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EXPERIMENTAL INVESTIGATION OF A SIMULATED LOX INJECTOR FLOW FIELD AND OTHER NONINTRUSIVE MEASUREMENT EFFORTS

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Introduction

Efforts to improve the characteristics of fuel-oxidizer mixing in liquid rocket combustors have lead to a swirl element design for a liquid oxygen injector which is being considered for use on the STME. For the design which is the subject of this investigation, the oxygen enters the injector element perpendicular to the injector axis and nearly tangent to the circular injector wall. This swirl element is at one end of a tube and the injector exit is at the other. This geometric configuration creates a plume in the shape of a conical sheet. This sheet is either primarily contiguous liquid or droplets depending on the pressure drop in the injector and the distance from the injector exit.

Probe-based devices such as two-dimensional grid patternators have been used to investigate simulated LOX injector flow fields (Hulka). The primary work described herein is an effort to use optical techniques to investigate the plume of a swirl injector element. For this investigation, a high pressure (500 psig) cold flow test facility was constructed. Water was used as the LOX simulate and air pressure was used to drive the injector flow field. Laser-induced fluorescence (LIF) from dye seeded into the water was used to obtain quantitative measurements of the time-averaged water concentration distribution in the plume. Scattered laser light and LIF were used for time averaged plume visualization and scattered light from a strobe with a 1 microsecond pulse was used for time-resolved plume visualization.

During the Summer Faculty Fellowship for which this report was developed, an additional effort, unrelated to the swirl injector investigation, was made to resolve fluctuations in the combustion product composition in the exhaust of a hybrid rocket motor. A brief description of this effort is included herein.

Hybrid Motor Investigation

Instabilities in the chamber pressure of a laboratory scale hybrid rocket motor have been observed and are possibly due to combustion instabilities induced by vortex shedding in the motor. To detect the combustion instabilities, a nonintrusive method for tracking the concentration of combustion products is needed. One fuel used in the motor is HTPB and a minor product of HTPB-oxygen combustion is NO_2. LIF from NO_2 has been used successfully to track number densities (Barnes, Gulati, Agarwal) and the potential for observing fluctuations in laser-induced NO_2 fluorescence signal in the exhaust plume of the hybrid motor appeared to be an attractive instrument for correlating combustion instabilities to observed pressure fluctuations. A system to observe NO_2 fluorescence was assembled and operated briefly. This system uses an argon ion laser tuned to the 488 nm line as an excitation source and a photomultiplier tube as the detector. To discriminate against the chemiluminescence of the plume and other backgrounds, an optical chopper and a lockin amplifier were used in the data collection.

Efforts to observe NO_2 fluorescence signals were unsuccessful for a small number of rocket firings and the effort was abandoned so that the swirl injector project could proceed. However, in the effort to use NO_2 fluorescence as a diagnostic tool, an approximate calculation of the equilibrium mole fraction of NO_2 in an HTPB-oxygen flame was conducted for a range of oxygen to fuel mole fraction ratios known to exist in the motor. A plot of the calculated mole fractions and the corresponding equilibrium temperatures is given in Figure 1. The chemical equilibrium code known as STANJAN was used for this calculation and the calculation is approximate in that the bond energy for the HTPB fuel was neglected. NO_2 has been observed using the basic LIF technique described above for mole fractions of 5×10^{-4} which is approximately two orders of magnitude higher than the maximum

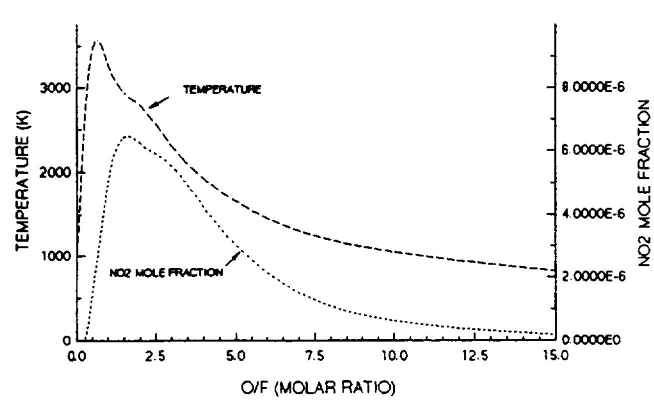

Figure 1: Approximate Equilibrium Calculation for HTPB - Oxygen Combustion

concentration found in Figure 1. This does not necessarily preclude the use of NO_2 as a detection molecule in the hybrid rocket flow field; however, signal to noise ratios will clearly be limited.

Swirl Element Injector Investigation

To begin an experimental investigation of a swirl element injector plume, a test rig was constructed. In this rig, high pressure (up to 500 psig) water is supplied to the injector using a network of stainless steel plumbing. An air bottle connected to the plumbing network is used to supply the high pressure. The plume from the injector empties into a stainless steel accumulator vessel. A centrifugal water pump is connected to this vessel and is used to fill the plumbing. Solenoid valves are used to isolate the air bottle, the injector, the water pump and a vent line. The injector is constructed with three axisymetric rows of three ports each exhausting into the head end of a 9.3 mm diameter tube. The liquid travels for 13 cm at this diameter before encountering a forward-facing step cut at 60^{0} to the axial direction. The tube diameter downstream of the step is 5.3 mm and this section extends 3 cm to the injector exit.

This investigation is composed of both efforts to understand the fluid mechanics of the swirl element injector and efforts to develop additional quantitative optical techniques for use in two-phase flows. In two-phase flows, strong signals from optical scattering are to be expected and are useful for visualization studies of phase boundaries and the plume structure. In the case of particulates or discrete liquid drops in a gas flow, highly developed scattering techniques such as Laser-Doppler-Velocimetry can be used to measure time dependent velocity components and particle sizes. However, for a dense liquid spray in which droplets are in the process of being formed from a liquid jet, the complicated directional dependence of the scattered light severely limits its use as a quantitative diagnostic tool. Signal levels from LIF are much lower than from scattered light; however, LIF is more attractive for quantitative measurements because the emission is isotropic. Intense scatter found in dense sprays can cause significant power reductions and spatial nonuniformities in a laser beam or sheet used as an excitation source thereby complicating the interpretation of the fluorescence signal. However, for the particular injector configuration investigated herein, a LIF technique for resolving the average radial liquid distribution in the plume has been implemented. This technique is based on the uniform illumination of the axisymetric plume and a subsequent inversion of the measured fluorescence.

For the time-averaged measurements and visualization work, a Spectra Physics Model 2016 argon ion laser tuned to the 514.5 nm line was used as a light or excitation source. A 35mm SLR film camera was used for the visualization photographs and a Xibion Electronic Systems intensified CID camera (model ISG-205-DUHMQ-2) was used for the quantitative measurements. To obtain fluorescence measurements in the plume, 3 mg of R6G dye were added to the approximately 40 liters of water in the accumulator. For the argon ion laser, the 514 line is one of the strongest and is spectrally closest to the strongest part of the R6G absorption spectrum. The time-averaged visualization work was completed with a laser sheet formed using a 1 cm diameter glass rod to fan out the beam and a 35 cm focal length spherical lens to recollimate and focus the sheet. For uniform illumination, a microscope objective was used to expand the laser beam and a pin hole at the focus was used to spatially filter the expanding beam. For the time resolved photography, a 1 microsecond light flash was generated with a Stroboscope from Pioneer Electric and Research Corporation.

Figures 2, 3 and 4 are representative examples of the photographic visualization effort. Figure 2 is a photograph of the light scattered by a laser sheet passing through the center of the plume with an injector pressure drop of approximately 50 psi. Figure 3 is a photograph of the LIF for the same conditions and Figure 4 is photograph using the strobe with a 300 psi injector pressure drop. Because of the pressure difference for these particular photos, no detailed analyses will be given here; however, it should be noted that for all of the time averaged visualization photographs, the plume boundary in the vicinity of the injector exit was significantly curved but was very nearly straight in this region in the time resolved photographs. Visualization photographs such as those presented herein were taken for pressure drops of 100 psi, 300 psi and 500 psi. These photographs will be analyzed in detail in the future.

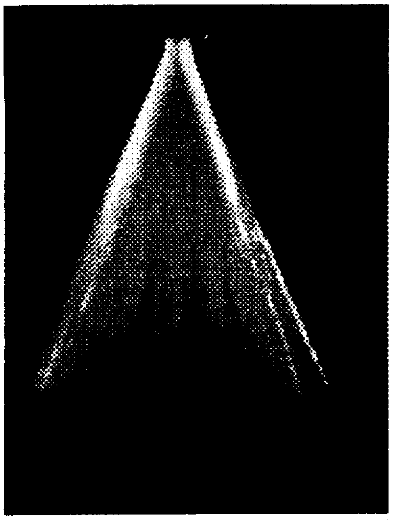

Figure 2: Photograph of Scattered Light From a Laser Sheet in Swirl Element Injector Plume

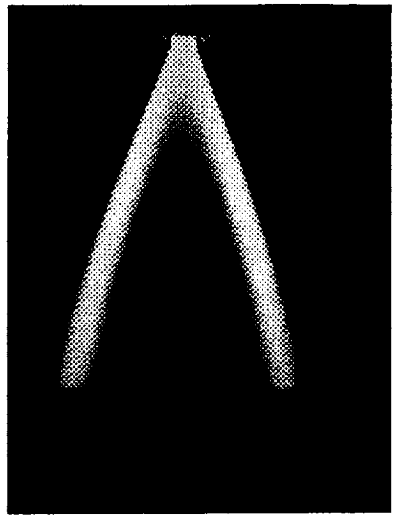

Figure 3: Photograph of Laser-Induced Fluorescence in Swirl Element Injector Plume

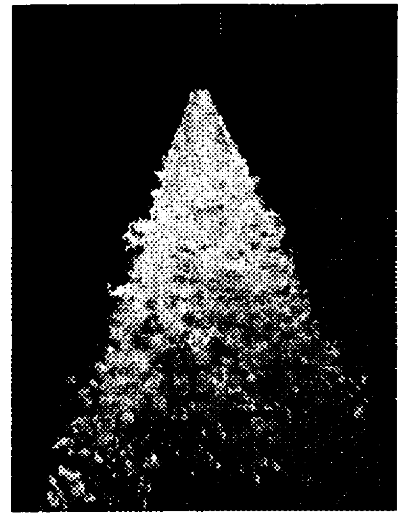

Figure 4: Photograph of Swirl Element Injector Plume Using a 1 Microsecond Strobe

The radial distribution of the liquid injectant was derived from fluorescence data collected using uniform illumination of the injectant plume. The plume data for a pressure drop of 105 psi was selected for this analysis. A three dimensional plot of normalized fluorescence intensity as a function of radial and axial position is shown in Figure 5. The general shape of the injectant plume is known to be a conical sheet (because of centrifugal forces associated with the swirl). As mentioned above, the interface between the two fluid phases results in scatter and, ultimately, nonuniformities in the excitation source; however, since the bulk of liquid injectant is concentrated in a sheet at the exit of the plume, the half of the plume which the beam enters first is illuminated uniformly. For this reason, the right half of the data shown in Figure 5 was selected for the axisymetric inversion process. The Abel inversion procedure (Shelby) was used to convert the spatially integrated axisymetric signal distributions into radial intensity (or time averaged liquid mass fraction) distributions. This integral inversion is dependent on both the value of the data and the derivative of the data. For this reason, it is necessary to fit a smooth curve to the data before it is inverted. To illustrate the inversion process, the data at the nozzle exit and its curve fit are shown in Figure 6 and the inversion of this data is shown in Figure 7. The uncertainty in this inversion is highest at the center because of the nature of the mathematics. Additionally, at the jet exit, interference from the nozzle affects signal quality; nevertheless, with the exception of the nonzero concentration along the centerline, the inverted signal reflects the expected liquid distribution in the plume. The Abel inversions of the data at 0.29 injector diameters away from the injector and at 1.14 injector diameters away from the injector exit are shown in Figures 8 and 9. Although there is no data collected using classical techniques readily available to compare with these measurements, at these locations where there is little interference, the inversions represent a mass distribution expected for this plume with most of the injectant concentrated at the edge of the plume and negligible amounts of liquid at the plume core. It should be noted that an additional source of error is the scattering of the fluorescence signal by the plume. Some proposed future work will address this issue.

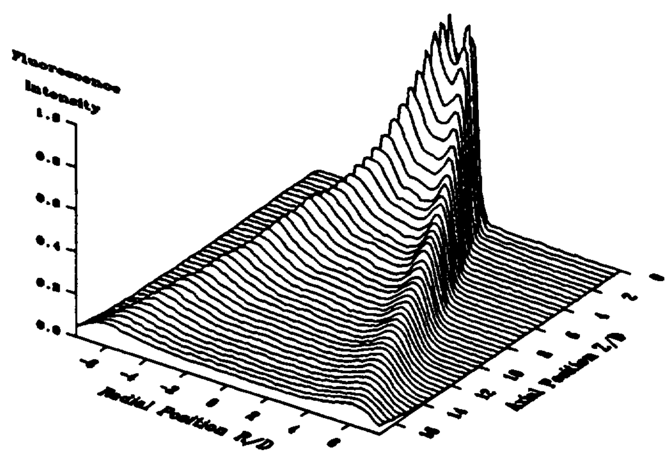

Figure 5: Fluorescence Data Collected at 105 psi With Uniform Illumination.

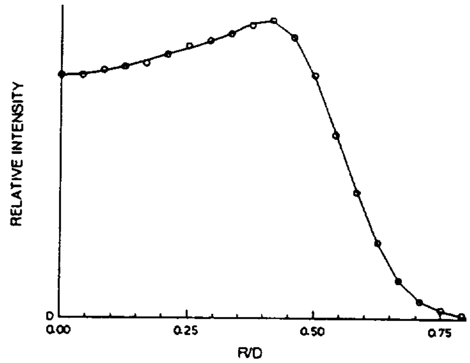

Figure 6: Data For Abel Inversion at Nozzle Exit

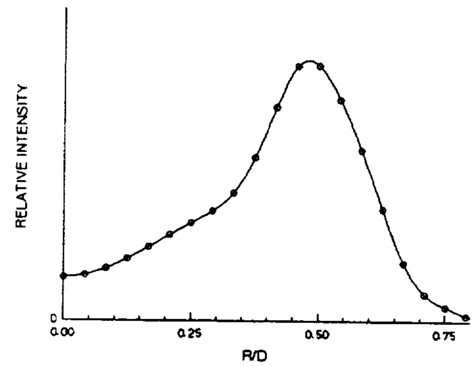

Figure 7: Abel Inversion at Nozzle Exit

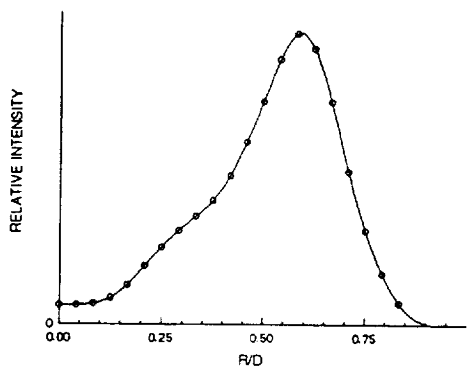

Figure 8: Abel Inversion at Z/D = 0.29

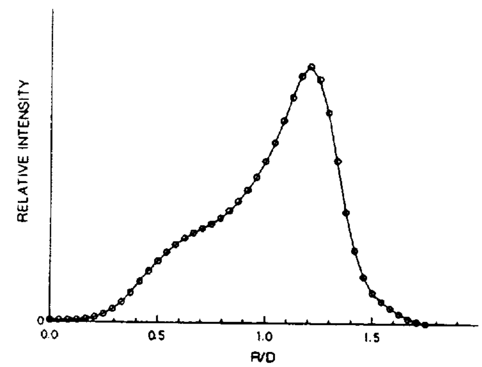

Figure 9: Abel Inversion at Z/D = 1.14

Conclusions

A swirl element injector flow field has been investigated using both visualization techniques and a new LIF technique for the quantitative measurement of the mass distribution of liquid in the plume. This work included the construction of a suitable spray rig, some film photography and the development of an appropriate quantitative measurement approach.

Acknowledgement

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References

1. Agarwal, Y., T. Hadeishi and Robben, F., "Measurement of NO_2 Concentration in Combustion using Fluorescence Excited by an Argon-Ion Laser," AIAA Paper 76-136, presented at the Fourteenth Aerospace Sciences Meeting, Washington, D.C., 1976.
2. Barnes, Russell H., Boiarski, Anthony A., and Kircher, John F., "Laser Spectroscopy For Continuous Combustion Applications," U. S. Department of Energy Report For Work Performed Under Contract No. W-7405-ENG-92-088.
3. Gulati, A. and Warren, R. E., Jr., "NO_2-Based Laser-Induced Fluorescence (LIF) Technique to Measure Cold-Flow Mixing," AIAA 92-0511, Presented at the AIAA Thirtieth Aerospace Sciences Meeting, Reno, NV (January 1992).
4. Hulka, J., Schneider, J. A., and Davis, J., "Single Element Injector Testing For STME Injector Technology," AIAA 92-3281, Presented at the Twenty-Eighth AIAA/SAE/ASME/ASEE Joint Propulsion Conference and Exhibit, Nashville, TN (July 1992).
5. Shelby, R. T., "Abel Inversion Error Propagation Analysis," Master of Science Thesis, The University of Tennessee, June 1976.