An Experimental Investigation of Solid-Propellant Erosive Burning in an Acceleration Field

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A technique was developed to ascertain the magnitude of combined erosive and acceleration induced burning rate increases of aluminized composite solid propellants as a function of acceleration. The results indicate that a propellant exhibits a decreased erosion sensitivity when subjected to an acceleration field which is directed normal and either into or out of the propellant burning surface.

Nomenclature

a = acceleration
a_0 = standard acceleration of gravity
B = mass flux per unit port area (lbm/in^2-sec); defined by Eq. (A4)
C = constant (sec^{-1})
g = acceleration in gravitational units a/a_0
h = channel height above the propellant sample (in.)
K = constant
r_e = erosive burning rate (in./sec)
$r_{x=0}$ = burning rate at fore end of an erosive motor (in./sec)
t = time (sec)
w = width of propellant sample (in.)
x = distance from fore end of an erosive motor (in.)
y = depth to which propellant has burned at station x (in.)
α = constant in erosive burning rate ratio equation
ϵ = erosive burning ratio $r_e/r_{x=0}$
ρ = density (lbm/in^3)

Introduction

IN a spinning rocket motor the portion of the propellant grain nearest the nozzle will experience an increased burning rate not only from the acceleration induced effects,[1,2,3] but also from the effect caused by the flow of hot gases from propellant at the fore end of the motor (erosive burning). The objective of this experimental investigation was to ascertain the magnitude of combined acceleration induced and erosive burning induced increases in the propellant burning rate as a function of acceleration level. This was accomplished by using motors in which the propellant grain was subjected simultaneously to erosive burning effects and an acceleration field directed normal to the propellant surface.

Experimental Equipment and Procedures

The burning rate experiments were conducted at the Naval Postgraduate School's Centrifuge Test Facility.[4] The centrifuge was designed to study solid-propellant burning rates at constant pressure and acceleration levels. A 1565 in.^{3} combustion bomb and surge tank system, mounted on the arm of the centrifuge, ensured essentially constant pressure during burning. The use of relatively thin, $\frac{3}{8}$ in., propellant samples at a centrifuge radius of 3 ft limited the total acceleration change during burning to less than 0.25% of the original value.

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The instrumentation that was provided for measurement of burning rate consisted of a pressure transducer to sense pressure within the combustion bomb and two timing wire circuits. Detailed information concerning the centrifuge and related equipment can be found in Refs. 4 and 5.

The propellant used in the erosive burning rate experiments was supplied by the Naval Weapons Center, China Lake, California. The specific formulation was: carboxy-terminated polybutadiene binder, 13.5%; tri-modal AP oxidizer, 69.5%; and Valley Metallurgical H-5 aluminum, 17.0%. The tri-modal AP consisted of 25% 10μ, 50% 200μ, and 25% 600μ mass mean diameter (mmd) particles. The mmd of the tri-modal AP was 195μ (micromerograph). The H-5 aluminum powder had a mmd of 7.1 (micromerograph).

Figure 1 is a schematic drawing of the motors which were used in the experiments. The motors had a port-to-throat area ratio of one. The motors were built around 0.375-in. × 0.373-in. × 2.75-in. propellant samples. Two 0.125-in. × 0.5-in. × 3-in. canvas phenolic motor side plates were secured to opposite sides of the propellant strand with RTV-102 silicone rubber (General Electric Company). The bottoms and aft ends of the motor side plates were flush with the bottom and aft end respectively of the propellant sample. A 0.025-in.-diam. hole was drilled through each of the motor side plates after the RTV rubber had cured. The holes, through which a nichrome ignition wire was threaded, were located at the fore end of the motor flush with the top of the propellant sample.

Approximately 5 mg of the Holex 14 ignitor material, moistened with a small amount of acetone, was painted on the top surface of the propellant sample for its entire 2.75-in. length. Holex 14 (Holex Inc., Hollister, California) was chosen as the ignitor because of its fast linear burning rate. Experiments showed that the entire length of the propellant sample could be ignited in less than 0.022 sec.

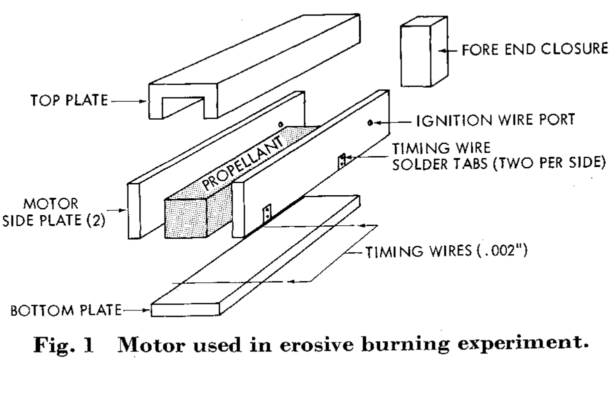

Fig. 1 Motor used in erosive burning experiment.

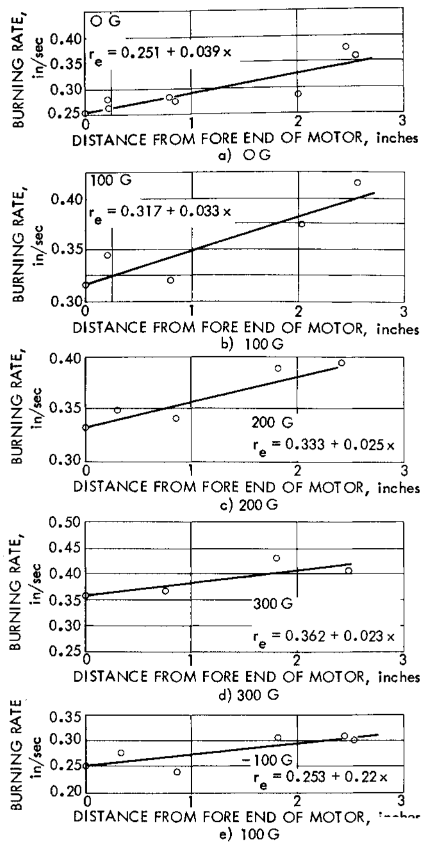

Fig. 2 Burning rate vs distance from fore end of erosive motor.

The motor top plate was a piece of 0.625-in. × 0.30-in. × 3-in. canvas phenolic in which a 0.375-in.-wide channel had been milled. The top plate was secured to the top of the motor side plates with high-temperature epoxy (APCO 210 resin and 180 hardener). The motor side plates and top plate formed a channel 0.3 in. high × 0.375-in. wide over the top of the propellant sample for its entire 2.75-in. length.

Two 0.002-in.-diam Pyro-fuse timing wires were then placed flush with the bottom of the propellant strand at known distances from the fore end of the propellant strand. The timing wires were soldered to tabs which had been cemented to the motor side plates. The 0.375-in. × 0.375-in. fore end of the propellant sample was inhibited with RTV rubber. The fore end closure, a 0.25-in. × 0.375-in. × 0.675-in. piece of canvas phenolic, was then secured to the motor side plates and top plate with APCO epoxy. The motor was completed by casting a 0.125-in. layer of Westglass 1013 laminating resin (Western Fibrous Glass Products Company) on the bottom of the propellant strand and motor side plates.

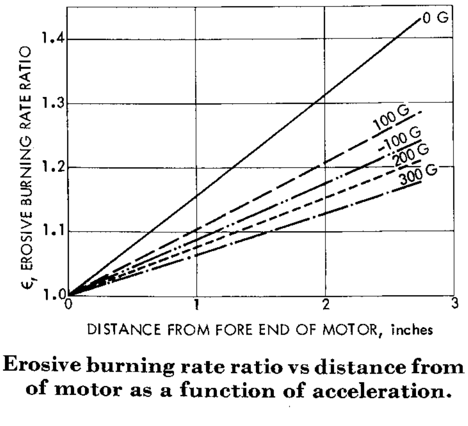

Fig. 3 Erosive burning rate ratio vs distance from fore end of motor as a function of acceleration.

Table 1 Erosive burning data

Acceleration, g	r, 0.7-in. strand	$r_{x=0}$	C	α	K
0	0.25	0.25	0.039	1.006	3.76
100	0.33	0.32	0.033	1.006	2.21
200	0.34	0.33	0.025	1.003	1.58
300	0.36	0.36	0.023	1.002	1.24
−100	...	0.25	0.022	1.004	2.34

The motor was fastened to an erosive motor mount which was positioned in the combustion bomb such that the acceleration field was directed normal to the burning surface of the propellant sample. When a motor was fired the pressure in the combustion bomb-surge tank system increased approximately 40 psia. The pressure-time trace showed a very rapid pressure rise. Ignition of the fore end of the propellant sample was assumed to take place at the beginning of this pressure rise. The average rate of combustion initiation along the top surface of the propellant was experimentally determined to be 127 in./sec. This lengthwise ignition propagation rate was taken into account in determining the average burning rate at positions removed from the fore end of the strand. This correction amounted to a change of approximately 1.0% in the propellant burning rate.

Experimental Results

The experiments were conducted at acceleration levels of 0, 100, 200, and 300g with the acceleration vector perpendicular to and directed into the propellant burning surface (defined as positive acceleration). In addition, experiments at 100g were conducted with the acceleration vector perpendicular to and directed outward from the burning surface (defined as negative acceleration). All experiments were conducted at 500 psia.

Generally two motors, each equipped with two timing wires, were fired at a given acceleration. These two motors provided four average burning rates at four different distances from the fore end of the motors. The burning rate values are shown in Figs. 2a–e. The data at each acceleration level suggest that a good first approximation for burning rate vs. distance from the fore end of the motor is a linear relationship. Accordingly, a linear least squares fit of the data to the equation $r_e = r_{x=0} + Cx$ at each acceleration level was made to obtain equations relating average burning rate to distance from the fore end of the motor.

The values of $r_{x=0}$ and C vary with acceleration level. The values of $r_{x=0}$ compare very favorably with the burning rate values obtained from 0.7-in.-length strands burned using the conventional strand-centrifuge technique discussed in Refs. 1, 2, and 5. The comparison is shown in Table 1.

Figure 3 is a plot of erosive burning rate ratio, ϵ, vs distance from the fore end of the motor, x, as a function of acceleration. The erosive burning rate ratio is defined as the ratio of the burning rate at a motor position experiencing erosive burning to the basic nonerosive burning rate of the propellant. As can be seen the erosion burning sensitivity of propellant decreases with increasing acceleration level.

Another method of presenting erosive burning rate data is as a plot of erosive burning rate ratio versus combustion gas mass flux per unit port area. The mass flux per unit area, B, is a measure of the time average mass velocity per unit port area in the flow channel above the burning propellant surface. The method used to determine values of B from the burning rate data is presented in the Appendix.

Figure 4 contains plots of ϵ vs B as a function of acceleration level. Linear least-squares fits were made to the ϵ vs B data to obtain equations of the form $\epsilon = \alpha + KB$. The values of α and K determined for each acceleration level are presented in

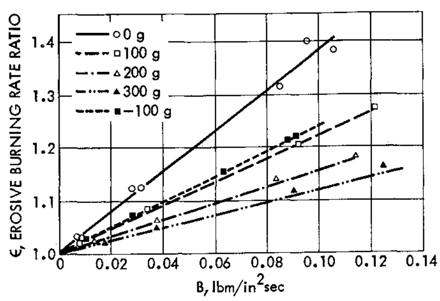

Fig. 4 Erosive burning rate ratio vs mass flux as a function of acceleration level.

Table 1. Since by definition $\epsilon = 1$ for the condition of no mass flow over the propellant surface (i.e., $B = 0$), the value of α should be exactly one. The values of α in Table 1 are very close to the expected value. The value of K decreases with increasing acceleration when the acceleration is directed into the propellant surface, indicating that the propellant becomes less sensitive to erosive effects as the acceleration level is increased. A probable explanation for the decreased erosive sensitivity is the following.

References 6 and 7 indicate that the erosive burning effect is more pronounced in slow burning propellants than in fast burning propellants. It is generally believed that the erosive effect is attributable to an enhanced rate of heat transfer to the solid propellant due to the presence of a gas flow parallel to the burning surface. Green[6] envisaged the inverse relationship between erosion sensitivity and basic burning rate as a boundary-layer effect; the greater the velocity, the thinner the boundary layer and the steeper the temperature gradient from the gaseous hot core to the cooler solid surface. Thus a fast-burning propellant would be expected to exhibit a relatively small erosion effect since the rapid evolution of gas normal to the burning surface would produce a thicker boundary layer (for a given parallel velocity) than would be obtained in the case of a slow-burning propellant. Since increasing the acceleration level results in a faster basic nonerosive burning rate and hence less convective heat transfer to the propellant surface, it follows that the erosion sensitivity of the propellant should be decreased.

In Fig. 5 are graphically presented values of K vs $r_{x=0}$ for positive accelerations. The inverse relationship between K and $r_{x=0}$ is evident. Also shown for comparison in Fig. 5 are values of K vs $r_{x=0}$ derived from data obtained by Lawrence and Deverall[8] for four different aluminized composite propellants. The values of K vs $r_{x=0}$ determined from Ref. 8 data are comparable to the values obtained during the course of this investigation.

The data obtained from experiments conducted at 100 g with the acceleration directed outward from the propellant surface indicate that the propellant in this acceleration environment has a basic nonerosive burning rate equal to the zero-g, nonerosive burning rate. However, the value of K at 100 g was 2.34, which is 38% less than the value of 3.76 obtained at zero-g acceleration. The data in Fig. 5 suggest that for a given pressure the value of K is a function of $r_{x=0}$. Since the basic nonerosive burning rates of the propellant under investigation were equal at zero g and 100 g directed out of the propellant surface, the difference in the values of K cannot be explained by differences in the basic nonerosive burning rate. However, it is probable, with the acceleration field directed away from the propellant surface, that the surface would be kept free of aluminum agglomerates, whereas at zero g an aluminized propellant is known to have aluminum agglomerates present on its surface.[9] The absence of these aluminum agglomerates on the surface could account for the smaller value of K because of the diminished heat-transfer rate.

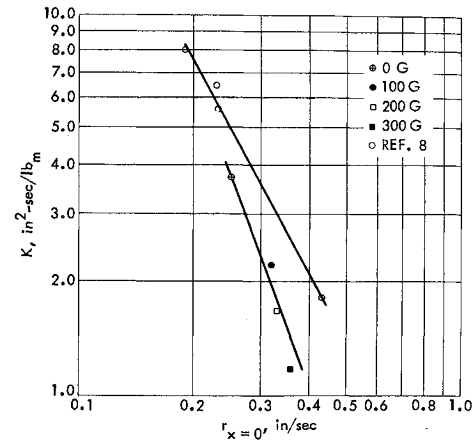

Fig. 5 Erosive constant K vs burning rate.

Conclusions

Aluminized composite solid propellants exhibit a reduced erosion sensitivity with increasing acceleration level when the acceleration field is directed normal and into the propellant burning surface. The reduction is attributed to the increased evolution of gas normal to the burning surface resulting from the higher basic nonerosive burning rate. It is concluded, on the basis of two experiments, that directing the acceleration out of an aluminized propellant surface also results in a decreased erosion sensitivity. This is probably caused by the removal of aluminum agglomerates from the propellant surface and the resulting diminished heat transfer rate from the hot reaction gases to the propellant surface.

Appendix

An expression for the mass flux per unit area, B, was derived based on the following assumptions: 1) The burning rate at a given distance from the fore end of the propellant strand can be expressed as $r_e = r_{x=0} + Cx$, where $r_{x=0}$ and C are determined from a least-squares fit to the experimental data. 2) The instantaneous burning rate at any distance x from the fore end of the propellant strand is constant and equal to the average burning rate at that x.

It follows from the first assumption that the propellant surface remains plane during burning. This allows geometric simplifications to be made in the determination of an expression for B. The second assumption was necessary because no practical way of determining instantaneous burning rate was available.

The depth to which the fore end of the propellant sample has burned after time t is given by

$$y_0 = r_{x=0}t \tag{A1}$$

The mass of propellant m which has passed the cross section at x in time is

$$m = \rho xw[(y_0 + y)/2] \tag{A2}$$

The time average channel cross-sectional area A, during propellant burning at the cross section x, is

$$A = \tfrac{1}{2}w[h + (h + y)] \tag{A3}$$

Now defining $B = m/At$ and using Eqs. (A1–A3), and the definition of t, yield after simplification

$$B = \rho x(2r_{x=0} + Cx)/(2h + y) \tag{A4}$$

References

[1] Anderson, J. B. and Reichenbach, R. E., "An Investigation of the Effect of Acceleration on the Burning Rate of Composite Propellants," *AIAA Journal*, Vol. 6, No. 2, Feb. 1968, pp. 271–277.

[2] Sturm, E. J. and Reichenbach, R. E., "Aluminized Composite Solid-Propellant Burning Rates in Acceleration Fields," *AIAA Journal*, Vol. 7, No. 11, Nov. 1969, pp. 2087–2093.
[3] Manda, L. J., "Compilation of Rocket Spin Data, Vol. II: Literature Survey," Rept. 3001-2, CR-66641, 1968, NASA.
[4] Anderson, J. B. and Reichenbach, R. E., "76-Inch Diameter Centrifuge Facility," TN 66T-4, Sept. 1966, Dept. of Aeronautics, Naval Postgraduate School, Monterey, Calif.
[5] Sturm, E. J., "A Study of the Burning Rates of Composite Solid Propellants in Acceleration Fields," Ph.D. thesis, AD-832206, March 1968, Naval Postgraduate School, Monterey, Calif.
[6] Green, L., Jr., "Erosive Burning of Some Composite Solid Propellants," *Jet Propulsion*, Vol. 24, No. 1, Jan–Feb. 1954, pp. 9–15.
[7] Wimpress, R. N., *Internal Ballistics of Solid Fuel Rockets*, 1st ed., McGraw-Hill, New York, 1950.
[8] Lawrence, W. J. and Deverall, L. I., "The Erosive Burning Behavior of Selected Composite Propellants," *Proceedings from the 4th ICRPG Combustion Conference*, Stanford Research Inst., Menlo Park, Calif., Oct. 1967, pp. 459–466.
[9] Crump, J., "Aluminum Combustion in Composite Propellants," *Proceedings of the Second ICRPG Combustion Conference*, Aerospace Corp., El Segundo, Calif., 1965.

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Particulate Matter in the Exhaust of a Boron-Loaded Solid Propellant

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Particles issuing from the primary solid-propellant combustor of a typical boron-loaded air-augmented rocket motor have been collected and analyzed for chemical composition and size distribution. It was found that substantial changes can occur in the chemical composition of the particulate effluent (notably, ammonium pentaborate and carbon were found), but the size analyses suggest that no important change in the size distribution of the remaining boron particles occurs. However, this last conclusion is subject to the uncertainties involved in any particle collection technique's influence on the size distribution results.

I. Introduction

BASIC engineering design techniques for air-augmented rockets have come under study in the last few years as a result of certain propulsion applications; in such devices a fuel-rich primary solid-propellant rocket motor is exhausted into an after-burner, or secondary combustor, where the exhaust is burned with air which is obtained from the ambient atmosphere. One of the critical design parameters is the volume or length of this secondary combustor necessary for complete combustion of the primary exhaust, and both analytical and experimental studies have been directed toward obtaining estimates of this parameter as a function of the overall engine operating parameters.[1,2]

Since the addition of boron (B) particles to the primary solid propellant has been used extensively to maintain its exhaust fuel-rich, and since these solid or liquid particles are the major combustible constituent of the primary exhaust, any analytical treatments of the secondary combustor are extremely complicated and must consider simultaneous turbulent mixing and combustion of the gas-particle flow. The conditions at the primary rocket exit serve as boundary conditions for analysis, and in this context it is of interest to characterize the state of the particles in the exit plane. In particular it is desired to know of any velocity or temperature lag of the particles, and their size and spatial distributions in the plume.

In general, because such information is not available, it has been assumed that initially the temperature and velocity of the particles equal the local values in the gas and that a unimodal size of particles is distributed uniformly over the plume.[2] Also, the chemical composition of the particles is postulated not to have changed during their residence time in the primary motor, that is, the B is assumed to remain chemically inert until it is exposed to air in the secondary combustor.

In this paper results dealing with the size distribution and chemical composition of these particles are presented. A typical B-loaded solid-propellant primary rocket was fired into a particle collection chamber, and the resulting samples were analyzed chemically by x-ray diffraction; size distributions were obtained both by electron micrography and photosedimentometry. In addition, optical methods which could lead to in situ determinations of particle size and spatial distribution in the primary exhaust have been discussed elsewhere.[3] Such methods are of interest because size measurements similar to those described here, due to unknowns such as effects of the sample collection and measurement techniques, cannot yield noncontroversial conclusions. Primarily because of the high optical depths involved in the primary motor plume, however, it was concluded that such experimental techniques would be unsuccessful.[3]

II. Experimental Apparatus

The basic design of the primary combustion chamber and the specifications of the boron-loaded propellant have been detailed elsewhere.[4] The combustor was of approximately 19 in.[3] volume when unloaded, and the propellant was mounted so as to burn in cigarette fashion. The only significant change

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Index categories: Properties of Fuels and Propellants; Subsonic and Supersonic Airbreathing Propulsion.

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