------------------------------------------------------
           100.                         .93491
           200.                         .92411
           300.                         .91100
           400.                         .89592
           500.                         .87924
           600.                         .86133
           700.                         .84256
           800.                         .82329
           900.                         .80385
          1000.                         .78460
          1100.                         .76587
          1200.                         .74798
          1300.                         .73125
          1400.                         .71598
          1500.                         .70242
          1600.                         .69080
          1700.                         .68128
          1800.                         .67397
          1900.                         .66891
          2000.                         .66607
          2100.                         .66538
          2200.                         .66668
          2300.                         .66980
          2400.                         .67451
          2500.                         .68061
          2600.                         .68785
          2700.                         .69603
          2800.                         .70494
          2900.                         .71440
          3000.                         .72428
          3100.                         .73444
          3200.                         .74477
          3300.                         .75521
          3400.                         .76567
          3500.                         .77611
          3600.                         .78649
          3700.                         .79677
          3800.                         .80695
          3900.                         .81702
          4000.                         .82700
          4100.                         .83693
          4200.                         .84685
          4300.                         .85684
          4400.                         .86704
          4500.                         .87756
          4600.                         .88860
          4700.                         .90037
          4800.                         .91313
          4900.                         .92718
          5000.                         .94288
-----------------------------------------------------------------------------
```

Table B-19
Compressibility Factor of Natural Gas

```
*****************************************************************************
        TEMPERATURE, oF                SPECIFIC GRAVITY
           90.                             .700

        PRESSURE psia.          COMPRESSIBILITY FACTOR Z
-----------------------------------------------------------------------------
           100.                          .93589
           200.                          .92615
           300.                          .91416
           400.                          .90024
           500.                          .88473
           600.                          .86799
           700.                          .85037
           800.                          .83221
           900.                          .81385
          1000.                          .79561
          1100.                          .77782
          1200.                          .76080
          1300.                          .74485
          1400.                          .73027
          1500.                          .71731
          1600.                          .70619
          1700.                          .69708
          1800.                          .69007
          1900.                          .68522
          2000.                          .68250
          2100.                          .68182
          2200.                          .68304
          2300.                          .68600
          2400.                          .69047
          2500.                          .69625
          2600.                          .70310
          2700.                          .71083
          2800.                          .71923
          2900.                          .72814
          3000.                          .73741
          3100.                          .74693
          3200.                          .75659
          3300.                          .76633
          3400.                          .77608
          3500.                          .78579
          3600.                          .79543
          3700.                          .80498
          3800.                          .81441
          3900.                          .82374
          4000.                          .83298
          4100.                          .84215
          4200.                          .85133
          4300.                          .86058
          4400.                          .87001
          4500.                          .87975
          4600.                          .88998
          4700.                          .90091
          4800.                          .91277
          4900.                          .92586
          5000.                          .94051
-----------------------------------------------------------------------------
```

Table B-20
Compressibility Factor of Natural Gas

****

TEMPERATURE, oF	SPECIFIC GRAVITY
100.	.700

PRESSURE psia.	COMPRESSIBILITY FACTOR Z
100.	.93677
200.	.92801
300.	.91706
400.	.90422
500.	.88981
600.	.87418
700.	.85765
800.	.84055
900.	.82321
1000.	.80594
1100.	.78906
1200.	.77287
1300.	.75769
1400.	.74378
1500.	.73141
1600.	.72078
1700.	.71207
1800.	.70538
1900.	.70074
2000.	.69814
2100.	.69750
2200.	.69868
2300.	.70150
2400.	.70577
2500.	.71127
2600.	.71778
2700.	.72510
2800.	.73304
2900.	.74144
3000.	.75016
3100.	.75909
3200.	.76814
3300.	.77724
3400.	.78633
3500.	.79538
3600.	.80434
3700.	.81320
3800.	.82195
3900.	.83059
4000.	.83914
4100.	.84763
4200.	.85612
4300.	.86467
4400.	.87340
4500.	.88242
4600.	.89190
4700.	.90204
4800.	.91307
4900.	.92527
5000.	.93894

Table B-21
Compressibility Factor of Natural Gas

TEMPERATURE, oF	SPECIFIC GRAVITY
60.	.750

PRESSURE psia.	COMPRESSIBILITY FACTOR Z
100.	.91676
200.	.89894
300.	.87920
400.	.85783
500.	.83515
600.	.81149
700.	.78720
800.	.76262
900.	.73811
1000.	.71403
1100.	.69075
1200.	.66866
1300.	.64813
1400.	.62953
1500.	.61318
1600.	.59936
1700.	.58829
1800.	.58009
1900.	.57483
2000.	.57244
2100.	.57280
2200.	.57572
2300.	.58092
2400.	.58813
2500.	.59701
2600.	.60728
2700.	.61862
2800.	.63080
2900.	.64357
3000.	.65675
3100.	.67019
3200.	.68378
3300.	.69742
3400.	.71106
3500.	.72463
3600.	.73811
3700.	.75147
3800.	.76471
3900.	.77782
4000.	.79084
4100.	.80381
4200.	.81680
4300.	.82990
4400.	.84324
4500.	.85699
4600.	.87136
4700.	.88660
4800.	.90302
4900.	.92099
5000.	.94090

Table B-22
Compressibility Factor of Natural Gas

```
***************************************************************************
         TEMPERATURE, oF              SPECIFIC GRAVITY
            70.                          .750

         PRESSURE psia.         COMPRESSIBILITY FACTOR Z
---------------------------------------------------------------------------
            100.                         .91829
            200.                         .90199
            300.                         .88377
            400.                         .86390
            500.                         .84268
            600.                         .82044
            700.                         .79751
            800.                         .77423
            900.                         .75093
           1000.                         .72797
           1100.                         .70573
           1200.                         .68457
           1300.                         .66487
           1400.                         .64698
           1500.                         .63124
           1600.                         .61791
           1700.                         .60721
           1800.                         .59927
           1900.                         .59415
           2000.                         .59179
           2100.                         .59208
           2200.                         .59481
           2300.                         .59974
           2400.                         .60657
           2500.                         .61499
           2600.                         .62472
           2700.                         .63545
           2800.                         .64694
           2900.                         .65898
           3000.                         .67137
           3100.                         .68398
           3200.                         .69671
           3300.                         .70946
           3400.                         .72217
           3500.                         .73482
           3600.                         .74735
           3700.                         .75977
           3800.                         .77206
           3900.                         .78423
           4000.                         .79630
           4100.                         .80832
           4200.                         .82036
           4300.                         .83250
           4400.                         .84487
           4500.                         .85764
           4600.                         .87099
           4700.                         .88517
           4800.                         .90047
           4900.                         .91723
           5000.                         .93584
---------------------------------------------------------------------------
```

Table B-23
Compressibility Factor of Natural Gas

```
****************************************************************************
         TEMPERATURE, oF           SPECIFIC GRAVITY
            80.                        .750

         PRESSURE psia.       COMPRESSIBILITY FACTOR Z
----------------------------------------------------------------------------
            100.                        .91968
            200.                        .90479
            300.                        .88798
            400.                        .86951
            500.                        .84968
            600.                        .82879
            700.                        .80716
            800.                        .78511
            900.                        .76299
           1000.                        .74113
           1100.                        .71989
           1200.                        .69965
           1300.                        .68076
           1400.                        .66358
           1500.                        .64844
           1600.                        .63561
           1700.                        .62530
           1800.                        .61764
           1900.                        .61268
           2000.                        .61039
           2100.                        .61064
           2200.                        .61323
           2300.                        .61792
           2400.                        .62442
           2500.                        .63244
           2600.                        .64168
           2700.                        .65186
           2800.                        .66274
           2900.                        .67410
           3000.                        .68577
           3100.                        .69763
           3200.                        .70955
           3300.                        .72148
           3400.                        .73336
           3500.                        .74514
           3600.                        .75681
           3700.                        .76835
           3800.                        .77976
           3900.                        .79105
           4000.                        .80225
           4100.                        .81339
           4200.                        .82454
           4300.                        .83580
           4400.                        .84727
           4500.                        .85911
           4600.                        .87151
           4700.                        .88470
           4800.                        .89895
           4900.                        .91458
           5000.                        .93197
----------------------------------------------------------------------------
```

Table B-24
Compressibility Factor of Natural Gas

```
*****************************************************************************
         TEMPERATURE, oF             SPECIFIC GRAVITY
            90.                          .750

         PRESSURE psia.        COMPRESSIBILITY FACTOR Z
-----------------------------------------------------------------------------
            100.                        .92094
            200.                        .90735
            300.                        .89186
            400.                        .87470
            500.                        .85618
            600.                        .83657
            700.                        .81618
            800.                        .79532
            900.                        .77433
           1000.                        .75352
           1100.                        .73327
           1200.                        .71391
           1300.                        .69583
           1400.                        .67936
           1500.                        .66482
           1600.                        .65248
           1700.                        .64257
           1800.                        .63520
           1900.                        .63043
           2000.                        .62823
           2100.                        .62847
           2200.                        .63096
           2300.                        .63546
           2400.                        .64168
           2500.                        .64935
           2600.                        .65815
           2700.                        .66784
           2800.                        .67816
           2900.                        .68890
           3000.                        .69992
           3100.                        .71108
           3200.                        .72227
           3300.                        .73345
           3400.                        .74455
           3500.                        .75554
           3600.                        .76640
           3700.                        .77714
           3800.                        .78774
           3900.                        .79821
           4000.                        .80860
           4100.                        .81892
           4200.                        .82926
           4300.                        .83969
           4400.                        .85033
           4500.                        .86131
           4600.                        .87283
           4700.                        .88509
           4800.                        .89836
           4900.                        .91294
           5000.                        .92919
-----------------------------------------------------------------------------
```

Table B-25
Compressibility Factor of Natural Gas

TEMPERATURE, oF	SPECIFIC GRAVITY
100.	.750

PRESSURE psia.	COMPRESSIBILITY FACTOR Z
100.	.92209
200.	.90969
300.	.89543
400.	.87951
500.	.86221
600.	.84382
700.	.82461
800.	.80490
900.	.78499
1000.	.76520
1100.	.74589
1200.	.72741
1300.	.71011
1400.	.69432
1500.	.68038
1600.	.66855
1700.	.65904
1800.	.65198
1900.	.64742
2000.	.64532
2100.	.64558
2200.	.64800
2300.	.65234
2400.	.65833
2500.	.66568
2600.	.67411
2700.	.68335
2800.	.69316
2900.	.70336
3000.	.71378
3100.	.72430
3200.	.73483
3300.	.74531
3400.	.75569
3500.	.76595
3600.	.77608
3700.	.78607
3800.	.79592
3900.	.80565
4000.	.81528
4100.	.82485
4200.	.83443
4300.	.84410
4400.	.85396
4500.	.86415
4600.	.87485
4700.	.88625
4800.	.89861
4900.	.91221
5000.	.92739

Appendix C

COMPILING THE FORTRAN SOURCE CODE

The FORTRAN source code, like any high level code, is a compiler language, and the programmer must translate (compile) the code to be recognized by the computer. An intermediate program called a compiler is required to expedite this translation. The compiler used for translating (compiling) the programs in this book is the **Microsoft (MS) FORTRAN Version 5** compiler, developed and marketed by the Microsoft Corporation. Both FORTRAN Compiler Version 5 and the latest Version 5.1 are designed for compiling a FORTRAN source program on the personal computer. The MS-FORTRAN compiler consists of a set of floppy diskettes, a reference manual, and a user's guide. These give information about the files on the diskettes, and how they are used.

To compile the FORTRAN source code, the programmer needs a personal computer with a hard disk having a minimum of five megabyte disk space. The FORTRAN source program is written and edited by using any text editor or word processor. This is entered on the program with an appropriate filename, with the extension FOR. An object program (extension OBJ) and an executable program (extension EXE) with the same filename as the source program are created during compilation and stored on the program. The source code is created using the Microsoft FORTRAN text editor or a word processor in non-document mode. Using Microsoft text editor, the source code of a file PROG11.FOR can be created from the C:\> prompt, command line by typing:

```
C:\>m PROG11.FOR
```

The following procedure compiles and links the source code.

From the C:\>prompt command line, type

```
fl /c /4Yb /FsCon PROG11.FOR
```

where /c = compiles without linking the source code
/4Yb = Enables the extended error handling at run time
/FsCon = Produces a source code listing on the screen

The following messages will appear on the screen:

```
Microsoft (R) FORTRAN Optimizing Compiler Version 5.00

Copyright (c) Microsoft Corp 1982–1989. All rights reserved.
```

The link command invokes the Microsoft segmented executable linker.

```
link PROG11,,nul,llibfore/exe/nodef,nul
```

The following messages will appear on the screen:

```
Microsoft (R) Segmented - Executable Linker Version 5.03

Copyright (C) Microsoft Corp 1984–1989. All rights reserved.
```

A few seconds are required to compile the link step. When the drive light stops blinking, the C:\>prompt will return to the screen. Compilation is then complete.

A directory listing the files will include the following:

- **PROG.FOR**
- **PROG11.OBJ**
- **PROG11.EXE**
- **PROG11.LST**

Files with extensions MAP, and LST can be created and stored at the direction of the compiler program during compilation. The text for these files many be displayed, however only two files, PROG11.FOR and PROG11.LST will be displayed in readable form. The files with the extensions OBJ, MAP and EXE will be displayed in machine codes.

Executing the FORTRAN Program

Results of PROG11 are obtained by executing or running the program from the C:\> prompt. The executable filename is typed either with or without the extension (EXE).

```
C:\>PROG11
```

After compilation has been completed, an executable file is created and stored, and the results are obtained. The files with extensions **FOR** and **EXE** are retained. Other files with the extensions **OBJ, MAP, LST,** and **BAK** resulting from editing the source program may be deleted to create more space on the hard disk drive.

Creating a Batch File

A batch file is a file containing one or more Disk Operating System (DOS) commands which are automatically executed one at a time when the batch command is initiated. A batch file can be assigned any suitable filename but must have the extension **BAT.** The batch file can be created by copying from the console (keyboard) with the internal COPY command or from a text editor or a word processor. Using the Microsoft text editor, creating a batch file **COMPILE.BAT** from compiling and running the computer program PROG11 involves the following sequence of commands.

From the C:\>prompt command line, type

```
C:\>m COMPILE.BAT
```

The text editor screen is displayed and the following commands can then be typed.

```
@ECHO OFF
@ECHO COMPILE THE SOURCE PROGRAM PROG11
fl /c /4Yb /FsCon PROG11.FOR
@ ECHO LINK THE OBJECT CODE OF PROGRAM PROG11
link PROG11,,nul,llibfore/exe/nodef,nul
@ECHO run the executable code of program PROG11
PROG11
```

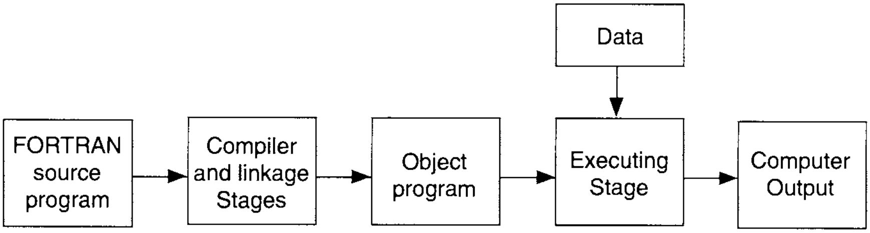
Errors

Errors detected during the compilation are located by the source program line number and appropriate numbered error messages are displayed. The error message numbers refer to the MS-FORTRAN error messages listed in the Microsoft FORTRAN User's Guide. Errors detected during the compilation are usually errors in FORTRAN syntax or procedure. Compilation is aborted when errors are detected, and the C:\>prompt is displayed. A source program may not be executed successfully even though no errors are detected during compilation. These are known as run time errors. These types of errors abort execution and display error messages to assist in identifying the errors. These error messages may be explicit and are sometimes difficult to detect. Examples of these errors are an attempt to calculate the square root of a negative number or divide by zero. A way of de-bugging errors is by having print or write statements at various stages of computation. Alternatively, a debugger software tool can be used to permit the programmer to execute his program one instruction at a time, and thus allows him to examine the state of his program variables after any instruction. Microsoft provides a high-level code degugger (CodeView) for this purpose.

Running the FORTRAN Program

Once the program has been typed into the computer using a text editor or a word processor in non-document mode and stored in a file, it must be compiled. A compiler is a program that translates a high-level language to machine language. The compilation step is the first stage in running the FORTRAN program on the computer. As the compiler translates statements, it also checks for syntax errors. These errors, also called compiler errors, are errors in the statements such as misspellings and punctuation errors. If these errors are detected, the compiler will print error messages or diagnostics for the programmer. After debugging the program, it can be recompiled using the MS-FORTRAN compiler. After a successful compilation, a linkage editor program performs the final stage before the program is executed.

The FORTRAN program is often referred to as the source program. The source code is converted into the machine language by the compiler and prepared for execution by the linkage editor. The linking process inserts pieces of the program in the right places in the object code to produce an executable program. This is sometimes known as a binary program, which is stored in a file. The data are inputted in the execution stage to obtain the output. This process is illustrated by the following block diagram.



The procedures given will enable users and readers of this book to readily compile and run all the source codes contained in the diskette.

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