Comparing the two Mach number cases, observe that for the higher Mach number case the amount of deflection of angle β_t is less for a specific β_b than for the corresponding β_b in the lower Mach number case.

Varying Freestream Mach Numbers

It will most likely be the case that when a hypersonic vehicle changes its flight Mach number it will also be changing its angle of attack, thus changing θ_i. The effect that changes in θ_i have on β_t at fixed M_∞ is shown in Fig. 3b.

First note the familiar result that at high M_∞ the effect that a change in θ_i has on β_t becomes relatively independent of the flight Mach number. In addition, note the general trend that, at large θ_i, a slight change in θ_i has more of an effect on β_t than for smaller θ_i. It is also shown in this plot that, over all probable flight Mach numbers and all probable inlet deflection angles of a transatmospheric vehicle, the transmitted shock angle can vary by as much as 20 deg for ratio of specific heats, γ, equal to 1.4.

Conclusions

This work has shown that whenever the inlet bow shock strikes the cowl bow shock near its stagnation region the transmitted shock angle will be very sensitive to small upstream variations. It was also noticed that, as the freestream Mach number increased, the shock/shock interaction exhibits a Mach number independence, in that the variations in the transmitted shock angle become less dependent on Mach number variations as the Mach number increases. On the contrary, at small supersonic freestream Mach numbers, small changes in the freestream Mach number and small changes in inlet deflection angle result in large changes in the transmitted shock angle.

In order to minimize the motion of the transmitted shock angle over a large range of flight Mach numbers the inlet deflection angle should be as small as possible; at large inlet deflection angles, θ_i, small changes in θ_i have a strong effect on the transmitted shock angle.

There remains a question as to the source of the unsteadiness associated with the type IV supersonic jet. This unsteadiness may be attributed to freestream disturbances or from the dynamics associated with the jet itself. This work suggests that upstream disturbances may be amplified in the shock/shock interaction region, producing "apparent" unsteadiness, although it is probable that the jet unsteadiness is due to a coupling of these two effects.

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Influence of Metal Agglomeration and Heat Feedback on Composite Propellant Burning Rate

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Introduction

THE combustion behavior of metals, particularly aluminum, in solid propellants has been studied extensively.[1] Most studies have aimed at understanding the agglomeration and ignition mechanisms with the hope of being able to reduce the extent of agglomeration at the propellant surface and thereby improve combustion efficiency.[2] Another aspect of metal combustion in solid propellants that has not received as much attention is the influence of the metal behavior on the burning rate of the propellant. While some progress has been made in this area, the role of metal combustion on propellant burning rate is still not clearly defined.

Metal addition affects several propellant properties that can influence the burning rate. Metal staples and wires embedded in propellants have the effect of increasing the propellant thermal conductivity in the direction normal to the regressing surface, which increases burning rate. Metal addition can also change the propellant stoichiometry and, thus, burning rate, depending on what ingredients the metal replaces in the formulation. Another factor associated with metal addition that may alter the burning rate is oxidation of the metal. Either slow or fast oxidation of the metal agglomerates as they reside on or near the surface of the propellant will tend to increase the propellant burning rate by transferring heat to the propellant.[1,3] Another way metals can affect burning rate is through the inert heating (or heat sink) effect. Until they ignite and move out of range of the hot AP/binder flames near the propellant surface, metal agglomerates can act as a heat sink, siphoning off energy from the primary AP/binder flames that otherwise would have gone to increase the burning rate of the propellant.[3,4] Radiative feedback from burning metal droplets can also enhance the burning rate. Recently, Ishihara et al.[5] used fiber optics to measure radiative feedback and microthermocouples (5-μm wire) to measure conductive heat feedback in AP/HTPB/Al propellants. Their results showed that with 20% Al loading at 1 MPa, radiation accounted for 26% of the total heat feedback.

Procedure

In this study, propellants were formulated varying only the metal content and type of metal. The AP-binder mass ratio

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was fixed (4.385:1). The ratio of coarse to fine AP was kept constant at 7:3. The AP was provided by Kerr-McGee. The coarse AP was 400-μm Rotary Round, and the fine AP was 90 μm. The AP was coated with tricalcium phosphate (TCP). Hydroxyl-terminated polybutadiene R-45 was used as the resin, and isophorone diisocyanate, IPDI, was used as the curative to produce the HTPB binder. The metal loading was varied from 0 to 30% in increments of 10%. Two types of metal were used: Alcoa 123 Aluminum and A.D. Mackey Mg-Al alloy. The alloy was 10% Mg and 90% Al. The alloy was sieved to match the size of the aluminum. Both the aluminum and the alloy size distributions were found using a Coulter Counter. The median diameter of the Alcoa 123 Aluminum was 13 μm, and of the alloy was 19 μm. The distributions were similar.

Propellant samples with dimensions 10 × 10 × 3 mm were mounted to a stainless steel plate and suspended inside a quartz tube. The propellant was attached to the plate by using three pins protruding from the plate. To eliminate foreign particle contamination of the quench bath, an Nd-YAG pulsed laser was used as the ignition source. The quartz tube was used to direct the flow of products downward into the bath. Buffered ethanol was used as the quench bath fluid. The buffer (ammonium acetate) was used to neutralize the HCl present in the products. Before the test was run, particulate contaminants above 2 μm were removed from the quench bath fluid by filtering. Collected samples were analyzed within 4 h for particle-size distribution using a Coulter Counter. To check the effect of aging, a sample was analyzed after 3 days, and no significant changes in the distribution were noted.

Burning rate was measured using a standard strand burner in conjunction with a video cassette recorder. The strands were 6 × 2 × 15 mm. It should be noted that with this small width, radiative and convective losses result in a lower measured burning rate than the actual burning rate. However, the same physical trends should be seen. The strands were coated with a thin film of petroleum jelly to inhibit the ignition of the sides of the propellant.

Results

The results of the particle size analysis are given in Table 1. There was a tendency for the propellants to produce a bimodal size distribution of metal particles leaving the propellant surface. A first peak in the distribution occurred at approximately the size of the ingredient metal, 20 μm, and a second peak occurred at much larger values, 100–200 μm. The first peak was thought to correspond to unagglomerated particles and the larger peak to agglomerates. As the metal content increased from 10 to 30% and as the pressure increased from 1.83 MPa (250 psi) to 5.27 MPa (750 psi), the number mean agglomerate size increased while the volume mean agglomerate size stayed relatively constant. These trends reflect an increase in the number of 130–180-μm agglomerated particles and a decrease in the number of 20-μm ingredient particles as pressure and metal loading increase. For either pressure tested (1.83 or 5.27 MPa), for any metal loading (10, 20, or 30%), and for either metal (Al or Mg-Al), the volume mean agglomerate size was relatively constant at 180 ± 20 μm with the notable exception that for 10% Al at 5.27 MPa the volume mean agglomerate size dropped to 100 μm (Table 1). This anomaly for 10% Al at 5.27 MPa is discussed further in connection with the burning rate results.

The variation of burning rate with metal loading is shown in Table 1 and Fig. 1. In general, the first addition of metal increased the burning rate. Further additions decreased the burning rate. The addition of any amount of metal (either Al or Mg-Al) decreased the pressure exponent. At 1.83 MPa, the influence of adding pure aluminum on burning rate was minimal, with only a slight increase in burning rate at the 10 and 20% Al loadings. With Mg-Al alloy, the burning rate at 1.83 MPa increased significantly at all metal loadings. At 5.27 MPa, the burning rate was relatively constant with Mg-Al loading while the burning rate for the aluminized propellants dropped sharply between 10 and 30% Al.

The increase in burning rate at 1.83 MPa for the Mg-Al propellants over that of the nonmetalized propellant is thought to be associated with enhanced heat transfer from the oxidizing/combusting Mg-Al alloy particles at the surface of the propellant. The Mg-Al propellants showed a greater burning rate enhancement than the Al propellants due to a lower ignition temperature for the Mg-Al agglomerates that ignite and depart the propellant surface at a lower temperature than pure Al agglomeratures.[6] Thus the Mg-Al agglomerates represent less of a heat sink siphoning energy from the AP/binder flames and possibly also provide more heat feedback than the Al agglomerates.

As the pressure increased from 1.83 to 5.27 MPa, the burning rate of the nonmetalized propellant increased 82% from 0.33 to 0.60 cm/s. This increase is due to an increase in conductive heat feedback from the AP and AP/binder flames. The burning rate of the Mg-Al propellants, however, increased by only 53%, indicating that the increase in Mg-Al metal heat feedback was not proportional to the increase in feedback from the AP/binder and AP monopropellant flames. The increase in burning rate of 53% for the Mg-Al propellants was constant for all three metal loadings, and the volume mean agglomerate size was also relatively constant at 180 ± 20 μm. Table 2 shows that the change in volume mean agglomerate size for the Mg-Al propellants was at most 24%. This indicates that if any difference in metal heat feedback (and thus burning rate) were anticipated on the basis of a difference in agglomerate size, it would not be observable in the Mg-Al propellants.

For the Al propellants, however, the increase in burning rate in going from 1.83 to 5.27 MPa did vary depending on

Table 1 Volume- and number-weighted median particle sizes (μm) and burning rate r

Propellant	P, MPa	Volume	Number	r, cm/s
0% metal	1.83	—	—	0.332
10% Al	1.83	181	29.3	0.365
20% Al	1.83	196	72.9	0.364
30% Al	1.83	169	137	0.330
10% Mg-Al	1.83	187	18.5	0.404
20% Mg-Al	1.83	155	16.3	0.411
30% Mg-Al	1.83	191	121	0.395
0% metal	3.55	—	—	0.469
10% Al	3.55	—	—	0.480
20% Al	3.55	—	—	0.422
30% Al	3.55	—	—	0.405
0% metal	5.27	—	—	0.601
10% Al	5.27	103	14.2	0.603
20% Al	5.27	201	184	0.520
30% Al	5.27	186	138	0.464
10% Mg-Al	5.27	205	152	0.619
20% Mg-Al	5.27	205	176	0.632
30% Mg-Al	5.27	179	125	0.595

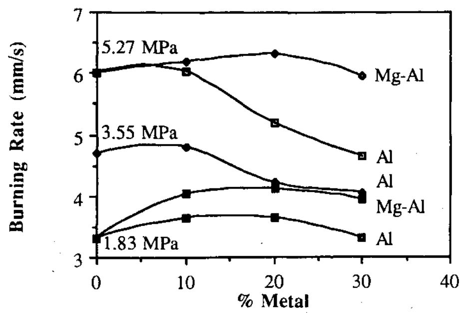

Fig. 1 Burning rate vs metal loading.

Table 2 Correlation between increase in burning rate and change in volume agglomerate size going from 1.83 to 5.27 MPa (250 to 750 psi)

Propellant	Increase in burning rate, %	Decrease in agglomerate size, %
0% metal	82	—
10% Al	65	76
20% Al	43	2
30% Al	44	9
10% Mg-Al	53	−9
20% Mg-Al	54	−24
30% Mg-Al	51	7

metal content. At 20 and 30% metal loading, the Al propellant burning rate increased by about 44% in going from 1.83 to 5.27 MPa while the volume average agglomerate size was constant at about 180 ± 20 μm. This increase of 44% for the Al propellants is less than the increase of 53% for the Mg-Al propellants, which is consistent with the hypothesis that the Al agglomerates either had a higher ignition temperature than the Mg-Al agglomerates or were otherwise less effective at transferring heat to the propellant for a fixed agglomerate size. At 10% metal loading, the burning rate of the Al propellants increased by 65% in going from 1.83 to 5.27 MPa, which is even greater than the 53% increase exhibited by the Mg-Al propellant. However, the volume mean agglomerate size for 10% Al at 5.27 MPa dropped by 76% to 100 μm (Tables 1 and 2). This would suggest that either the ignition temperature of the agglomerates decreased with decreasing agglomerate size or the heat feedback from the agglomerates increased with decreasing agglomerate size. This correlation between burning rate and agglomerate size is illustrated in Table 2. There is no obvious reason why the particular case of 10% Al at 5.27 MPa should be so different from the other runs in terms of agglomerate size and burning rate, and one might be inclined to suspect the data except for the fact that anomalous values were obtained for both burning rate and agglomerate size, which represent independent measurements.

It should also be pointed out that these results give some insight into the relative importance of the change in overall propellant stoichiometry and propellant thermal conductivity associated with metal addition that have been mentioned as possible factors for influencing burning rate. The differences between the burn rates of the Al propellants and the Mg-Al propellants at 5.27 MPa for 20 and 30% metal show that the change in burning rate with addition of metal is probably not a result of a change in propellant overall stoichiometry or thermal conductivity since the stoichiometry and conductivity of two metalized propellants (one containing 10% Mg-Al and the other containing pure Al) with the same metal loading are about the same, but the difference in burning rate is quite substantial. This indicates that the difference in burning rate must be more related to a difference in agglomerate ignition temperature (which may be a function of agglomerate size as well as metal type) and/or a difference in heat transfer from the agglomerates to the propellant.

Summary and Conclusions

The influence of aluminum and Mg-Al agglomeration on propellant burn rate was studied by measuring agglomerate size and burn rate in a series of AP/HTPB composite propellants. The AP/HTPB ratio was held constant so that the AP/binder flame structure would be similar for the various propellants. A correlation between burn rate and the agglomerate size was observed, indicating that smaller agglomerates are more conducive to enhanced burn rate. This effect was attributed to more efficient heat transfer from smaller agglomerates to the propellant and a smaller heat sink effect imposed on the AP/binder flames due to lower ignition temperatures for smaller agglomerates. Lower ignition temperatures for Mg-Al alloy compared with pure Al were also found to be more conducive to higher burning burn rates.

The conclusion drawn from this study is that metal heat feedback and heat sink effects are important and need to be better understood to make sense out of metalized composite propellant burning rate data. The temperature of the metal at the surface, the extent of agglomeration (i.e., percent metal participating in agglomeration), and the size of the agglomerates may be important parameters in the surface energy balance and burning rate determination. Furthermore, because the implications of these results are so significant, especially for understanding oscillatory pressure-coupled response behavior, it is recommended that further studies be conducted with more extensive variation of pressure and oxidizer size distribution.

Acknowledgments

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Effect of Gas/Particle Coupling on Combustion Efficiency in Aluminized Solid Rockets

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Introduction

SEVERAL models for predicting aluminum combustion efficiency in solid rockets have been developed. The first models were based on uncoupled particle trajectory analyses

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