N95- 70890

A Laser-Based Sizing/Velocimetry Technique to Investigate the Secondary Atomization of Aluminum Gel Propellants

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SUMMARY:

A laser-based, forward-scatter diagnostic technique, employing a single laser sheet, has been developed to simultaneously measure the size and velocity of individual 10-150 μm droplets in a dilute polydisperse droplet stream (<1000 particles/cc) and to detect the presence of burning aluminum in these same droplets. Spectral emission from aluminum vapor in the 390-400 nm wavelength region is used as an indication of burning aluminum. The technique utilizes a 4-mm uniformly illuminated probe volume, eliminating trajectory-dependent particle sizing and size-dependent system detection bias. Particle sizing is based on a correlation of particle size with near-forward scattered light intensity. Calculations show average particle sizing variation to be within 3.5% over the expected range of refractive indices. Calibrations using a range of optical pinholes (10-100 μm) were used to verify the above sizing correlation.

DISCUSSION:

Recent theoretical rocket performance studies indicate that aluminum gel propellants, consisting of very fine solid particles suspended in a gelled liquid propellant, may offer increases in engine specific impulse and/or propellant density over conventional liquid propellants.[1-3] Increased propellant combustion times and condensed Al_2O_3 particles in the flowfield, however, may result in sufficient performance losses to eliminate the potential performance gains of aluminum gel propellants.[4] One potential mechanism for reducing these losses is to burn smaller droplets, but the viscous nature of gel propellants may make fine gel atomization difficult to achieve. Fortunately, secondary atomization, in which a droplet spontaneously shatters into a number of smaller droplets due to an internal vaporization of the liquid carrier, may produce the desired small droplets.

Previous research on secondary atomization,[5-7] however, has focused primarily on large droplets (200-1200 μm), while practical applications will require smaller droplets (10-150 μm).

Since small-droplet secondary atomization may differ from that of large droplets, primarily due to a difference in the number of aluminum particles present in a given droplet,[8] we are currently investigating the combustion of aluminum/hydrocarbon gel droplets in the range of practical interest (10-150 μm). One objective of the present investigation is to develop non-intrusive diagnostic techniques to study the combustion of 10-150 μm diameter gel droplets. In light of this objective, a laser diagnostic technique, based on near-forward Mie scattering, has been developed to measure the size and velocity of individual droplets in a dilute stream of burning gel droplets and to detect the presence of burning aluminum in these same droplets.

A problem inherent to laser-based sizing systems is the Gaussian distribution of the laser-beam intensity in the radial direction. In a typical system, the probe volume spans the entire beam cross-section, making probe volume illumination non-uniform and scattered light intensity dependent on trajectory through the probe volume. Since particle size is correlated with scattered light intensity, measured particle size in a single-beam system is dependent on trajectory in addition to actual size.[9] In a two-beam laser system, particle trajectory does not play a role in determining measured particle size since a second, coaxially aligned, smaller-diameter beam is used to limit the probe volume to a uniform-intensity region near the center of the sizing beam.[10] In both single and two-beam systems, non-uniform probe volume illumination yields a probe volume cross-sectional area that increases with increasing particle size.[10] Consequently, a system detection bias is introduced, in which smaller particles are underrepresented. While the above phenomena can be corrected for in post-collection processing,[9-11] the material refractive index must be known or constant, and in the case of a single-beam system, all particles must have approximately the same velocity.[9]

Since the shape and refractive index of a gel droplet change as the droplet burns (i.e., Al particle/hydrocarbon → Al particle agglomerate → molten Al → Al_2O_3) and particle velocity may vary significantly because of secondary atomization, the post-collection processing mentioned above can not be employed. Therefore, our system is designed such that the probe volume is uniformly illuminated by a horizontal laser sheet. While this technique eliminates uncertainties associated with a non-uniformly illuminated probe volume, the burning droplet stream and the horizontal slit control the probe volume dimensions, limiting the technique to narrow-diameter droplet streams.

A schematic of the diagnostic system and droplet burner is presented in Fig. 1. In brief, a 1.1-mm diameter He-Ne laser beam (Spectra-Physics 124B) is passed through a 750 mm focal length plano-convex spherical lens (L1, Oriel 40815) and a 19 mm focal length plano-convex cylindrical lens (L2, Newport CKX019), producing a horizontal laser sheet over the burner. This sheet has a calculated $1/e^2$ thickness of 550 μm and a width of 36 mm at the focal point of the lens combination. Gel droplets passing through this sheet scatter light which is collected in the near-forward direction and collimated by a 350 mm plano-convex spherical lens (L3, Oriel 40800), which has a strip of flocking material across its center to block direct laser light. An adjustable aperture (A1, Newport ID-1.5) is used to limit the total light collection angle. The collimated light passing through this aperture is then focused on a 200 μm horizontal slit (S1) by a second 350 mm lens (L4, Oriel 40800). Light passing through this slit is recollimated by a 50 mm plano-convex lens (L5, Oriel 41340) and is separated into two components by a beam splitter cube (BS1, Melles-Griot 03-BSC-009). The first component, used for particle sizing, is refocused through a second 50 mm spherical lens (L6, Oriel 41340), passes through a 632.8 nm line filter (F1, Oriel 52720), two optical diffusers (not shown, Oriel 48010) and enters a photomultiplier tube (PMT) (Hamamatsu R928) where the particle sizing signal is generated. The second component, used to detect aluminum combustion, passes through a 400-nm narrow bandpass filter (F2, Oriel 53800) and enters a second PMT (Hamamatsu R928) to produce the aluminum combustion signal. A detailed discussion of the aluminum combustion system can be found in prior work.[12] A two-channel 20 MHz A/D acquisition board (Rapid Systems 2040) is used to collect the above signals, which are then analyzed using a personal computer.

In general, Mie scattering intensity is highly sensitive to both particle shape and refractive index, making a correlation between scattered light intensity and gel particle size difficult to achieve. Light scattered in the near-forward direction, however, is relatively insensitive to shape and refractive index[13] and can be accurately correlated with particle size over a range of refractive indices. In order to obtain a good sizing correlation, defined as a monotonic function with good insensitivity to refractive index, a parametric study of light collection geometry was conducted. From this study and a consideration of system physical limitations, the scattering response for light collected at a 1.95° angle from the forward direction and over an angle of 1.72° was found to yield the best response. This collection geometry corresponds to a flocking strip thickness of 2 mm and an aperture (A1) diameter of 32 mm.

The series of lines in Fig. 2 shows normalized scattering intensity as a function of particle size for various anticipated material refractive indices calculated using Mie theory. From this plot it is evident that refractive index variations should affect particle sizing in the 10-125 μm range by at most 12% since the range of refractive indices employed here represents a worst-case scenario. In addition, a range of optical pinholes, which scatter light in the forward direction in the same manner as equivalent particles, were used to verify that the system scattering response matches the theoretical sizing correlation. These measurements demonstrate excellent agreement between the calculated correlation and actual system response. The optical pinholes were also used to verify the uniformity of probe volume illumination.

Figure 3 is a plot of maximum normalized system response as a function of horizontal pinhole location for a number of different size pinholes. From this plot it can be seen that worst-case probe volume response is within 7.5% of maximum in the center 2 mm of the probe volume and 19% for the entire volume. Since virtually all particles will pass through the center 2 mm, the uniformity is quite good. In addition to providing accurate single-particle sizing, the system must be able to perform in a reasonably dense spray without interference from other particles, since signals generated by more than one particle must be rejected. The probability of only one particle being in the probe volume was calculated using a Poission distribution and was found to be reasonable (>50%) for particle number densities of 1000 particles/cc or less.[14]

In summary, the above results indicate that the diagnostic system is performing as expected and should provide accurate particle sizing/velocimetry measurements in a dilute burning droplet stream over a range of material refractive indices. In addition, a uniformly illuminated probe volume is employed to reduce particle size distribution uncertainties associated with a changing material refractive index and/or particle velocity, making this an ideal technique for investigating the secondary atomization of aluminum gel propellants.

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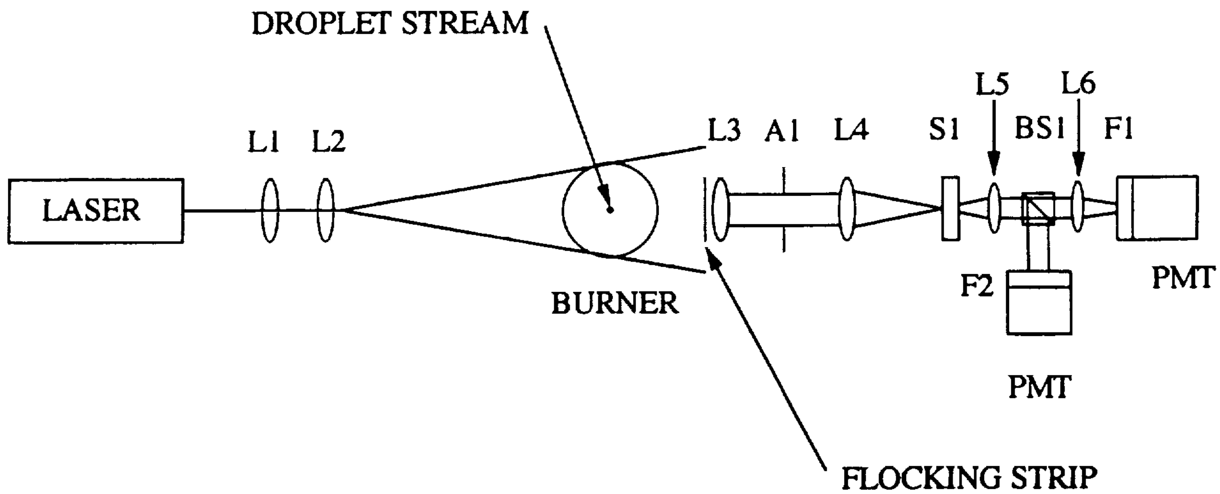

Figure 1. Schematic of the laser diagnostic technique.

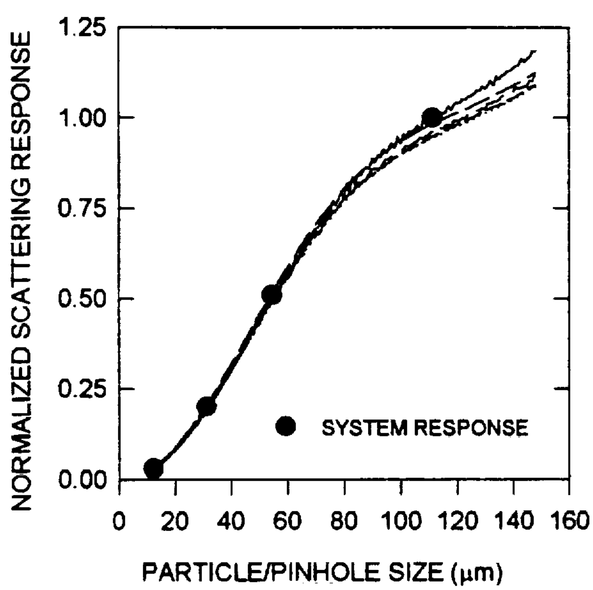

Figure 2. Calculated normalized scattering intensity and actual system response as functions of particle/pinhole diameter.

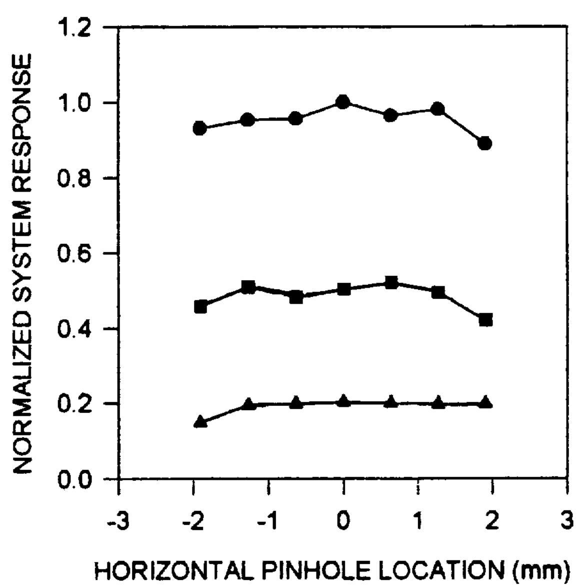

Figure 3. Normalized system response as a function of optical pinhole horizontal position in the probe volume for several pinhole sizes. (● - 111 μm, ■ - 55 μm, ▲ - 31 μm)