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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References

[1]Price, E. W., "Combustion of Metalized Propellants," *Fundamentals of Solid-Propellant Combustion,* edited by K. K. Kuo and M. Summerfield, Vol. 90, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1988, pp. 479–513.

[2]Sambamurthi, J. K., Price, E. W., and Sigman, R. K., "Aluminum Agglomeration in Solid-Propellant Combustion," *AIAA Journal*, Vol. 22, No. 8, 1984, pp. 1132–1138.

[3]Zennin, A. A., Glaskova, A. P., Leipunskyi, O. I., and Bobolev, V. K., "Effects of Metallic Additives on the Deflagration of Condensed Systems," *Proceedings of the 12th Symposium (International) on Combustion*, Holt, Winston and Rhinehart, New York, 1968, pp. 27–35.

[4]Hardt, B. E., and Brewster, M. Q., "Investigation of Al and Mg/Al Alloy Behavior in Composite Solid Propellant Combustion," *Proceedings of the 25th JANNAF Combustion Meeting*, Chemical Propulsion Information Agency, Johns Hopkins Univ. Applied Physics Lab., Laurel, MD, CPIA Pub. 498, Oct. 1988, pp. 199–206.

[5]Ishihara, A., Brewster, M. Q., Sheridan, T. A., and Krier, H., "The Effect of Radiative Heat Feedback on Burning Rate of Metalized Propellants," *Combustion and Flame*, Vol. 84, Nos. 1 and 2, 1991, pp. 141–153.

[6]Verneker, P., "Role of Alloys in the Thermal Decomposition and Combustion of Ammonium Perchlorate," *Combustion and Flame*, Vol. 67, No. 2, 1987, pp. 163–173.

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

Eric G. Bradley* and M. Quinn Brewster†
University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

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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*Graduate Research Assistant, Department of Mechanical and Industrial Engineering. Associate Member AIAA.

†Associate Professor of Mechanical Engineering, Department of Mechanical and Industrial Engineering. Member AIAA.

and Culick's inviscid, rotational solution for gas flowfields.[1] The solutions to a large number of these runs have been used to develop correlations based on key nondimensional parameters in a rocket chamber. Hermsen[2] presented a correlation later employed by the Solid Performance Program (SPP)[3] that assumed a constant value of the oxidizer concentration factor A_k. King[4,5] developed a more realistic model that assumed that A_k varied according to the depletion of oxidizing species within a gas-particle "pocket" and hence termed his analysis a pocket model. Larson[6] included the effects of particle velocity slip and found that neglect of variations in the oxidizer concentration leads to significant errors when the combustion efficiency is substantially less than unity. One effect that has not been investigated is that of mass, momentum, and energy coupling between the aluminum droplets and the gas phase. In this study, the effect of gas/particle coupling on aluminum combustion efficiency was studied by incorporating an aluminum droplet combustion model into the two-phase, unsteady, implicit, viscous flow solver CELMINT (Combined Eulerian Lagrangian Multidimensional Implicit Navier-Stokes Time Dependent) that has been developed by Scientific Research Associates.[7-11] Appropriate modifications were made in CELMINT to account for distributed aluminum combustion.

Combustion-Flow Model

Details of the combustion-flow model have been described elsewhere.[12] Only a brief description of key terms, equations, and assumptions is given here. The propellant composition is 70% AP, 14% PBAN, and 16% $Al_{(s)}$ by mass. The gas phase reaction between the binder (PBAN) and oxidizer (AP) products is assumed to reach equilibrium (2400 K) at the propellant surface. Aluminum agglomerates formed at the propellant surface burn in a distributed fashion throughout the circular-cylindrical motor chamber. The equilibrium temperature assuming complete aluminum combustion is 3380 K. The rate of aluminum combustion is taken from the diffusion-limited droplet burning law[13] that was incorporated into SPP:

$$D^{1.8}_{Al(l)} = D^{1.8}_0\left(1 - \frac{kt}{D^{1.8}_0}\right) \tag{1}$$

$$k = 2.17 \times 10^{-5}\, R_k A_k^{0.9}\, P(\text{MPa})^{0.27}\ (\text{cm}^{1.8}/\text{s}),\ R_k = 2.7 \tag{2}$$

$$A_k = 100\,\frac{\Sigma fm_i}{1 - fm_{Al_2O_3}},\qquad i = H_2O,\ CO_2,\ O,\ OH,\ O_2 \tag{3}$$

The factor A_k is the relative percentage of oxidizer in the gas phase. A global, single-step reaction between aluminum and the restricted equilibrium products of the AP/binder flame is assumed. With this assumption, the mass generation rate of every species is proportional to the depletion rate of $Al_{(l)}$ and may be expressed in terms of the composition of the restricted equilibrium state and the hypothetical final equilibrium state. The important effect of this assumption is that all of the otherwise independent species equations collapse to a single equation. For dilute particle loadings or negligible velocity slip, this equation is equivalent to conservation of mass of the particulate phase. The Lagrangian particulate (or discrete) phase consists of the burning $Al_{(l)}$ droplets and is treated using a Lagrangian description. The Eulerian continuum phase consists of $Al_2O_{3(l)}$ particles and gas species that are assumed to be in thermodynamic and hydrodynamic equilibrium.

A circular-cylindrical chamber with a radius of 1.257 m and a length of 16 chamber radii (20 m) was chosen as the geometry for computations. A 60×60 mesh was used. Along the curved wall of the first half of the chamber wall, from the head end down to a chamber length of 8 radii (10 m), mass was injected at a constant flux as determined by the propellant burning rate. The remainder of the flow from 10 to 20 m was treated as pipe flow (no mass injection) to allow the flow to reach a fully developed condition. It was found through preliminary calculations that the added chamber with no injection was necessary to achieve solution convergence. A comparison was made between a simple flow using CELMINT without particles and Culick's inviscid, rotational solution to verify that the downstream section did not influence the flowfield solution in the upstream section.[14]

The initial aluminum droplet size was assumed to be 400 μm. This value is close to the upper limit of observed agglomerate sizes.[3] Size distribution effects were not investigated. The combustion efficiency was defined as the fraction of aluminum that burned in the chamber

$$E = 1 - \frac{m_{out}}{m_{in}} \tag{4}$$

where m_{out} is the mass flow rate of $Al_{(l)}$ droplets leaving the chamber and m_{in} is the mass flow rate of aluminum into the chamber.

Results

Figure 1 shows the particle trajectories until burnout occurs. Particle burnout occurs at about 0.35 chamber radii from the propellant surface in the radial direction. Figure 2 shows the radial variation of the oxidizer concentration factor A_k. The value of A_k is initially 46.6 at the propellant surface and rapidly drops to 20 within the first 10th of a chamber radius from the propellant surface. At a distance of 0.2 chamber radii from the propellant surface, the value of A_k is within 6% of the final value of 17.6.

To test the assumption of constant oxidizer concentration, a reacting flow case was run using a fixed value of the oxidizer concentration factor A_k. The oxidizer concentration factor was obtained from the approximate expression used in SPP,[3] Eq. (5):

$$A_k = 100\left[\left(\frac{1 - fm_{Al_2O_3}/2}{1 - fm_{Al_2O_3}}\right)\Sigma fm_i + \frac{3}{2} fm_{Al_2O_3}\right] \tag{5}$$

Equation (5) is based on an average between initial and final compositions for representative propellant compositions and gives a value of $A_k = 28$ in this case. (This value is reasonably

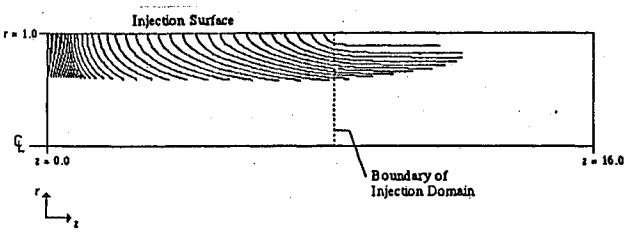

Fig. 1 Particle trajectories in combustion chamber for variable A_k (not to scale).

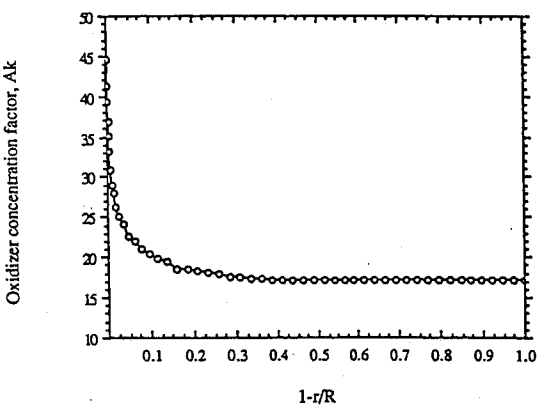

Fig. 2 Radial profile of oxidizer concentration factor A_k vs distance from propellant surface (r = radial location, R = chamber radius).

close to the actual arithmetic average value for the propellant used of $A_k = 31$.)

The results for aluminum combustion efficiency are compared in Table 1. The combustion efficiency predicted by SPP with $A_k = 28$ (98.7%) is approximately 2% larger than the CELMINT value with $A_k = 28$ (96.8%). Since the only significant difference between the two analyses is the inclusion of interphase mass, momentum, and energy coupling, the overpredicted SPP value of combustion efficiency could be attributed to the effects of particle/gas coupling. For example, energy released from the aluminum combustion would raise the continuum temperature while also decreasing the continuum density. Since the continuum density would be lower than that of an equivalent uncoupled flow, fluid velocities in the coupled analysis would be higher to conserve mass. Hence aluminum combustion efficiency would be lower in the coupled analysis due to reduced droplet residence time. In the uncoupled analysis of SPP, however, velocity increases due to the heat release effect would not be incorporated so that overpredictions in combustion efficiency would result.

To illustrate the effects of heat release on gas velocity, the axial velocity component at the exit of the injection domain for the case with variable A_k was compared with Culick's inviscid, rotational solution with initial velocities based on a gas density corresponding to the initial gas temperature (2400 K). Figure 3 shows that Culick's uncoupled flow analysis underpredicts the exit fluid velocity, as would be expected. However, if a correction is made on Culick's solution by scaling the velocity profile by the ratio of the surface fluid density to the average fluid density at the exit, then Culick's adjusted analysis agrees much more favorably with CELMINT calculations. This would indicate that the flowfield used in SPP is not accurate in accounting for energy coupling between the particle and continuum phases unless the temperature of the gas is adjusted in some manner.

Another interesting result comes from comparing the variable A_k CELMINT prediction of combustion efficiency with the constant A_k CELMINT prediction, as shown in Table 1. The variable A_k result of 92.8% is lower than the constant A_k result of 96.8% by 4%. This difference is attributable to the variation of oxidizer concentration near the propellant surface. It was shown previously in Fig. 2 that A_k rapidly drops from its initial value of 44.6 to 18 within a 10th of a chamber radius, suggesting that the average value of 28 estimated by Eq. (5) is too high. The combustion efficiency of 93.3% that results from using Hermsen's correlation with a value of $A_k = 17$ (Table 1) is more in agreement with the CELMINT value of 92.8%.

Table 1 Comparison of aluminum combustion efficiency from SPP and CELMINT for 400-μm particles

	SPP	CELMINT
$A_k = 28$	0.9871	0.9681
$A_k = 17$	0.9325	—
A_k variable	—	0.9280

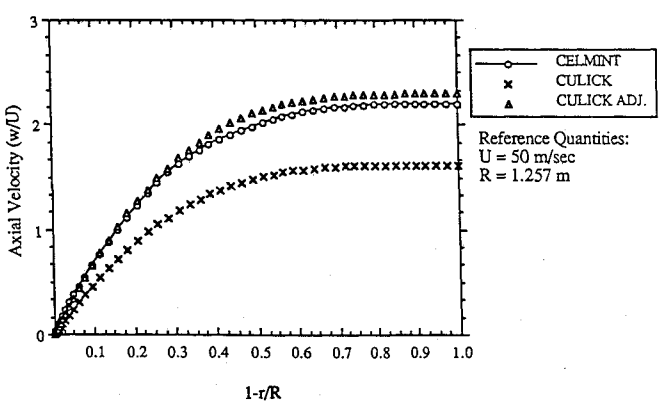

Fig. 3 Comparison of radial profiles of axial velocity w at the exit of the injection domain for CELMINT, Culick's uncoupled analysis, and Culick's analysis with adjustment for density change.

Summary

Two important conclusions may be drawn from this study. First, mass, momentum, and energy coupling between gas and particle phases is potentially important in predicting aluminum combustion efficiency in solid rocket motors, particularly with very large agglomerates (400 μm). Further study is needed to determine the impact with smaller agglomerates. Second, the use of a constant value of A_k based on an arithmetic average of initial and final equilibrium compositions results in significant overprediction of combustion efficiency. If an average value were to be used (to simplify computations), then a value weighted more towards the final value should be used.

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References

[1]Culick, F. E. C., "Rotational Axisymmetric Mean Flow and Damping of Acoustic Waves in a Solid Propellant Rocket," *AIAA Journal,* Vol. 4, No. 8, 1966, pp. 1462–1469.

[2]Hermsen, R. W., "Aluminum Combustion Efficiency in Solid Rocket Motors," AIAA Paper 81-0038, Jan. 1981.

[3]Nickerson, G. R., Coats, D. E., Hermsen, R. W., and Lamberty, J. T., Jr., "A Computer Program for the Prediction of Solid Propellant Rocket Motor Performance (SPP)," Vols. 1–5, Air Force Rocket Propulsion Lab., TR-83-036, Edwards AFB, CA, Sept. 1984.

[4]King, M. K., "Prediction of Metal Combustion Efficiency in Low Port-to-Throat Area Ratio and Nozzleless Solid Rocket Motors," AIAA Paper 82-1202, June 1982.

[5]King, M. K., "Metal Combustion Efficiency for Low L* Rocket Motors," *Journal of Spacecraft and Rockets,* Vol. 22, No. 5, 1985, pp. 512–513.

[6]Larson, R. S., "Prediction of Aluminum Combustion Efficiency in Solid Propellant Rocket Motors," *AIAA Journal,* Vol. 25, No. 1, 1987, pp. 92–101.

[7]Briley, W. R., and McDonald, H., "Solution of the Multidimensional Compressible Navier-Stokes Equations by a Generalized Implicit Method," *Journal of Computational Physics,* Vol. 24, No. 4, 1977, pp. 372–397.

[8]Briley, W. R., and McDonald, H., "On the Structure and Use of Linearized Block Implicit Schemes," *Journal of Computational Physics,* Vol. 34, No. 1, 1980, pp. 54–73.

[9]Sabnis, J. S., Choi, S. K., Buggeln, R. C., and Gibeling, H. J., "Computation of Two-Phase Shear Layer Flow Using an Eulerian-Lagrangian Analysis," AIAA Paper 88-3202, July 1988.

[10]Sabnis, J. S., Gibeling, H. J., and McDonald, H., "A Combined Eulerian-Lagrangian Analysis for Computation of Two-Phase Flows," AIAA Paper 87-1419, June 1987.

[11]Madabhushi, R. K., Sabnis, J., deJong, F., and Gibeling, H., "Navier-Stokes Analysis of Aft Dome Flowfields in Solid Rocket Motors with Submerged Nozzles," AIAA Paper 89-2780, July 1989.

[12]Bradley, E. G., and Brewster, M. Q., "A Multi-Dimensional Combustion Model for Solid Propellant Flowfields with Burning Aluminum Droplets," 26th JANNAF Combustion Meeting, Chemical Propulsion Information Agency, Pub. 529, Vol. II, Johns Hopkins Univ. Applied Physics Lab., Laurel, MD, pp. 57–68.

[13]Davis, A., "Solid Propellants: The Combustion of Particles of Metal Ingredients," *Combustion and Flame,* Vol. 7, Dec. 1963, pp. 359–367.

[14]Bradley, E. G., "Multidimensional Combustion Flow Modeling of Aluminized Solid Propellants," M.S. Thesis, Univ. of Illinois, Urbana, IL, 1990.