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OPTICAL MEASUREMENTS IN ROCKET ENGINE LIQUID SPRAYS

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INTRODUCTION

The performance of liquid propellant rocket engines is dependent upon many elements of the entire system. One of the most fundamental and most critical is the performance of the injector elements. Their characterization is an important part of the development of combustion devices. Optical measurements within these environments have proven to be invaluable tools in quantifying the physical environment of two phase flows. The effort reported herein involves the measurement of drop velocity, drop size, and most importantly mass flux using Phase-Doppler Particle Anemometry within a spray generated by a single swirl injector element operating in atmospheric pressure conditions. The mass flux has been determined and validated by mechanical patternation methods and by profile integration of the mass flux.

EXPERIMENTAL METHODS

The single element injector test facility utilized during the course of the laboratory investigations has been previously developed and described [3]. A photograph of the test hardware is shown in reference 3. The major features of the system include six pressurized accumulators which are first filled with water and then pressurized with compressed air. These accumulators can deliver approximately six gallons of water at constant delivery pressures up to 500 psia.

A transparent, acrylic, swirl injector element has been characterized in the present investigation which has been previously designed to examine the internal flow environment in the central posts of tangential-entry, swirl coaxial injector elements typical of those used in liquid propellant rockets [2]. Several such injectors have been tested and analyzed [2] for their internal geometry and measurements were made of the axial pressure distribution, the shape of the air core formed in the post, the velocity profile in the liquid film, and the near exit spatial mass flow distribution of the spray cone. The H-3, I-9 injector from this group was selected for the effort. The injector element was calibrated and later operated at plenum stagnation pressures of 75 to 85 psig (90 to 100 psia) where the water mass flow rate was 1.1 to 1.2 lbm/s (499 to 544 gm/s). Under these conditions the injector could be operated for approximately 50 seconds.

A one-dimensional 23 tube mechanical patternator was used as a mass collection device in order to compare with the Phase-Doppler Particle Anemometry mass flux profile results. The patternator consists of 23 thin-walled, square, cross-sectioned tubes. These tubes have a nominal outer size of 0.125 inches by 0.125 inches and square inner cross-section of 0.101 inches by 0.101 inches. During testing the tube bank was positioned in the spray at the desired measurement position, normal to the spray. The mass of water collected from each tube was suctioned by a vacuum pump into a column of glass collection tubes. The mass collected by each tube in the spray is hereby recorded over a period of time which enables a mean mass distribution profile to be determined across a section of the spray. The mass flux, $\dot{m}''$, for each tube was determined from the water column heights using Eqn. 1:

$$\dot{m}'' = \frac{m_{H_2O}}{A_t \bullet T_d} \qquad (1)$$

where m_{H_2O} is the mass of water collected by each individual tube, A_t is the capture cross-sectional area of each tube (0.1 in^2), and T_d is the test duration time.

A Phase-Doppler Particle Anemometry (PDPA) Optical System was used to measure the droplet velocities, droplet size, and mass flux. A thorough explaination of the theory, applicability, and assessment of the PDPA can be found in references 4, 5 and 6. A schematic of the present setup is shown in Figure 1. The system is a commercial one-dimensional system fabricated by Aerometrics, Inc. The 514.5 nm line of an Argon-Ion 100 mW laser was aligned into the transmitting optics where the laser beam is split, collimated with a 160 mm lens, and the two beams are focused by a 1000 mm transmitting lens. The laser beams intersect to form fringes which are aligned horizontally, normal to the spray. The collection optics were positioned at 30° off the transmission optics axis where the light scattered by the fringes is dominated by refraction through the drop as opposed to reflection or diffraction. The collection optics consisted of a 500 mm collimating lens and a 238 mm aperture lens. This configuration enabled a droplet size range of 47.7 μm to 1671 μm to be measured. The objective in using the PDPA was to assess the effectiveness and accuracy of the PDPA system to make accurate mass flux measurements in the dense spray. Hence, it was important in the present effort to capture the largest drops since they contain most of the mass. The probe cross-sectional area is corrected for drop size and it is noted, that the largest probe cross-sectional area computed and used by the software to calculate the volume flux, was 5.0 x 10^{-3} cm^2.

Figure 2 shows a schematic of the orientation and overview of the flow field. The injector was mounted to a traversing mechanism which allowed the injector to be traversed horizontally, vertically, and rotated in order to align the PDPA measurement volume (horizontal fringes) and the mechanical patternator normal to the most dense portion of the liquid sheet breakup region within the spray cone. The injector was rotated at an angle of 25° which was the experimentally determined spray cone angle. Traverses were made at two axial locations of approximately 17 and 30 injector exit diameters (8.7 mm) from the exit of the injector.

RESULTS AND DISCUSSION

A 1 ms strobe photograph of the swirl spray with an injection pressure of 80 psig is shown in Figure 3. At the exit of the injector a rotating, annular, cross-sectional, liquid sheet exits at a measured mean thickness of 635 μm and axial velocity of approximately 35 m/s (Ref. 2). As the liquid sheet leaves the injector body the radial momentum of the fluid induced by the tangential entry ports at the entrance of the post causes the liquid sheet to move radially outward and enhance the breakup of the sheet into ligaments and eventually drops. The photograph attempts to show the evolution of the breakup process.

As indicated above, measurements of mass flux were made using the patternator and the PDPA at axial stations of approximately 17 and 30. The objective was to verify if accurate measurements of mass flux could be made. In addition the mass flux profiles were integrated in order to verify if the total mass could be captured. If tangential symmetry is assumed, the integral of the mass flux profile can be performed using Eqn. 2:

$$\dot{m} = 2\pi \int_{s=0}^{s_{max}} \dot{m}''(s)\cdot s\cdot ds \qquad (2)$$

where s is the axis of traversal which for the present measurements is not a true radial coordinate as indicated in Figure 2. In order to evaluate Eqn. 2, discretization was required yielding Eqn. 3:

$$\dot{m}_{Total} = \pi \bullet \sin(90-\gamma) \bullet \sum_i \dot{m}''(s_{i+1}, s_i) \bullet (s_{i+1}^2 - s_i^2) \qquad (3)$$

where $\dot{m}_{Total}$ is the calibrated total mass flow rate, $\dot{m}''(s_{i+1}, s_i)$ is the mean value of the measured mass flux between positions s_{i+1} and s_i, and γ is the spray cone angle of 25°.

The raw PDPA data includes individual drop velocity and particle size. The software calculates the statistical properties of velocity and size as well as the volume flux. Information such as this was collected at several locations within the spray along the two traverse axes. The maximum velocities occur in the most dense portion of the spray where most of the mass is concentrated. The RMS velocity fluctuations range from about 30 to 50 % at both axial stations. The maximum velocities measured were as high as 30 m/s which is less than the calculated injector exit velocity of 35 m/s [2]. The largest drops are found in the dense spray region and the maximum individual drop sizes measured were 1670 μm. This is in agreement with the measured mean exit liquid film thickness at the injector exit of 635 μm [2]. The RMS fluctuations in the measured drop sizes are 35 % which corresponds to the dynamic range of the PDPA detectors. The smallest drops measured in the dense spray region were 48 μm. Smaller drops exist; however, were not measured because of the limited dynamic range of the detector.

As noted earlier, the present effort was focused on obtaining accurate mass flux measurements and therefore it was necessary to capture the largest drops since they contain most of the mass. Figures 4 and 5 show the patternator and PDPA measured mass flux profiles in gm/s/cm^2 at both axial positions respectively. The patternator and PDPA mass flux profiles are in agreement at L/D of 30; however, at L/D of 17 the PDPA under predicts the mass flux. This can be explained by noting that in the PDPA method non-spherical particles are rejected. The profiles at L/D of 17 show either the PDPA is not capturing all of the mass, because the breakup of the liquid shear layer is incomplete, or the spray is too dense. However, at L/D of 30 the breakup is complete and the region is comprised of discrete drops. As noted above, if the profiles are correct, integration of the mass flux profiles over the discretized surface areas should recover the total mass flow rate. This has been completed and the results are shown in Table 1.

Table 1

Axial Position	Total Mass Flow Rate (gm/s/cm^2)	Result of Patternator Profile Integration (gm/s/cm^2)	Result of PDPA Profile Integration (gm/s/cm^2)
L/D = 17	499	493	144
L/D = 30	544	518	544

CONCLUSIONS

The following conclusions can be drawn from the results presented:

1. The maximum velocity measured by the PDPA (i.e. 30 m/s) is less than the calculated injector exit liquid film velocity (i.e. 35 m/s).
2. The maximum measured individual drop size (i.e. 1670 μm) is consistent with the independently measured mean liquid film injector exit thickness (i.e. 635 μm).
3. The PDPA can accurately measure mean mass flux in the discrete droplet region of a spray as verified by the patternator mass flux measurements and profile integration at L/D of 30.

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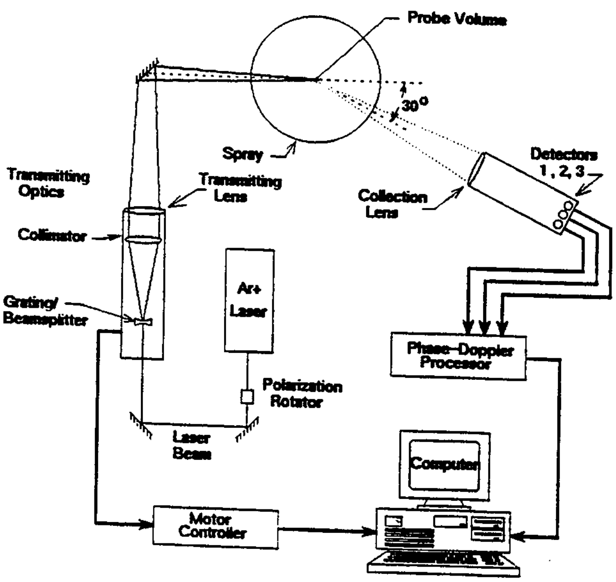

Figure 1 Schematic of the Optical Setup for the Phase-Doppler Particle Anemometry System.

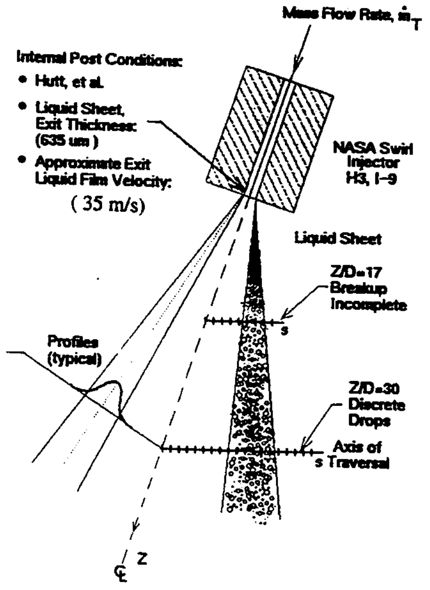

Figure 2 Overview of the Injector Orientation and Axes of Traverse.

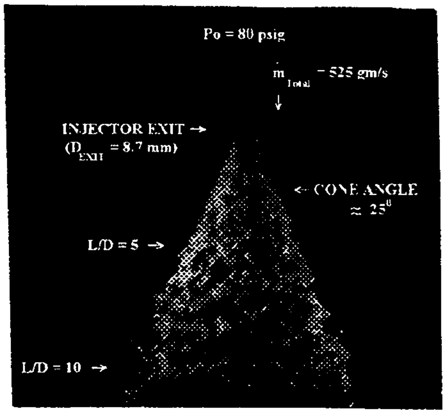

Figure 3 Photograph of the Swirl Spray at a Plenum Injection Pressure of 80 psig and Mass Flow Rate of 525 gm/s.

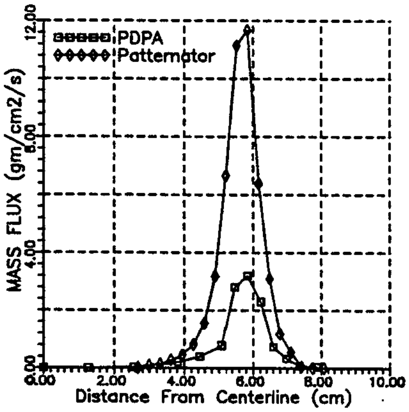

Figure 4 Comparison of Mean Mass Flux Profiles at L/D = 17 for the Patternator and PDPA.

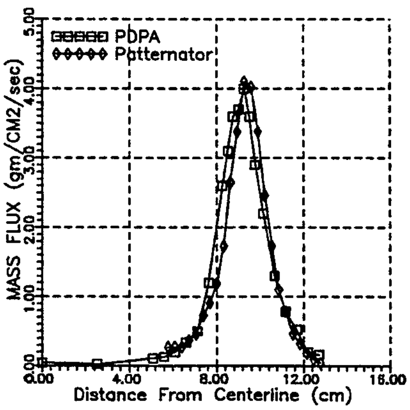

Figure 5 Comparison of Mean Mass Flux Profiles at L/D = 30 for the Patternator and PDPA.