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Breakup of Al/Al_2O_3 Agglomerates in Accelerating Flowfields

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Aluminized propellants often produce large Al/Al_2O_3 agglomerates which burn slowly compared to rocket motor stay times. Two-phase flow velocity lags in the nozzle cause breakup of sufficiently large agglomerates and thereby permit reasonable combustion efficiencies to be achieved. High-speed photographs of the agglomerate processes in a windowed rocket motor were used to obtain data on breakup as a function of agglomerate size and two-phase flow velocities. The breakup process produces a cloud of much smaller droplets. A correlation of the minimum agglomerate size for breakup was obtained in terms of the ratio of Al/Al_2O_3 surface tension and shear forces. Generally, agglomerate breakup occurs when the Weber number exceeds the range of 20 to 30.

Nomenclature

C_D = drag coefficient
d_{ag} = diameter of agglomerate, m
F = drag force on agglomerate, N
M = Mach number
Re_d = Reynolds number based on diameter of agglomerate
u = velocity, m/s
We = Weber number
ρ = density, kg/m^3
σ = surface tension, N/m

Subscripts

ag = agglomerate
g = gas

Introduction

THE burning of aluminized propellants often produces relatively large Al/Al_2O_3 agglomerates which are entrained in the flow stream. Each agglomerate may contain thousands or even millions of the original aluminum particles which were added to the propellant. For solid propellants, agglomerate size depends on many factors; e.g., the propellant type, original particle size, chamber pressure, burning rate, and aluminum concentration. In general, the chamber pressure effect is one of the most prominent parameters: as chamber pressure (and burning rate) increases, the agglomerates become smaller.[1,2] Recent studies revealed[2,3] that agglomerates produced by burning a double-base propellant containing relatively small aluminum particles (i.e., original size of ~ 6 μm) were especially large as they entered the flowfield; typically, they achieved a mean size diameter of ~ 250 μm at 7 MPa (~ 1000 psi) and ~ 600 μm at 4 MPa. Observations and calculations based on a combustion model of Al/Al_2O_3 agglomerates[1] indicate that only a small fraction of the Al in such large agglomerates has time to burn inside the chamber of high performance motors. Taking into account the unburned Al, a large reduction in the motor performance compared with the theoretical would occur. Studies[4] of the overall combustion efficiency of aluminized propellants burning in rocket motors reveal the performance losses due to incomplete combustion of aluminum and particle lag.

It has been hypothesized that the two-phase flow processes in the nozzle produce breakup of sufficiently large agglomerates and thereby permit reasonable combustion efficiencies to be achieved. However, until now, direct observations of agglomerate breakup under rocket motor nozzle flow conditions did not exist.

Experimental Approach

In order to visualize the breakup processes and to obtain data on breakup as a function of agglomerate size and flow conditions, experiments were conducted using a two-dimensional windowed rocket motor (see Fig. 1). A graphite test section with gradual slopes in the convergent section (e.g., half angle of 15 deg) was located in the motor chamber and permitted flow velocities as high as Mach 0.2. Since the desired magnification of the images on the 16 mm film was approximately one, the size of the graphite test section was designed to fit within a 9×15 mm field of view. Typical cross-sectional dimensions for the throat were 3×3 mm. Several nozzle and propellant grain configurations were used to vary the two-phase flow conditions. The front wall of the nozzle was made of tempered glass. The agglomerates burned in the flow and were self-illuminating and, thus, they could be photographed at 4000-5000 pictures/s, without external lighting. Only a portion of the propellant grain was aluminized so that no more than a few agglomerates were in the field of view at any time.

The maxtrix propellant was the same as used in Refs. 2 and 3 experiments. It contained 53.7% nitrocellulose, 39.3% trimethylolethane trinitrate, and 7.0% triethylene glycol dinitrate. The aluminized portion of the propellant grain contained 13% aluminum. Since only about 10% of the propellant grain was aluminized, the chamber gas temperature was approximately 2500 K. However, the oxidizing potential of the chamber gases was high and the agglomerates

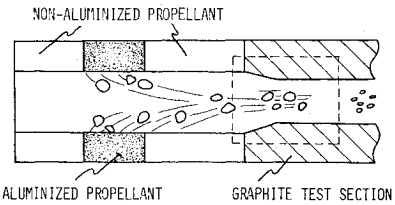

Fig. 1 Laboratory apparatus for observing agglomerates in accelerating subsonic flowfield.

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burned with a surface temperature in excess of 3600 K. The movement of the large burning agglomerates in the convergent section of the nozzle can be seen very distinctly in the films. At sufficiently high two-phase flow lags the agglomerates begin to be deformed and then suddenly (within ~0.2 ms) break up. The result is a large number of much smaller agglomerates. On the film it is seen as a sudden expansion of the flame. Each film sequence reveals a variety of events; e.g., breakup of the larger agglomerates, smaller agglomerates passing through the nozzle without break up, medium size agglomerates deforming but not breaking up, agglomerates colliding with the wall and being deflected (with or without breakup), and agglomerates adhering to the wall.

The Weber number,

$$We = d_{ag}\rho_g (u_g - u_{ag})^2/\sigma$$

which is the ratio of inertial forces to surface tension forces, was found to be a good correlation parameter. The surface tension of Al_2O_3 at 2300 K is 0.69 N/m (summarized in Ref. 5). The surface tension of aluminum is between 0.85 and 0.90 N/m in the temperature range of 970 to 1020 K (tabulated in Refs. 5 and 6). The surface tension of Al_2O_3 was used in the calculations. Although during steady state burning the molten alumina coating on the agglomerate concentrates in a local region (see Ref. 7), the surface tension of the remaining molten aluminum should be of the same order. It is known that for low *We* numbers, droplets are spherical. They tend to distort when the Weber number exceeds about 4. The distortion increases with increasing *We* until breakup occurs in the range of $We = 12\text{-}20$. Similar arguments are given in Ref. 8 for theoretical calculations of the maximum size of Al_2O_3 droplets passing through a rocket nozzle. However, the emphasis of Ref. 8 was on explaining the particle sizes of agglomerates after they passed through the nozzle. Several sections of Ref. 9 survey droplet behavior in combustion gas flows.

Figures 2-4 are prints of consecutive high-speed film images showing agglomerates in the test section. Because of their brightness, the agglomerate diameters appear to be 10-20% larger than the actual diameters. Also, direct projection of the original high-speed sequences reveal much more detail than the prints such as those in this paper. Figure 2 is a typical sequence of a relatively large agglomerate being accelerated and breaking up after it has been subjected to the maximum two-phase fow lag which occurred at the throat. Figure 3 shows two sequences resulting in breakup and gives a good indication of the degree of dispersion following breakup. Figure 4 illustrates the variety of events which are observed.

The particle paths of over 70 agglomerates were measured on a frame-to-frame basis and used to calculate the agglomerate velocities. The gas velocity through the nozzle was calculated taking into account the flow area restriction due to the agglomerates. The Weber number was calculated along the direction of flow and usually achieved its maximum value at the beginning of the parallel sided throat. Figure 5 illustrates the results of the data reduction for a single agglomerate in which breakup was not observed. Note that the velocity differential between the gas and agglomerate is approximately 10 to 1.

Figure 6 summarizes results obtained from four tests and demonstrates that agglomerate breakup usually occurs when a critical Weber number of approximately 28 is exceeded. Thus, the observed critical Weber number is close to the maximum

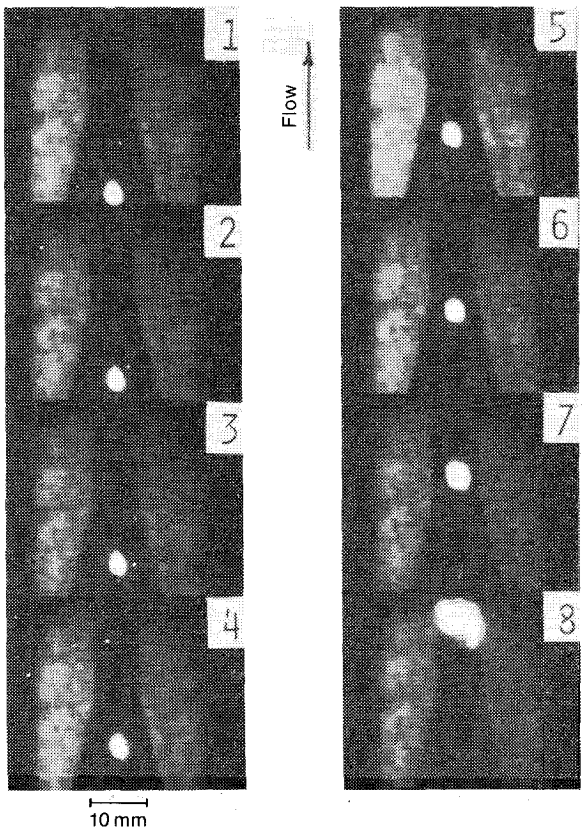


Fig. 2 Sequence of prints from high-speed film showing agglomerate being accelerated and breaking up in subsonic nozzle.

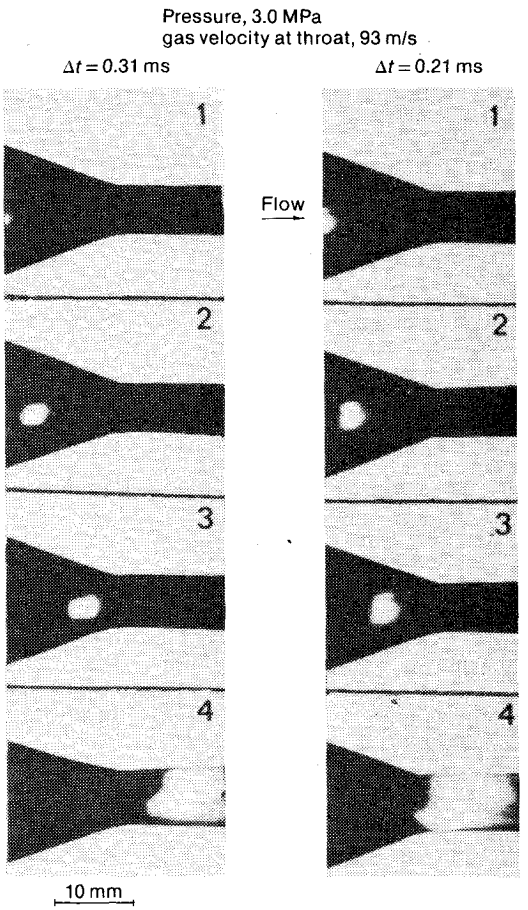
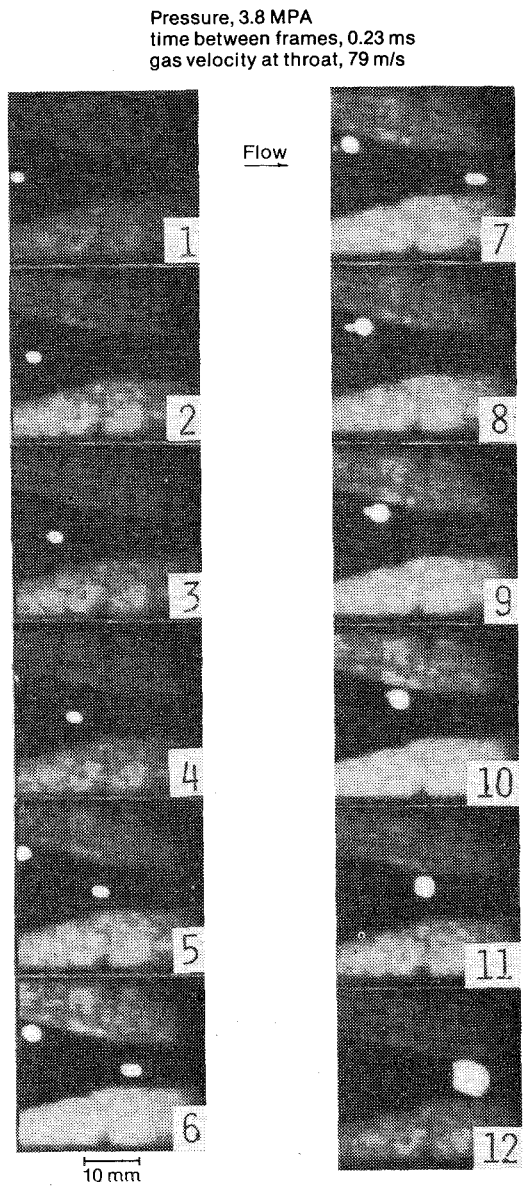


Fig. 3 Agglomerates breaking up in nozzle.



—First agglomerate (830 μm) does not break up.
—Second agglomerate (120 μm) possibly interacts with wall prior to breaking up.
—Third agglomerate (500 μm) overtakes larger second agglomerate.

Fig. 4 Examples of events observed in high-speed films.

values observed in less hostile environments for carefully characterized liquids. Because of the uncertainty in the agglomerate diameter and composition, the calculated Weber numbers are probably systematically high.

The breakup time of a droplet suddenly exposed to a gas stream[9] has been approximated as

$$t_b \simeq \frac{d_{ag}}{2(u_g - u_{ag})}\left(\frac{\rho_{ag}}{\rho_g}\right)^{1/2}$$

For the experimental conditions considered in this paper, t_b is approximately 0.1 ms, which is very consistent with the breakup events observed in the experiments.

Analysis

For the purpose of approximating the influence of the gas flow on the molten agglomerates, calculations of the mean gas flow properties and agglomerate behavior along the nozzle were performed using the stagnation properties of the gas in the combustion chamber and one-dimensional flow approximations along the nozzle. Gas velocities, agglomerate velocities, and agglomerate burning process vs axial distance were calculated. The correlations of Ref. 1 were used to calculate the agglomerate burning times. The drag force on the burning agglomerates was approximated as

$$F = 0.5 C_D \rho_g (u_g - u_{ag})^2 (\pi/4) d_{ag}^2$$

where (see Ref. 7, p. 70)

$$C_D = 27/Re_d^{0.84} \quad \text{for } Re_d \leq 80$$

$$C_D = 0.271\, Re_d^{0.217} \quad \text{for } 80 < Re_d < 10^4$$

and

$$C_D = 2.0 \quad \text{for } Re_d \geq 10^4$$

A check on the consistency of the agglomerate mass and two-phase flow lags was obtained by comparing the calculated and measured agglomerate flow velocities.

As an example, the analysis was applied to representative full-scale combustion chamber conditions which result from an aluminized double-base propellant (at 7 MPa and 3200 K) and a nozzle with the following characteristics: throat diameter, 10 cm; convergence angle, 60 deg; divergence angle, 15 deg. Figure 7 shows the variation of the gas and agglomerate velocities if the agglomerates did not break up for a range of initial agglomerate diameters. The differences between the gas and agglomerate velocities develop very rapidly for the larger agglomerates. In this example, if no breakup occurred, the fraction of unburned aluminum would

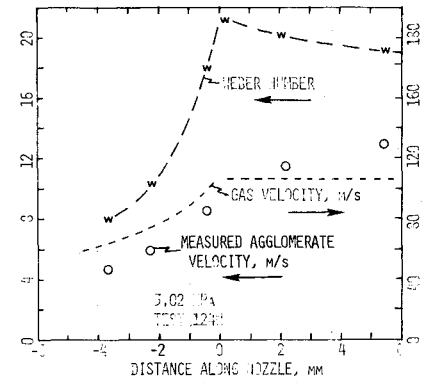


Fig. 5 Measured particle velocity, calculated gas velocity, and corresponding Weber numbers for agglomerate that did not break up (580 μm size).

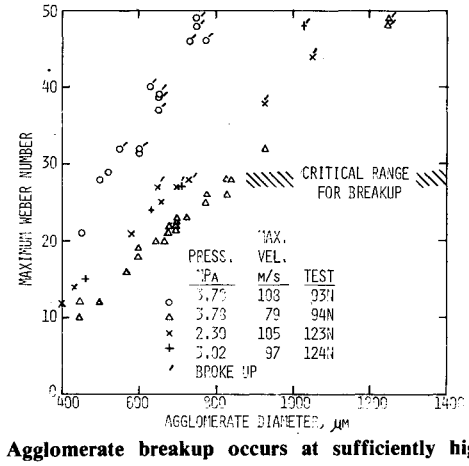


Fig. 6 Agglomerate breakup occurs at sufficiently high Weber numbers.

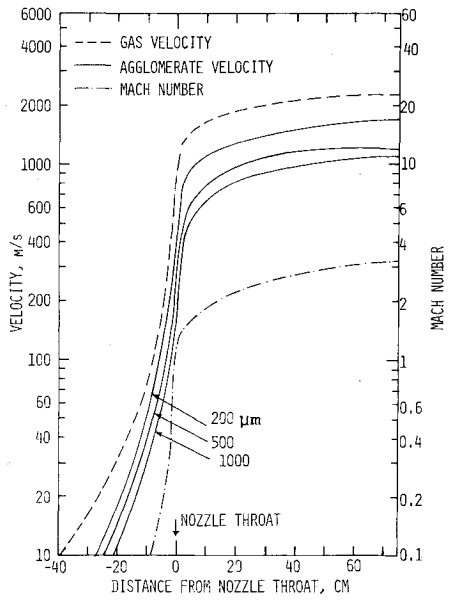


Fig. 7 Calculated gas and agglomerate velocities along the nozzle. Numbers show the agglomerate size entering the nozzle.

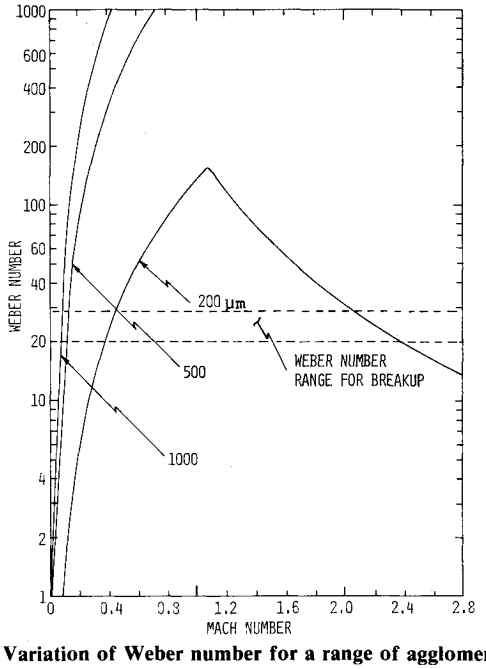


Fig. 8 Variation of Weber number for a range of agglomerate sizes entering the nozzle.

be very large, e.g., 80% for 1000 μm agglomerates and 55% for 500 μm agglomerates. If no other mechanism enhanced the aluminum burning rate, the aluminum would be very poorly utilized and the specific impulse efficiency would be unsatisfactory.

Examination of the Weber number along the nozzle (Fig. 8) reveals a very rapid increase toward the nozzle throat. Using a critical Weber number range for breakup, $We = 20\text{-}30$, one finds that the larger agglomerates (~ 1000 μm) exceed this range in the first section of the convergent part of the nozzle (at $M \simeq 0.08$), those of 500 μm at $M \simeq 0.1$, and the agglomerates of 200 μm at $M \simeq 0.5$. Agglomerates of 100 μm or less should burn completely before entering the throat.

Conclusions

In the process of developing an approach for studying agglomerate behavior in accelerating flowfields, both experiments and analyses were performed. Calculations show that in a rocket motor flowfield the burning agglomerates are subjected to shear conditions (expressed as Weber numbers) which increase rapidly as the larger agglomerates enter the nozzle and experience critical conditions for droplet breakup. The experiment for studying agglomerate breakup produces accelerating flowfield and shear flow conditions that approximate those in rocket motor chambers. The experiments revealed that as the flow accelerated, the velocity differential between the agglomerates and the gas deformed the agglomerates, causing them to break into small droplets which burn much more rapidly. Thus, the molten agglomerates behave in a manner similar to liquid droplets in less hostile environments. The process observed during this study is the previously hypothesized mechanism permitting efficient combustion of large agglomerates under rocket motor conditions.

Rocket motor performance conclusions cannot be based only on the dimensions of agglomerates leaving the propellant surface; the important effect of the accelerating flowfield on the moving agglomerates must be considered also, and agglomerate breakup criteria are required. If agglomerate breakup results in sufficiently small droplets, the agglomerates can burn inside the nozzle and, hence, the motor efficiency increases.

Acknowledgment

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