516-20

1996

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER

THE UNIVERSITY OF ALABAMA

SPRAY DIAGNOSTICS IN ROCKET ENGINES USING PHASE DOPPLER ANALYZER

Prepared by: Kakkattukuzhy M. Isaac, Ph. D.

Academic Rank: Associate Professor

Institution and Department: The University of Missouri-Rolla
Department of Mechanical & Aerospace Engineering and Engineering Mechanics

NASA/MSFC:

Laboratory: Propulsion Laboratory
Division: Engine Systems
Branch: Combustion Physics Laboratory

MSFC Colleagues: John Hutt, Richard Eskridge

INTRODUCTION

Characteristics such as drop velocity, drop size, number density, volume flow rate, volume flux, and evaporation rate of the fuel spray in a rocket engine are directly related to engine performance. Several studies of shear coaxial atomization have been done in the past[1, 2]. However, additional work related to sprays at supercritical and transcritical conditions would be useful. The author undertook a study of the feasibility of using a phase Doppler particle analyzer (PDPA) for spray measurements in rocket engines as a part of the Summer Faculty Fellowship Program at the NASA Marshall Space Flight Center.

The PDPA is a single particle counter (SPC) system based on light scattering from spherical particles. The PDPA instrument is based on refractive and reflective scattering as opposed to other instruments based on diffractive scattering. The main advantage of the PDPA instrument is its ability to provide point-wise information.

The following sections describe the principle of operation of the PDPA system and the data obtained using a PDPA instrument in a spray formed by a commercially available fuel injection nozzle.

PHASE DOPPLER SYSTEM

A light ray incident on a transparent sphere will emerge at an angle dependent on the path of the ray and the size of the sphere. Snell's Law of refraction, which states: $\cos\tau = m\cos\tau'$, in which m is the refractive index of the drop medium, and τ and τ' are the angles made with respect to the interface tangent by the incident and the refracted rays, respectively, may be used to determine the path traced by a ray as it traverses a transparent sphere. For a ray emerging from the drop without any reflection, van de Hulst[3] has shown that the scattering angle θ is given by the expression: $\theta = 2(\tau' - \tau)$. When there are two beams incident on the sphere, they will interfere after they emerge from the sphere. Defining a new parameter η as

$$\eta = 2\alpha(\sin\tau - m\sin\tau') \tag{1}$$

in which the parameter α is defined as: $\alpha = \pi d/\lambda$.

The amplitude functions associated with beams 1 and 2 for linearly polarized light, for $\sigma = \eta$, are given by

$$S_{11}(m,\theta,d) = \sqrt{i_1}exp(j\sigma_1) \tag{2}$$

$$S_{12}(m,\theta,d) = \sqrt{i_2}exp(j\sigma_2) \tag{3}$$

The first subscript in the above equations is used to denote Polarization 1, perpendicular the scattering plane. When a spherical particle travels through the intersection of two laser beams, it will scatter light from each beam. The scattered light due to the two beams may be described using the following expressions.

$$E_1(m,\theta,d) = S_{11}(m,\theta,d)exp(-jkr + j\omega_1 t)/jkr \tag{4}$$

$$E_2(m,\theta,d) = S_{12}(m,\theta,d)exp(-jkr + j\omega_2 t)/jkr \tag{5}$$

where k = 2 π/λ, is the wave number, and ω is the angular frequency. The total scatter is obtained by summing the complex amplitude from each beam. The resultant intensity is given by

$$I(m,\theta,d) = ((\mathrm{mod} E_1)^2 + (\mathrm{mod} E_2)^2 + 2\ \mathrm{mod}\ (E_1)\ \mathrm{mod}\ (E_2)\cos\sigma) \tag{6}$$

where σ is the phase difference between the scattered signals. Notice that the first two terms are independent of σ, and therefore, represent the pedestal component of the signal, and the last term involving σ gives rise to a sinusoidal intensity variation. Since the beam intersection angle, γ, is small (less than 10 deg.), the scattering angles, θ_1 and θ_2, of the pairs of rays that reach a common point and interfere are nearly equal. Therefore, the amplitude functions, S_1 and S_2, of the two beams are also nearly equal. Figure 1 (reproduced from Ref. [4]) is a photograph of the scattered light intensity pattern. When the drops travel through the probe volume, the fringe pattern appears to move at the Doppler difference frequency, which is a function of drop velocity, beam intersection angle and the light wavelength. The spatial frequency of the fringe pattern is a function of the drop diameter, angle of observation, light wave length, and drop refractive index. The fringe pattern can be detected by using a photomultiplier tube (PMT) whose output can be displayed on an oscilloscope as a Doppler burst signal.

A schematic diagram of the instrument is shown in Figure 2. The fringe spacing, δ, is given in terms of the wave length, λ and the beam intersection angle, γ, by the following expression

$$\delta = \lambda/2\sin(\gamma/2) \tag{7}$$

The drop velocity, v, is directly related to the Doppler difference frequency, f_d, and is given by

$$v = f_d\delta \tag{8}$$

The particle magnifies the fringe pattern onto a receiver to different degrees relative to its size. The fringes move past the detectors at the Doppler difference frequency producing identical signals, but with a phase shift proportional to the fringe spacing. The spatial wave length, Δ, is given by the following expression

$$\Delta = 2\pi S_{1-2}/\phi_{1-2} \tag{9}$$

in which S is the spacing and ϕ is the phase angle between Detectors 1 and 2.

RESULTS AND DISCUSSION

The spray investigated in this study was that of the Delavan 27700-1 fuel injector[5] used in jet engines. The injector is a pressure atomizer having a flow rate of 0.5-1.0 kg/hr. Distilled water was used as the injection fluid, and the injection pressure was 90 psig. A flow visualization study was conducted first to establish the overall features of the spray. The spray was illuminated using a laser light sheet, and still pictures of the spray was taken at different camera shutter speeds, the maximum of which was 1/8000 s. These flow visualization pictures provided the time-averaged and instantaneous overall features of the spray. The PDPA system was then used to make quantitative measurements. Radial profiles of mean velocity and mean drop size were obtained at different axial locations. Volume flux, volume flow rate and number density information was also provided by the PDPA software.

Figure 3 is a representative result from the PDPA measurements. The figure shows a radial profile of the Sauter mean diameter (SMD) at an axial distance of 38.1 mm measured from the injector exit. Characteristic of this class of injectors, the drop size is smallest at the axis and increases to a maximum towards the edge of the spray. A few very large drops were seen at the outer edge.

FUTURE WORK

The present work has demonstrated that the PDPA is a useful instrument for investigating rocket engine performance. The instrument, with careful implementation, can provide critical information regarding the complex mechanisms involved in the high pressure combustion environment. However, any such study should be carefully designed and implemented in order for it to provide further understanding of rocket engine behavior. It is recommended that the PDPA instrument be used to participate in the NASA/LeRC study of single particle counter (SPC) instruments[6].

References

[1] Isaac, K. M., Missoum, A., Drallmeier, J. A., and Johnston, A. P., "Atomization Experiements in a Coaxial Coflowing Mach 1.5 Flow," AIAA Journal, Vol. 32, No. 8, pp. 1640-1646, Aug. 1994.

[2] Pal, S., Moser, M. D., Ryan, H. M., Foust, M. J., and Santoro, R. J., "Flowfield Characteristics in a Liquid Propellant Rocket," AIAA Paper 93-1882, Jun. 1993.

[3] van de Hulst, Light Scattering by Small Particles, Wiley, Now York, 1957.

[4] Bachalo, W. D. and Hauser, M. J., "Phase/Doppler Spray Analyzer for Simultaneous Measurements of Drop Size and Velocity Distributions," Optical Engineering, Vol. 23, No. 5, pp. 583-590, 1984.

[5] Mao, C. P., "Drop Size and Velocity Data for Delavan 27700-1 Fuel Injector," Private communication, July 1996.

[6] Zaller, M., "Single Particle Counter Interlaboratory Study," Memorandum dated, May 1996.

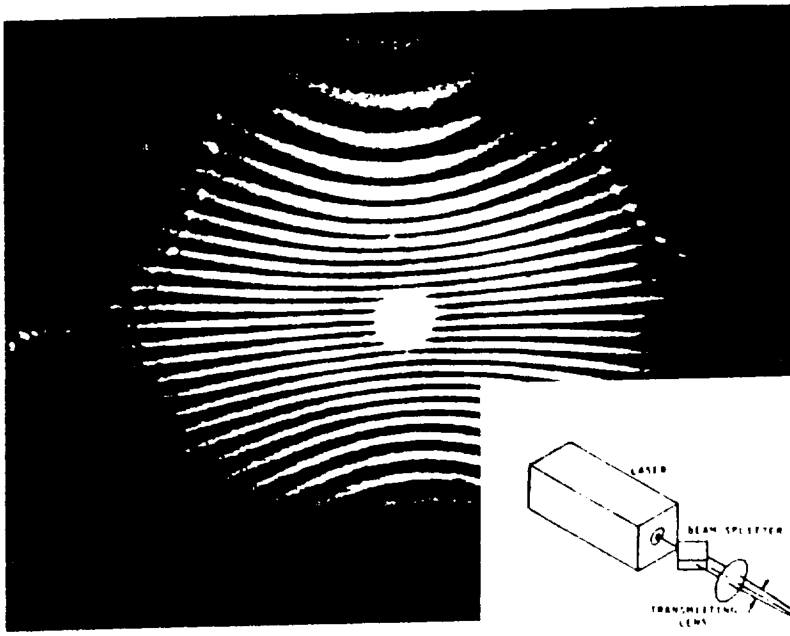

Figure 1

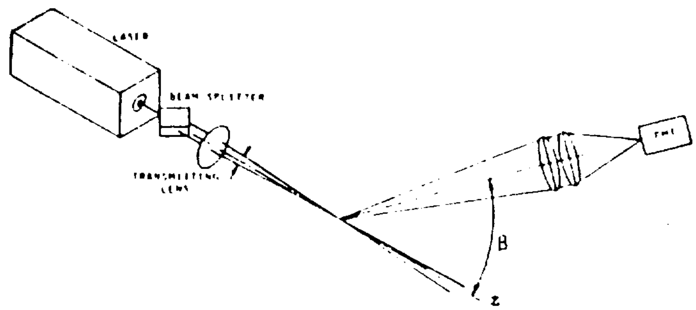

Figure 2

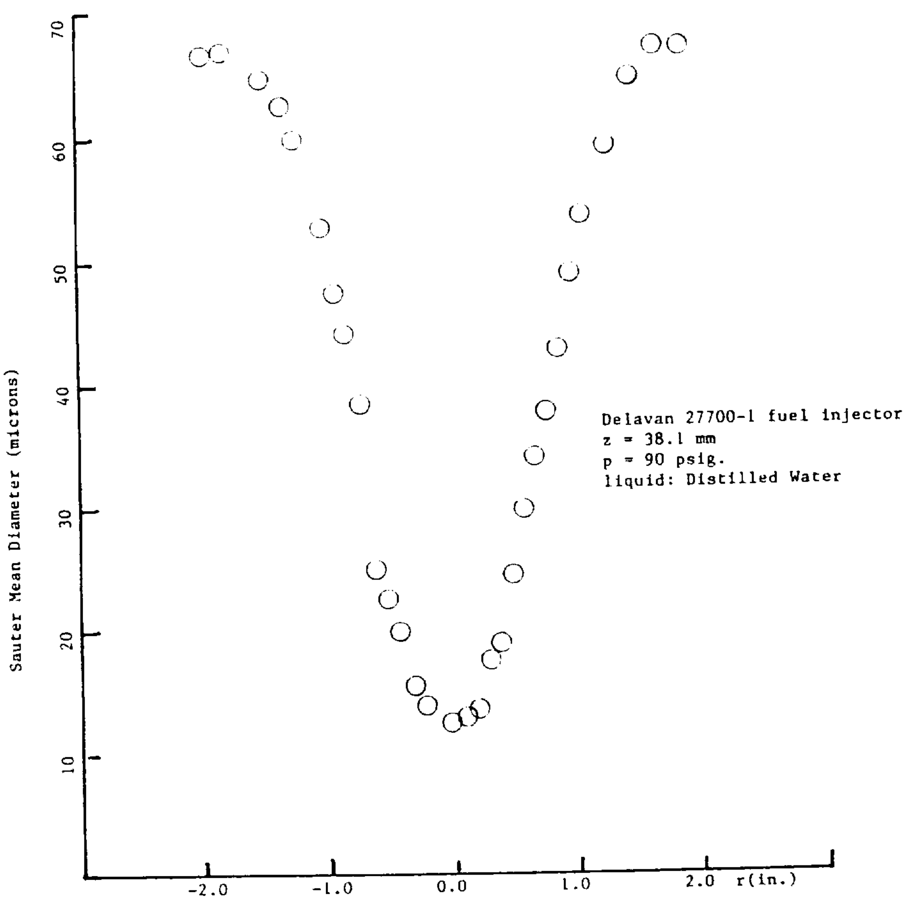

Figure 3