A REVIEW OF SOLID PROPELLANT BURN RATE ENHANCEMENT BY MECHANICAL METHODS

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Abstract. The inclusion of metal fibers in a solid propellant grain has been shown to increase its bulk burning rate dramatically, and is a technology that was applied in several early sounding rockets. This review covers historical and current applications for the technology, as well as the theoretical basis for burning rate enhancement. Though technically successful, the use of wires to achieve high burning rates has largely been replaced with the use of reactive catalysts and other high burning rate energetic materials. However, recent concern over the sensitivity of such propellants is generating interest in other means of accelerating burn rates. As such, several practical research topics involving wire enhancement of burning rates are presented to reintroduce this technology into the motor designer's toolbox.

1. Introduction

The usefulness of solid rocket motors in many applications is limited by the burning rate of the propellant which they contain. Propellants are typically burned in the combustion chamber either radially, with a center perforation, or axially along a solid length. Since burn duration is proportional to the thickness of propellant being burned, such geometry constraints restrict the burn times achievable using typical solid rocket propellants to either relatively short or extremely long durations. A high burning rate propellant (>1 in/sec) opens up a further range of possibilities, allowing motors of moderate burn duration (15-60 sec) to be fabricated in aspect ratios favorable to applications in missiles and sounding rockets. Techniques for creating high burning rate composite propellants include chemical catalysis, inclusion of high burning rate energetics in the composite, modification of constituent particle size, and mechanical modification of the propellant grain to increase thermal diffusivity.

The inclusion of energetic materials and burning rate catalysts from the metallocene family (e.g., ferrocene and catocene) was shown early in the history of composite propellant technology to be a promising avenue for increasing propellant burning rate efficiently [1]. However, such chemicals also greatly increase propellant sensitivity, presenting significant processing and handling hazards.

Particle size modification is a current research topic, and the advent of nanomaterials shows significant promise for generating predictable high burn rates without the inclusion of sensitive materials. Problems arise, however, from the significant rheology and processing problems presented by the inclusion of ultra-fine particles, and the current cost of nanoenergetics remains a barrier to full-scale production.

Mechanically modifying the thermal diffusivity of the composite with the inclusion of solid metal filaments was shown to be a useful technique as early as 1955 [2]. Indeed, several patents were granted on wired burning rate technology in the early 60s [3][4]. The inclusion of wires in the propellant shows promise for generating extremely high bulk burning rates (2-5 in/sec) without modification of the composite chemical composition. The downsides to the technology include processing difficulties, increased radar signature, and usefulness only in certain grain geometries [5].

Perhaps for these reasons, very little current research into and production of motors using wires to enhance burning rate exists. This paper will highlight current state of the art applications for wire-enhanced burning rate technology. In addition, the theoretical basis for this burning rate mechanism will be examined, and several models presented for review. Encouraging areas for future research will also be presented.

2. Current Applications

In the United States, the concept of increasing propellant burn rates with embedded metal wires was first explored by Rumbel, et al. at Atlantic Research Corporation in 1955 [2]. ARC used this technology in several sounding rockets, beginning in 1958 [6]. The most successful of these vehicles, ARCAS, remained in use until 1991 [7]. These sounding rockets were designed using PVC plastisol propellant [8], and the inclusion of axially embedded wires in the propellant grain produced a burning rate enhancement of nearly 400%. This allowed the vehicles to use an endburning grain geometry, resulting in gentle vehicle acceleration and burn times between 17.5 and 29.2 seconds – ideal for fragile electronic payloads [6].

Wire enhancement of burning rate also proved popular for missile development. The endburning configuration pioneered by ARC produced not only longer action times, but also higher mass fractions, allowing the developed missiles to be smaller. As such, wire-enhanced motors were fielded extensively in the Redeye and Stinger missile programs [9].

3. Theory of Operation

The seminal model of the combustion process of a propellant with embedded metal wires was developed by Caveny and Glick in 1967 [5]. It was the first model to account for both transient and steady-state burning rates of propellants with embedded wires, and thus can be used to model either chopped wire distributed throughout the propellant, or stranded wire embedded as a single piece in the grain.

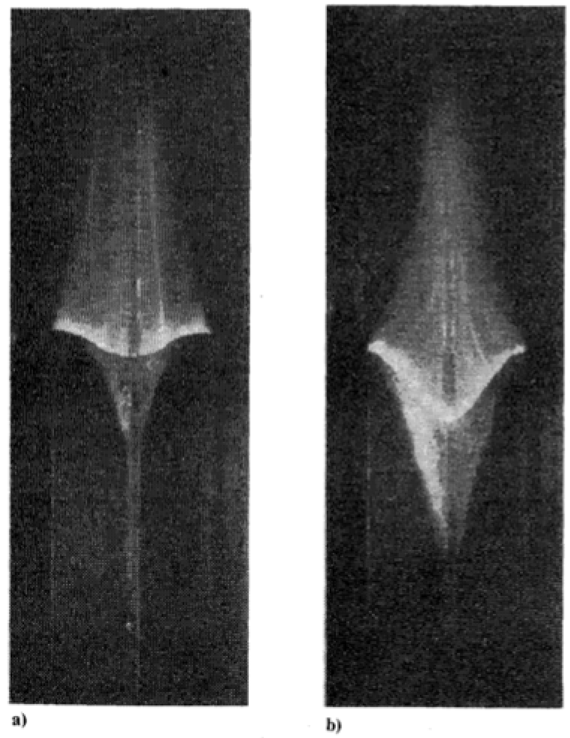

FIGURE 1. Infrared imaging of a propellant strand surrounding a silver wire at ignition (a) and during regression (b). Note the cone-shaped burning surface. [14]

The mechanism by which the local burning rate increases is essentially that of increased thermal diffusivity in a narrow region around the wire. This region forms the shape of a cone (shown in Fig 1), with the half-angle $\theta_c = \sin^{-1}\left(\frac{\dot{r}_m}{\dot{r}_w}\right)$, where $\dot{r}_m$ is the burning rate of the propellant matrix, and $\dot{r}_w$ is the burning rate of the propellant along the wire. This geometry is illustrated in Fig 2.

The Caveny-Glick model examines a 2D slice of burning propellant with a single rectangular wire embedded in its center. Experimental results show burning occurring in three phases: a start transient, accompanied by an increase in burning rate as the wire is exposed; a steady-state burn; and a stop transient, accompanied by another increase in burning rate.

To model the phases successfully, the combustion process was divided into four zones, as shown in Fig 2. The *propellant thermal zone* is the zone in which heat conduction occurs from the burning surface into the propellant. For the purposes of calculation, this zone is assumed to be very thin, as typical composite propellant is a good thermal insulator. The *fiber thermal zone* surrounds the metal fiber embedded in the propellant, and thus

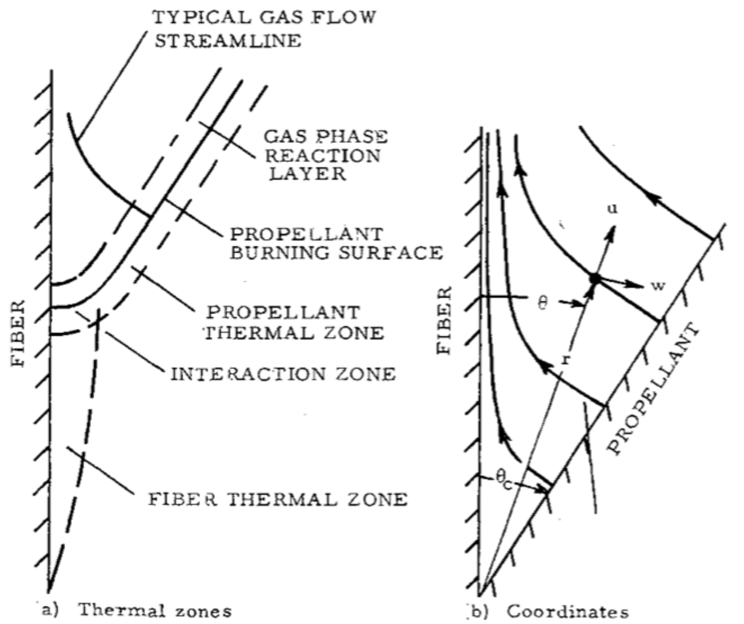

FIGURE 2. Important geometry in the Caveny and Glick combustion model. [5]

contains propellant that has been preheated by the wire. It is assumed that the propellant maintains contact with the wire; investigations by King [10] have shown that the separation of propellant from the wire has a large effect on burn rate. The *interaction zone* is defined as the intersection of the fiber thermal zone and the propellant thermal zone, and finally the *gas phase reaction zone* is where the bulk of the chemical reactions in the propellant occur. As with most models of propellant regression, gases are modeled as exiting normal to the burning surface of the grain; the gases are then assumed to gently turn to flow parallel to the embedded fiber.

For ease of calculation, several basic assumptions are made as well. The propellant is assumed to be homogeneous and isotropic, and the gas flow inside the motor is assumed to be inviscid quasi-steady flow at a low Mach number. Since the temperature gradient across the embedded wire is large, it is assumed to be "thermally thin", as the thermal conductivity of the wire is typically two orders of magnitude higher than the thermal conductivity of the propellant. Additionally, heat transfer in the interaction zone and out the end of the wire is assumed to be negligible, since these regions are physically very small. Finally, an "ignition temperature" model is assumed, such that the propellant does not undergo any reaction until this temperature is reached. With these assumptions in place, the calculation process can begin.

The heat transfer problem which drives the burning rate can be divided up into three mechanisms: heat convection into the fiber, heat conduction along the fiber into the propellant grain, and heat conduction into the propellant from the fiber. By solving these three sub-problems, the local temperature increase around the wire may be modeled, and the resulting change in burn rate calculated using the propellant temperature sensitivity σ_p, as predicted by the equivalence principle.

Convection into the fiber is governed by the convective heat transfer equation,

$$q''(z) = h_g(z)(T_g - T_f) \ , \tag{1}$$

where $q''(z)$ is the heat flux into the wire at distance z from the apex, h_g is the convective heat transfer coefficient, T_g is the gas temperature, and T_f is the fiber temperature. This equation is solvable with knowledge of h_g, which the Caveny-Glick model calculates by way of the flat plate heat transfer equations for laminar flow. These equations are a function of Reynolds number, which requires knowledge of the flow velocity. Since a thin gas phase reaction zone is assumed, the propellant cone surrounding the wire can be modeled as infinitely long, thus making all components of the gas velocity solely dependent on the values of θ:

$$u = v_s \mathrm{sin}(\theta_c - \theta) \tag{2}$$

$$w = v_s \mathrm{cos}(\theta_c - \theta) \tag{3}$$

with boundary conditions determined from inspection as

$$u(r, \theta_c) = w(r, 0) = 0 \tag{4}$$

and

$$w(r, \theta_c) = -v_s \ . \tag{5}$$

u and w are the axial and radial flow velocities, respectively, v_s is the gas flow velocity at the propellant surface, θ is the angle of the gas flow, θ_c is the propellant cone angle as described above, and r is the radial distance from the apex of the cone to the point under consideration. Using the assumptions of quasi-steady incompressible flow and two-dimensional temperature distribution, the Navier-Stokes equations in cylindrical coordinates may be simplified to give the relations

$$\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{1}{r}\frac{\partial w}{\partial \theta} = 0 \tag{6}$$

$$u\frac{\partial u}{\partial r} + \frac{w}{r}\frac{\partial u}{\partial \theta} - \frac{w^2}{r} = -\frac{1}{\rho}\frac{\partial P}{\partial r} \tag{7}$$

$$ru\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial \theta} + uw = -\frac{1}{\rho}\frac{\partial P}{\partial \theta} \ . \tag{8}$$

Differentiating Eq 7 with respect to θ and Eq 8 with respect to r and combining results in a second-order differential equation with u and w as independent variables. In combination with Eq 6, this allows the velocity field to be solved, and thus h_g derived. Caveny and Glick note that "for cone angles of practical interest, flow convergence increases the heat transfer to the fiber by approximately 40% over that obtained for a flat plate," likely due to the turbulent mixing zones that are generated as the gas flows unite around the wire.

Conduction along the fiber exists in two distinct zones: that of the exposed fiber above the surface, and that of the fiber beneath the surface. For any region, the conduction along the fiber is given by

$$(\rho C_p)_f \left(\frac{\partial T_f}{\partial t}\right) = k_f \left(\frac{\partial^2 T_f}{\partial z^2}\right) + \frac{pq''}{A_f} \ , \tag{9}$$

where $(\rho C_p)_f$ are the density and specific heat capacity of the fiber, T_f is the temperature of the fiber, k_f is the thermal conductivity of the fiber, z is the distance along the fiber, p is the perimeter of the fiber, q'' is the instantaneous heat flux into the fiber (as given in Eq.s 10 and 11), and A_f is the cross-sectional area of the fiber. This equation must be solved numerically using boundary and initial conditions from heat transfer laws.

Beneath the surface, simple conduction governs the heat transfer:

$$q''_p = k_f \left(\frac{\partial T_p(0,z,t)}{\partial x}\right) \tag{10}$$

where subscript p denotes conditions in the propellant. Above the surface, convection dominates, with the addition of a radiative heat flux term:

$$q''_e = h_g(T_g - T_f) + \sigma F(T_g^4 - T_f^4) \ . \tag{11}$$

where subscript e denotes conditions in the exposed fiber. From observation, the initial condition for Eq 9 is given by the initial temperature of the system T_i:

$$T_f(z,0) = T_i \ . \tag{12}$$

To solve the boundary conditions, both melting and non-melting fiber cases need to be considered. If the propellant flame temperature is below the melting temperature of the wire, $q''_e(0,t)$ can be solved easily, as the fiber remains intact:

$$q''_e(0,t) = k_f \frac{\partial T_f(0,t)}{\partial z} \tag{13}$$

However, if the fiber melts, the behavior is a bit more complex; Eq 13 expresses the boundary condition only until the fiber begins to melt. After melting begins, the temperature at the end of the fiber is regulated to the phase change temperature, and the boundary condition becomes

$$A_f k_f \frac{\partial T_f(z_m,t)}{\partial x} + A_f \rho_f L_f s = A_m q''_e(z_m,t) \ , \tag{14}$$

where subscript m indicates the melted fiber condition and s is the melting rate of the fiber.

The last step to be analyzed in order to complete the model is the heat transfer via conduction from the wire into the propellant. Using the model assumptions in combination with the definition of thermal diffusivity α, the rate of temperature change of a single propellant cell at cone location x is given as

$$\frac{\partial T_p}{\partial t} = \alpha_p \left(\frac{\partial^2 T_p}{\partial x^2} \right) , \tag{15}$$

where subscript p indicates conditions in the propellant. Initial conditions are given as in the previous problem as

$$T_p(x, z, 0) = T_i \tag{16}$$

and, using the negligible interaction zone depth assumption, the boundary conditions for the propellant heat transfer are simply

$$\begin{aligned} T_p(\infty, z, t) &= T_i \\ T_p(0, z, t) &= T_f(z, t) \end{aligned} \tag{17}$$

where $x = \infty$ exists at the edge of the propellant grain. The second boundary condition is a function of fiber temperature, and thus must be solved simultaneously with Eq 9. Caveny and Glick rely on Goodman's heat balance integral and Eq 15 to solve the heat flux distribution into the propellant:

$$q_p''(z, t) = \frac{2{k_p}^2 [T_f(z, t) - T_i]^2}{3\alpha_p \int_0^t q_p''(\lambda) d\lambda}$$

where q_p'' is the heat flux into the propellant cell and λ is a dummy integration variable. Discretizing this equation for a digital solution gives another form:

$$q_p''(t + \Delta t) = \frac{1}{2\Delta t} \left[\left(Q_n^2(t) + \frac{8{k_p}^2}{3\alpha_p} \left[T_f(z_n, t + \Delta t) - T_i \right]^2 \Delta_t \right)^{1/2} - Q_n(t) \right] \tag{18}$$

where Δt is the digital simulation timestep, and $Q_n(t)$ is the integral of the heat flux into the nth propellant node at time t. This equation shows that heat flux – and ultimately, burning rate – is proportional to the magnitude of the thermal conductivity of the propellant, and proportional to the square root of the thermal diffusivity.

The result of this solved model is shown in Fig 3. These predictions have been corroborated with experimental data by other workers. Both King [10] and Kubota [11] investigated the effect of wire size on burning rate enhancement. Both experimenters noted a limit in the increase of burning rate with increasing wire size; beyond this size, the burning rate slowly began to decrease again as the wire's thermal mass became more important. Such data verifies the Caveny-Glick assumption of a "thermally thin" wire. Kubota did, however, note that gas phase effects become important as propellant composition varies; the extent to which these effects influence the model is not currently known.

In additional macro-scale testing, King applied a modified version of the Caveny-Glick model to predict the burning rate of a wire-enhanced propellant grain with surprising accuracy. King's results are shown in Fig 4. King also notes another shortcoming of the Caveny-Glick model: the assumption of perfect conduction from the wire into the propellant, with no "contact resistance" to account for potential gaps between the wire and the propellant surface, can be a large source of error, as processing problems or thermal cycling of the motor can cause significant gaps to form.

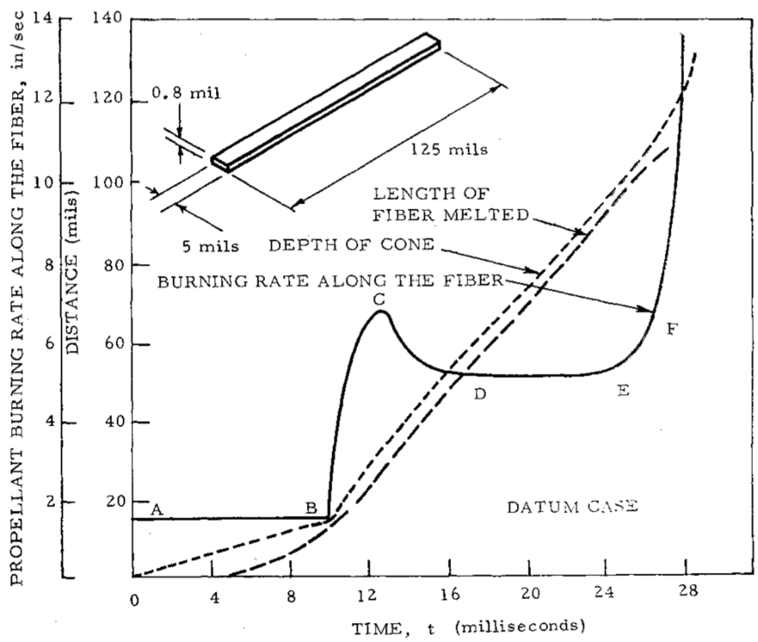

FIGURE 3. Results of Caveny-Glick Model for typical burning case. Noted on the plot are initial steady-state burn (a-b), increase in regression rate as wire is exposed (b-c), burning rate stabilization as wire melts (c-d), steady state wire-enhanced burning operation (d-e), and final rate enhancement as propellant regression reaches end of wire (e-f). [5]

Even with its shortcomings, the Caveny-Glick model still remains the fundamental basis for more modern computational codes, notably those developed by Gossant et al. [12] for solving the ratio of bulk augmented and non-augmented burning rates, and Coats et al. [13] for solving a complete regression model for wire-enhanced grains with the computationally intense Solid Performance Program code.

The Caveny-Glick model illustrates the importance of propellant thermal diffusivity α_p and wire thermal conductivity k_f on increased burn rate. Rumbel [2] confirmed the importance of k_f expressed by Caveny and Glick by comparing the burn rates of a standard propellant with different wire materials. Additionally, King [10] and Winch et al. [15] both describe the importance of the melting temperature of the wire; silver wire plated with palladium undergoes an alloying reaction before melting, thus increasing the effective melting temperature and allowing greater thermal transfer into the propellant.

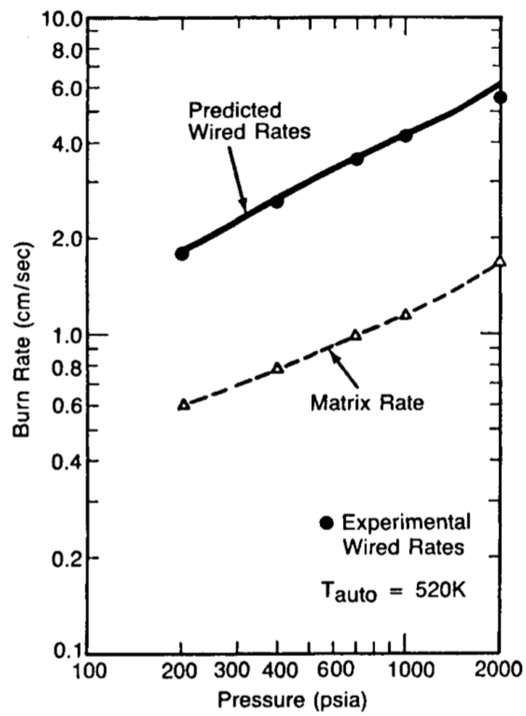

FIGURE 4. Results of Caveny-Glick model compared with data from experiment using Arcite 155 propellant (74.62% solids loading, AP-based PVC Plastisol propellant containing no thermic agents) and tungsten wires. [10]

4. Future Research & Conclusions

With several numerical models existing for various wire geometries, most of the research that remains to be conducted lies in the realm of applied research. New interest is appearing in high burn rate propellant research, and many such application requirements could successfully be met using wire augmentation of burn rates.

- *Effect of wires on propellants with high thermal conductivity:* Much of the current existing research is focused on propellants with low combustion temperatures for use in endburning motors. Such propellants (e.g., Arcites) have little to no metal content, and as such have relatively low thermal conductivities. What effect does the inclusion of high metal content in the composite matrix have on wire burn rate enhancement effectiveness? Typical metals included in composite propellants include aluminum and boron. Does the addition of a metal powder with high thermal conductivity affect the propellant burning rate modification as much as would be expected?

- *Applications to novel propellant development:* The Caveny-Glick model assumes a homogeneous, isotropic propellant, but is often applied to composites. Kubota's work [11] focused on wire enhancement of burning rates for double-base propellants. Does the addition of highly conductive wire have a strong effect on propellants with extreme values of k_f (e.g., pressed nanometallics, pressed AP/Al)?
- *Use of alloys and non-standard filament materials:* King [10] and Winch [15] both illustrated the usefulness of increasing effective melting temperature by use of a self-alloying combination of silver and palladium. Other metal combinations exist that may provide a better combination of high melting temperature and high thermal conductivity, or present a reasonable cost compromise (e.g., copper). Additionally, the inclusion of nonmetallic conductive elements (e.g., ceramics) may represent a useful research topic; the inclusion of a conductive ablator or refractory material would allow the development of a smokeless high burn rate propellant ideal for use in missiles.
- *Development of processing techniques:* The major hurdle to widespread acceptance of wired endburning motors lies in processing and handling concerns – namely, separation of the wire from the propellant grain during thermal cycles. Debonded wires significantly reduce the effect on propellant burn rate. Chemical bonding agents are commercially available for inclusion of inorganic materials in composite propellant matrices (e.g., HX-752 and HX-878); could a similar compound be developed to chemically involve the wires in the propellant grain? What processes (etching, removal of oxide coatings) could be used to improve mechanical bonding between the wire an the propellant grain? Would processing the propellant in a resonant vibratory mixer (rather than a standard planetary mixer) allow a more consistent final product?

Much has been reported in the literature on the use of wires for increasing the burn rate of a solid propellant grain, yet the application of the technology is still in its infancy. As the need for safer high burn rate propellants becomes greater, further investigation of burn rate enhancement using wires seems extremely worthwhile.

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