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Subatmospheric Burning Rates and Critical Diameters for AP/HTPB Propellant

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Introduction

During the development of a base-bleed artillery round, it became desirable to measure the burning rate of the base-combustor propellant as a function of pressure at pressures low enough to simulate unchoked operation at altitudes up to 10 km. The results of these burning-rate measurements for two different propellants are described in this Note. Though burning rates were the objective of this study, the tendency of small-diameter strands to self-quench led us to give some attention to critical-diameter extinction phenomena.

The burning-rate measurements were conducted in a windowed strand burner modified for vacuum operation. The samples were burned cigarette fashion with a constant-flow-rate axial shroud of nitrogen gas helping to control smoke obscuration and inhibiting flamespread down the sides of the strand (no chemical inhibition of the sides was necessary). During a run the pressure was held constant to within 10%. Ignition of the sample was achieved by a resistively heated hot wire. Combustion of the sample was recorded using time-coded video and motion-analyzed with a video coordinate digitizer. The pressure associated with each burning rate is the average pressure during the measurement interval. Further experimental details may be found in Ref. 1.

Results

Two propellant formulations were investigated. The first, designated AP-1 here, consists of 73% (by weight) ammonium perchlorate (oxidizer), 14.95% hydroxy-terminated polybutadiene (binder), 5% oxamide (burn-rate modifier), 2% iron oxide (burning-rate modifier), 2% dioctyl azelate (plasticizer), 1.4% isophorine diisocyanate (curing agent), 1% zirconium carbide (ballistic modifier), 0.3% tepan (binding agent), 0.15% agerite white (anti-oxident), 0.1% triphenyl bismuth (cure modifier), and 0.1% magnesium oxide (cure modifier). The second formulation, here termed AP-2, is the same except that the iron-oxide catalyst is omitted, being replaced with 1% AP and 1% oxamide. Strands of AP-2 were prepared employing cork borers of various diameters to core motor grains. The AP-1 tended to crack when this method was employed; therefore square strands were cut with a knife. The AP-1 strands were prepared and burned in a stable laboratory relative humidity of about 40%; however, during the AP-2 runs, the laboratory humidity increased to about 80-90%. To guard against possible inconsistencies arising from this variable, AP-2 strands were routinely placed in a desiccator after preparation and before combustion tests. Later tests showed that storage humidity did not influence the burning rate.

The AP-1 strands with 6.4-mm sides were burned with no difficulty at pressures down to 0.033 mPa and the measured burning rates are shown in Fig. 1 along with a least-squares fit to the usual power-law function. The remainder of this Note concerns only AP-2, which is the propellant of choice in the current application. AP-2 strands of 6.4 mm diam would not burn stably even at 0.1 mPa. This instability arose from the fact that this diameter is below the critical diameter for steady combustion. A plot of the burning rate as a function of strand diameter exhibits an abrupt fall-off near the critical diameter. For diameters at or slightly below the critical value, the strand typically ignites and burns about 1 cm before self-extinguishing. Over this distance the burning rate is about 85% of the value for "super-critical" (i.e., larger than critical) diameters. As the pressure decreases, the critical diameter in-

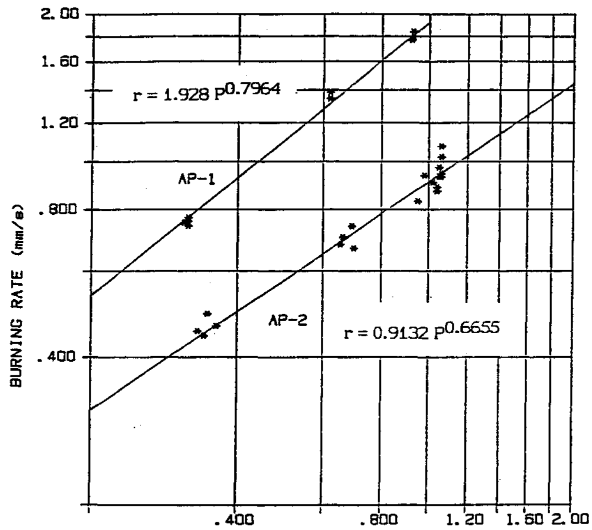

Fig. 1 Experimental burning rates and power-law fits.

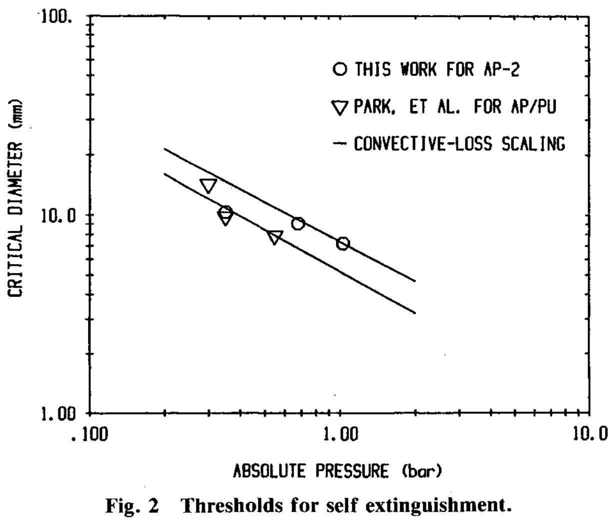

Fig. 2 Thresholds for self extinguishment.

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creases as shown in Fig. 2. The burning rates for AP-2 strands of super-critical diameters are summarized in Fig. 1.

The purge flow rate was varied from 2.5 to 10 standard liters per min (SLPM) to determine if it influenced the burning rates. Although the burning rate was not sensibly affected, there is a suggestion that the extinction diameter increases with increasing flow rate, an effect which would be consistent with a convective-cooling quench mechanism at the lateral surface of the strand.

Discussion of Critical Diameter Observations

Since the matter of critical diameters was incidental to our burning-rate objective, the resulting precision and number of measurements are not optimum for a discussion of extinction phenomena. However, the measurements can be usefully related to previous work in the same vein. A brief literature search revealed much past discussion of the circumstances and causes of pressure deflagration limits for AP and AP-based propellants but few determinations of the critical diameter as a function of pressure at the low-pressure limit.

The first and most extensive measurements were done by Cookson and Fenn[2] for AP propellants with a polyester binder. In that work, the pressure at which a square strand self-extinguishes was determined by igniting the strand at higher pressures and carefully lowering the pressure until it went out, noting the pressure at which this happened. Consistent with our results, they found that strands of their faster-burning propellant extinguished at a lower pressure than strands of the same cross-sectional area in the slower formulation. Arguing that the ratio of surface to volume of the hot gas column should be a relevant parameter if heat loss is responsible for the critical-diameter extinction, Cookson and Fenn plotted the ratio of strand perimeter to cross-sectional area vs the respective extinguishing pressure. Plotted in this way, some two dozen data points fell neatly onto two straight lines, one for each of the two formulations. The intercept of this plot, corresponding to strands of infinite diameter, occurred at a finite value of pressure, which was presumed to be "the" low-pressure deflagration limit for one-dimensional combustion. Plotting the reciprocal of critical diameter from our Fig. 2 vs pressure places the infinite-diameter intercept for our data at negative pressures even taking the uncertainties of our go/no-go method into account. Likewise, Park et al.,[3] using both the dynamic method of Cookson and Fenn and a go/no-go method, failed to find a positive value for the extinction-pressure intercept. Thus, the low-pressure deflagration limit cannot be reliably obtained by this linear-extrapolation scheme.

The notion of convective heat loss as a mechanism for critical-diameter extinction can be pursued further, however. If one assumes that convective cooling of the surface and subsurface layers is responsible for the diameter-extinction phenomenon, and estimate of its pressure dependence can be made by the following arguments. The heat generation at the surface is proportional to the cross-sectional area of the strand. The convective heat loss from the lateral surface of the strand is proportional to the perimeter of the strand multiplied by the depth of the heated layer, which can be approximated by the ratio of thermal diffusivity to near burning rate. If one assumes that the strand extinguishes when the ratio of heat generated to heat lost falls below some critical value, one finds that the critical diameter should be inversely proportional to the burning rate just prior to extinction. Since we found experimentally that the burning rate falls off very abruptly as a function of strand diameter near the extinction diameter, we may use the super-critical, burning-rate pressure dependence in this relation. This functional dependence is shown in Fig. 2 for both our data and those of Park et al.[3] (who used an AP propellant with polyurethane binder) normalized in each case to the point at highest pressure. In both cases, the convective-loss scaling is in rough accord with the data. (Unfortunately, burning rates for the Cookson and Fenn data were not given in the same pressure range as their diameter-extinction data.) The fact that the faster-burning AP-1 did not self-extinguish is quantitatively consistent with this scaling law. In the large-diameter limit, the scaling is expected to break down as the mechanism for the low-pressure deflagration limit assets itself. In the small-diameter limit, the above scaling is likely to underestimate the critical diameter because the actual heat-generation area falls below the cross-sectional area due to the growing thickness of the cooled lateral layer relative to the strand diameter. One would also expect that square strands might behave differently from cylindrical ones in the small-diameter limit because of the nonuniform thickness of this lateral layer in the former case. (Both data sets in Fig. 2 are for cylindrical strands.) Though probably oversimplified, this analysis does show that the diameter-extinction data are consistent with a convective cooling mechanism.

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