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**ATOMIZATION CHARACTERISTICS OF SWIRL INJECTOR SPRAYS**

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## INTRODUCTION

Stable combustion within rocket engines is a continuing concern for designers of rocket engine systems. The swirl-coaxial injector has demonstrated effectiveness in achieving atomization and mixing, and therefore stable combustion. Swirl-coaxial injector technology is being deployed in the American RL10A rocket design and Russian engine systems already make wide spread use of this technology. The present requirement for swirl injector research is derived from NASA's current Reusable Launch Vehicle (RLV) technology program. This report describes some of the background and literature on this topic including drop size measurements, comparison with theoretical predictions, the effect of surface tension on the atomization process, and surface wave characteristics of liquid film at the exit of the injector.

## BACKGROUND AND LITERATURE

High frequency combustion instabilities in liquid-propellant rocket engines are considered the most destructive and continues to challenge the designer due to the complex interactions of turbulent combustion processes<sup>1, 2</sup>. The periodic combustion within the chamber results in pressure oscillations and often periodic flow of propellant. Historically, these instabilities have been reduced by joining baffle plates to the injector face which serve to damp the coupled, unsteady combustion and oscillating propellant flow. These effects can result in periodic atomization of the liquid propellants which include fluctuations in drop size, local mixture fraction of combustible mixture, and position of the flame front. Such changes within the reaction zone are important since they affect wall heating and chamber pressure. The approach selected to better understand these high pressure combustion phenomenon is to test single injector elements inside a windowed combustion chamber where detailed measurements and flow visualization can be conducted. Prior to making high pressure measurements, atmospheric atomization studies are made for diagnostic purposes as well as to validate computer models.

The objective of this study was to investigate some properties of atomization provided by pressure-swirl type injectors. The parameters which affect the atomization process have been extensively reported<sup>3, 4, 5, 6, 7, 8</sup>. Atomization is a process whereby a volume of liquid is transformed into a large number of small drops<sup>9</sup>. The principle aim is to produce a high ratio of surface area to mass of the liquid phase which promotes high evaporation rates and more rapid combustion. Means of controlling the drop size is important in this application and is understood by examination of the mechanisms by which the liquid sheets breakup<sup>10</sup>. The fundamental principle for the disintegration of a liquid involves increasing the surface area of the sheet until it becomes unstable and disintegrates. Disintegration of the liquid sheet is promoted by turbulence in the liquid flow prior to exiting the injector, and by the action of aerodynamic forces<sup>11</sup>, and is opposed by the viscosity and surface tension forces of the liquid sheet<sup>7</sup>. For the swirl injector considered in this study a conical sheet<sup>3</sup> forms upon exiting the injector body and previous drop size measurements<sup>4</sup> and theory<sup>10</sup> suggest that the thickness of the liquid sheet is important in predicting the drop size in the atomized liquid.

The present effort attempts to investigate some parameters important for the atomization of a liquid propellant simulant injected with a swirl, hollow-cone injector operating at atmospheric pressure. Optical measurements within these environments have proven to be invaluable tools in quantifying the physical environment of two phase flows. The effort reported herein attempts to investigate the role of the injected liquid film and surface tension on the atomization process and resulting drop size.

## EXPERIMENTAL METHODS

The single element injector test facility utilized during the course of the laboratory investigations has been previously developed and described<sup>4</sup>. 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 which has been previously designed to examine the internal flow environment in the central posts of tangential-entry, swirl injector elements typical of those used in liquid propellant rockets<sup>3</sup>. Several such injectors have been tested and analyzed<sup>3</sup> 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 40 seconds.

Optical measurements of the exiting liquid film just before exiting the injector were made to investigate the wave structure of the water/air interface. A Questar QM1 magnifying microscope with a large working distance was used along with a synchronized 1 ms strobe to record the flow of the water film. The time resolved images were stored on standard video with the use of CIDTEC (Model: CID2710) street camera. The video was digitized into a image processing software package and the two dimensional wave structure was represented as a curve. Fourier analysis of this wave was completed in order to determine if dominant wave lengths exist.

## RESULTS AND DISCUSSION

### *Drop size measurements<sup>4</sup> and breakup mechanism<sup>10</sup>*

At the exit of the injector a rotating, annular, cross-sectional, liquid sheet exits at a measured mean thickness of 635  $\mu\text{m}$  and axial velocity of approximately 35 m/s (Ref. 3). The turbulence intensity in the axial direction of the liquid film was measured to be 10%. 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. At the injector exit waves are formed due to disturbances resulting in local thickening and thinning of the conical sheet normal to the sheet propagation direction. The thickened regions sever from the sheet into rings which then break apart into ribbons and ligaments. The ribbons and ligaments then breakup into drops by the Rayleigh mechanism and interactions with other drops. This mechanism applies only for the case when the atomizing liquid is below the supercritical pressure, where surface tension plays an important role. Above the supercritical pressure the surface tension becomes zero and is believed to have little or no effect upon the atomization process; however, little information is available to either confirm or deny this statement.

Previous measurements<sup>4</sup> have shown that the largest individual drops are found in the dense spray region and the maximum individual drop sizes measured were 1670  $\mu\text{m}$  and appear consistent with the measured mean exit liquid film thickness at the injector exit of 635  $\mu\text{m}$ <sup>3</sup> which is in agreement with the value presently measured. It is important to point out that the maximum drop size is 2.6 times the measured exiting liquid sheet thickness. It also is interesting to note that a liquid jet which breakups purely due to the Rayleigh mechanism is 1.89 times the jet diameter<sup>8</sup> even though the mechanism for breakup of the conical sheet is physically much different. The mechanism proposed by York et al.<sup>10</sup> resulted in a method for estimating the mean drop size for conical sheets produced by pressure-swirl,

$$D_d = 2.13(t_s \cdot \lambda^*)^{1/2} \quad (1)$$

hollow cone atomizers. In Eqn. 1,  $t_s$ , is the sheet thickness at the injector exit and  $\lambda^*$  is the wavelength corresponding to the maximum growth rate. In estimating the wavelength corresponding to the maximum growth rate they define two Weber numbers as:

$$We_1 = \frac{\rho_A \cdot U_R^2 \cdot t_s}{\sigma_L} \qquad We_2 = \frac{\rho_A \cdot U_R^2 \cdot \lambda^*}{\sigma_L} \qquad (2)$$

These parameters are dependent upon the gas/liquid density ratio  $\rho_A/\rho_L$ . The various parameters as they relate to the present conditions are shown in Table 1. The calculated wavelength corresponding to the maximum growth rate,  $\lambda^*$ , is predicted to be 464  $\mu\text{m}$ . The predicted mean diameter after Eqn. 1 is 1150  $\mu\text{m}$  which is in qualitative agreement with the measured maximum diameter (1670  $\mu\text{m}$ ) but is larger than

the arithmetic mean diameter,  $D_{10}$ , (330  $\mu\text{m}$ ). It is proposed that the measured mean diameter is smaller than predicted by Eqn. 1 since the break-up mechanism of York et al., does not account for drop collisions and aerodynamic breakup effects.

Table 1 Parameters used in Eqns. 1 and 2

$\rho_A$ (kg/m <sup>3</sup> )	$\rho_L$ (kg/m <sup>3</sup> )	$U_R$ (m/s)	$\sigma_L$ (kg/s <sup>2</sup> )	$\mu_L$ (kg/m/s)	$We_1$	$We_2$
1.2	1000	35	0.0717	$8.5 \times 10^{-4}$	13.0	9.5

#### Effects of Surface Tension:

Surface tension is a force or pressure exerted along a liquid/gas interface which results from the difference of the cohesive intermolecular forces present in the liquid and gas. The action of surface tension on the atomization process has two important effects. In the initial stages surface tension opposes the development of surface distortions into ligaments and the formation of drops from the ligaments, but it assists in the final stages of disruption<sup>6</sup>. Figure 1 and 2 show the surface tension of liquid hydrogen<sup>12</sup> and oxygen<sup>13</sup> respectively. Above the critical conditions the surface tension becomes zero. The use of surfactants in atomization phenomenon is common in many applications since low concentrations of the surfactant can greatly change the surface forces at a liquid/gas interface. However, use of surfactants to study rocket atomizers is impracticable since the adsorption of surfactants is slow and the liquid breaks up initially as if no surfactant is present<sup>7</sup>.

#### Water Film Surface Wave Characteristics

Figure 4 shows an instantaneous digitized image of the water film thickness at the exit of the injector. The thickness agrees with the measurements previously reported<sup>3</sup>. Figure 5 shows the Fast Fourier Transform (FFT) of the measured wave in Figure 4. Several such FFT's have been constructed for many different realizations at the same location and they all have the same form as Figure 5. The FFT's show that long wavelength water waves at low frequencies are dominant. Other frequencies exist but none appear dominant. This supports the hypothesis that the surface is chaotic suggesting that the turbulence in the liquid film determines the surface wave structure.

### CONCLUSIONS

The following conclusions can be drawn from this summer's results:

- 1) The York mechanism is in qualitative agreement with drop size measurements.
- 2) The present liquid film thickness measurements agree with previous measurements<sup>3</sup>.
- 3) The liquid film is statistically flat as verified by the video images and the FFT.

- 4) The dominant frequency/wavelength of the surface wave at the liquid/gas interface corresponds a low frequency or long wavelength disturbance. Turbulence appears to determine the wave structure.

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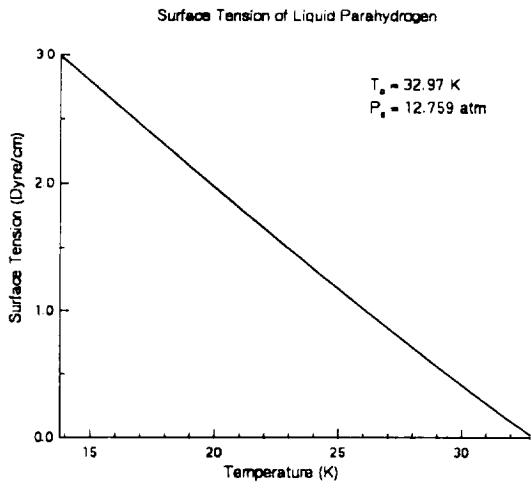


Figure 1 Surface Tension Liquid Hydrogen, Pressure Corresponds to the Saturation Pressure.

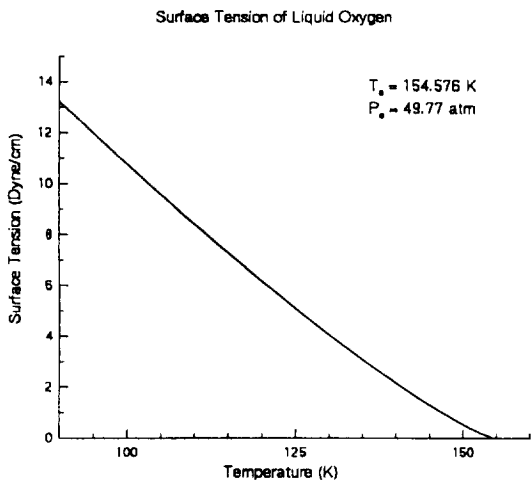


Figure 2 Surface Tension Liquid Oxygen, Pressure Corresponds to the Saturation Pressure.

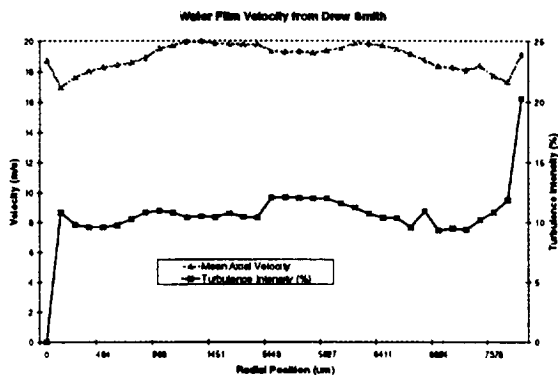


Figure 3 LDV Measured Mean Axial Velocity and Turbulence Intensity Across the Film Thickness 0.22 inches from the Injector Exit. (Conditions Different from the present)

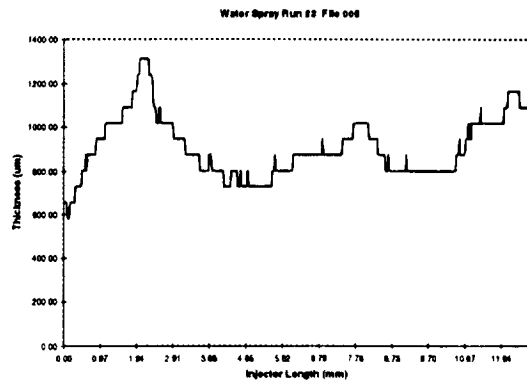


Figure 4 Instantaneous Two-Dimensional Surface Wave Thickness at the Injector Exit.

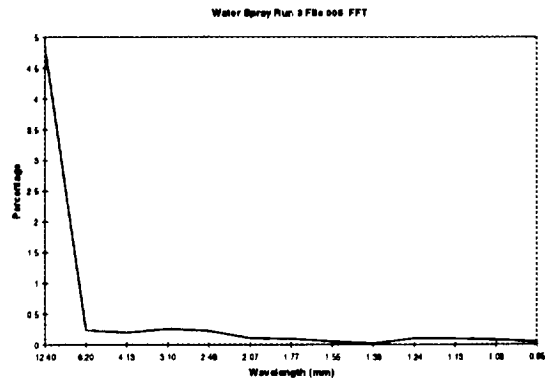


Figure 5 Fast Fourier Transform of the Water Wave Shown in Figure 4 (Wave Length decreases from right to left).

