

## Author



# Experimental Study of Simulated MMH/MON-25 Sprays Generated by Doublet Injectors

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## Abstract

Vu Phi's work at UCI's Combustion Laboratory fostered his interest in combustion technology and instilled a desire to pursue a career in this field. Vu's research focuses on a project being sponsored by the Kaiser Marquardt Corporation. Vu found his experience with the Mars Ascent project to be extremely exciting because of the uncertainties of the project. He commented that his favorite experience was working with the laser sheet and watching the spray scattering on it. Vu also gained skills and knowledge about the tools and equipment with which he worked. Vu recommends that everyone take advantage of research in order to see textbook concepts "in action."

Low temperature (-40 °C) storable liquid propellant was considered as the propulsion source by the NASA Jet Propulsion Laboratory (JPL) to return samples from the planet Mars. The propellant combination selected was Monomethylhydrazine (MMH) fuels and Mixed Oxides of Nitrogen (MON) 25 oxidizers. Different sized doublet injectors were used to inject the two liquids. In this study, the basic properties of the sprays were characterized under cold flow test conditions, thereby allowing direct comparison of the results to corresponding hot fire tests. The strategy involved the use of simulants that met a variety of constraints. The characterization consisted of visualization for a variety of geometric and operational conditions. Once these results were reviewed, a reduced set of conditions was identified for a more detailed investigation using Planar Laser Induced Fluorescence (PLIF). The visualization results demonstrated the effects of the impingement angles, O/F ratio, and the liquid properties associated with the two temperatures (25 °C and -40 °C). The visualization indicated that greater impingement angles improved dispersion. Optimal performance was indicated at O/F ratios between 2 and 3 for the -40 °C case and at O/F ratios between 1 and 2 for the 25 °C cases. The PLIF results were obtained for four select cases at O/F ratios of 1.6, 2.0, 2.53, and 2.8. The case that demonstrated superior mixing and performance for the -40 °C case occurred at O/F = 2.0 (corresponded to Re ratio of 6.35).

## Faculty Mentor



This research is at the leading edge of liquid-fueled rocket technology. The technological challenges of space exploration are requiring creative solutions and the latest in laser diagnostics to overcome the key hurdles. Liquid fuels provide the attribute of flexibility over solid fuels, but demand new solutions for chamber injection if proposed interplanetary mission scenarios are to be successfully met. These results allow the design of optimized fuel/oxidant injectors, and form the foundation for the next generation "smart spray system" technology that will be required to support the demands of future space exploration. Vu Phi's efforts are recognized as contributing to the research projects of the Combustion Laboratory at UCI.

~ Scott Samuelsen

Henry Samueli School of Engineering

## Key Terms:

- ♦ High Speed Video (HSV)
- ♦ O/F ratio
- ♦ Planar Laser Induced Fluorescence (PLIF)
- ♦ Reynold Number (Re)
- ♦ Rotameter
- ♦ Rupe Number
- ♦ Simulant
- ♦ Viscosity

## Introduction

Humankind has always wanted to know more about terrestrial evolution and whether or not life exists elsewhere in the universe. One way to address these curiosities is to study other planets. Mars is of great interest because it is more similar to Earth than any of the other nearby planets. Consequently, much attention has been placed upon the study of Mars' surface and atmosphere. Researchers are addressing questions regarding the natural resources, the atmosphere, the presence or lack of water, the possibility of life, and many others. A key strategy to help answer such questions is a physical examination of specimens obtained from Mars.

To achieve this goal, NASA's Jet Propulsion Lab (JPL) established a program ("The Mars Ascent") in which a probe will be sent to Mars to collect physical samples and return them to Earth. Of course, the technical challenges for this program are significant, and many new fundamental issues have to be addressed before this goal can be accomplished. One main issue, which is being addressed by this research, is the ability to fire an engine on the surface of Mars.

Based on research done by NASA, advanced storable fuels offer attractive features for this project. The liquid fuels (Monomethylhydrazine, abbreviated MMH) and oxidizers (Mixed Oxides of Nitrogen, abbreviated MON 25) remain separate from each other on board the ascent vehicle. To create propulsion, the two liquids are introduced into the combustion chamber in the proper proportions to induce critical mixing processes, which result in spontaneous ignition. For these fuels, there are concerns about operation at -40 °C. First, will these two liquids ignite upon contact? Second, assuming ignition can be achieved, what is the optimum injection strategy (i.e., relative flowrates, impingement angle, injector geometry) to achieve the necessary engine performance to return a significant payload of specimens? The performance of the engine operating on these liquids depends on the ability of the injector to break up the liquid fuels and oxidizers into fine droplets and to evenly mix them together before ignition. As the temperature drops, liquids become thicker (viscosity increases) and at -40 °C the viscosity could prevent the fuels and oxidizers from either mixing or breaking up. Testing with rocket fuels at such low temperatures is very costly, and thus, tests using simulants at room temperature are used as a precursor to narrow the hot fire test requirements.

The purpose of this project is to help reduce the developmental costs by allowing testing to be done at conditions that mimic the conditions found on the Mars surface. By screening injectors and oxidizers to fuels (O/F) ratio inexpensively, the cost of the engine development was reduced significantly.

## Methods

The approach was to conduct an experimental study of the spray structures, generated by a pair of impinging injectors, and to establish the relationship between laboratory-scaled cold flow tests and the hot fire performance test. For safety reasons, diagnostic requirements, and cost factors, it was not practical to use the actual hypergolic (ignitable) liquids. Thus, simulants with suitable properties were developed. In addition, a test rig was constructed to allow injector pairs to be precisely positioned relative to one another. This allowed injection angle, impingement distance, O/F ratio, and liquid properties to be varied systematically while enabling advanced diagnostics to be utilized in order to characterize the spray structure in a systematic manner.

Since it was impractical to use the actual liquids from the hot fire tests, it was necessary to develop simulants that had the following attributes:

- match the viscosity, surface tension, and density of MMH and MON-25 at both 25 °C and -40 °C
- could be used safely in a laboratory environment
- allowed fluorescent dyes to dissolve to facilitate mixing studies
- could be generated in reasonable quantities at relatively low cost.

Based on analyses conducted by the project sponsor, Kaiser Marquardt, a scaling rationale for the simulants was developed. Since it was impossible to find simulants that could match all the physical properties of the actual fuels and still maintain the required attributes, it was necessary to develop a scaling rationale.

The Rupe number has been a traditional correlating ratio for these types of injectors (Rupe, 1953). In developing the correlation, the density ratios between the oxidizers and fuel simulants were kept in the same range as most of the hypergolic propellants density ratios, ( $\rho_o/\rho_f \approx 1.4$  to 1.6).

$$\text{Rupe number} = (O/F)^2 \frac{\rho_f}{\rho_o} \left(\frac{d_f}{d_o}\right)^3 \quad (1)$$

where

$d$  is injection diameter

$\rho$  is liquid density

$O/F$  is mass flow ratio of oxidizers to fuels

The subscript  $f$  stands for the fuels and  $o$  stand for oxidizers

Some of the current requirements precluded density matching, thus the decision was to match viscosity. This strategy, while precluding the use of the Rupe number, allowed the Reynolds number (Re) to be utilized as a similarity parameter:

$$Re = \frac{\rho u d}{\mu} \quad (2)$$

where

- d* is injection diameter
- $\rho$  is liquid density
- u* is the speed of the flow
- $\mu$  is the liquid viscosity

Dynamic similarity between the reacting and the non-reacting study can be achieved if the ratio between the oxidizers' Reynolds number and the fuels' Reynolds number are maintained:

$$\frac{Re_{oh}}{Re_{fh}} = \frac{Re_{os}}{Re_{fs}} \quad (3)$$

where the subscript

- oh* stands for oxidizers for hot fire,
- os* stands for simulant oxidizers,
- fh* stands for fuels for hot fire, and
- fs* stands for simulant fuels

In the present strategy, viscosities were closely matched between the propellants and simulants, and the same injectors were used for both the non-reacting study and hot fire tests. Therefore, viscosities and diameters could be removed from the Reynolds number equation. The Reynolds number criterion can be written as

$$\frac{\rho_{oh} u_{oh} d_{oh}}{\rho_{fh} u_{fh} d_{fh}} = \frac{\rho_{os} u_{os} d_{os}}{\rho_{fs} u_{fs} d_{fs}} \quad (4) \quad \text{or} \quad (O/F)_h = (O/F)_s \quad (5)$$

With the rationale developed for matching viscosity, a survey of candidates was conducted and four base liquids for mixing with distilled water were selected: 1) acetone, 2) glycerin, 3) ethanol, and 4) methanol. Different concentrations of acetone, glycerol, ethanol, and methanol at room temperatures were characterized at the University of California at Irvine Combustion Lab (UCICL) to establish the mixture(s) that matched the viscosities of MON-25 and MMH at -40 °C and 25 °C. In addition, it was desirable to quantify the surface tension and density of the resulting combinations. The correlation between viscosity and concentration for each mixture was established, and the points of interest were identified. Prior to developing the

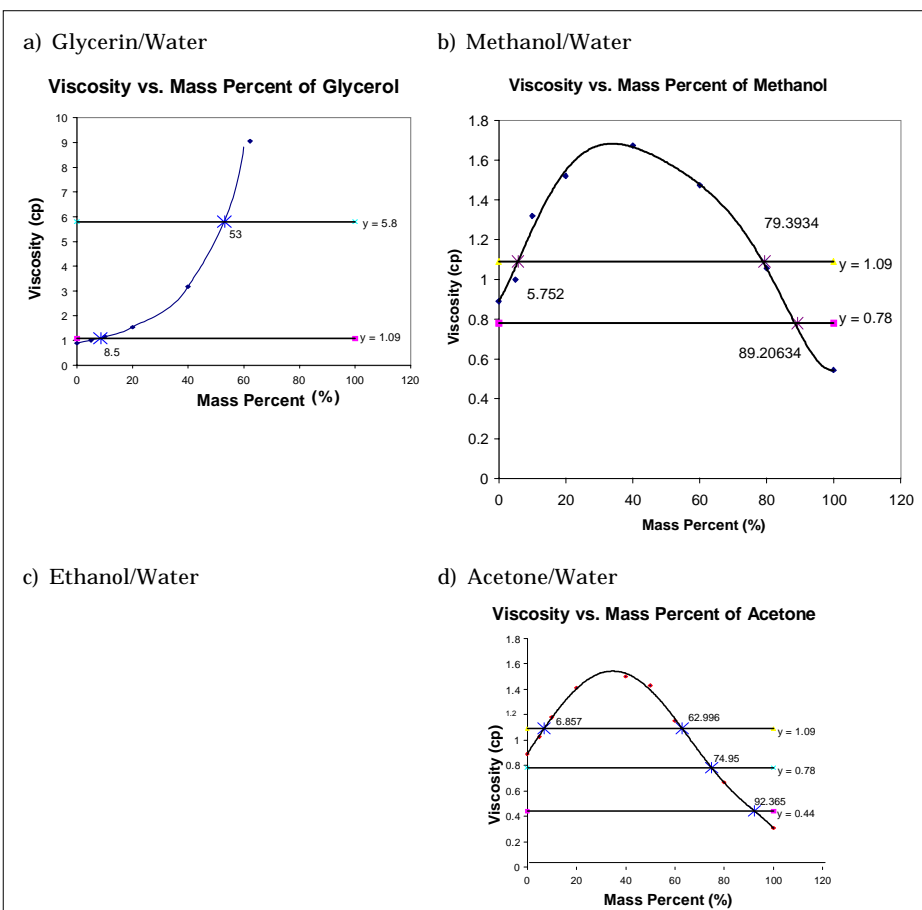


Figure 1

Viscosity versus mixture concentration of the four solutions. The desired viscosity was obtained by mixing the correct amount of the chemical with water.

correlation, a literature survey was conducted and some information regarding mixtures of the liquids was found. Consequently, the viscosity curves for glycerin/water and ethanol/water were already available (The CRC Handbook of Physics and Chemistry, 1995). The remaining task was to generate similar curves for acetone/water and methanol/water. A Gilmont Instrument's falling ball type viscometer model #GV-2100 was used to calculate these curves (see Figure 1). Concentrations with suitable viscosities were then further characterized for surface tension and density. Surface tension was measured using a "Q" Glass Company, Inc. Surface Tension Apparatus model #14-818, and density was measured using a precision digital balance. The final selection of liquids and the associated measured properties are shown in Table 1.

### Experiment

In parallel with the development of simulants, a test fixture was designed to accommodate the doublet injectors, which were made of titanium with gold-coated tips. There were three desired variables for the test fixture. First, there was the ability to exchange injector orifice geometry

quickly and easily. Second, there was the ability to vary the impinging angles of the two injectors ranging from 50-90 °C in increments of 5 °C. Finally, there was the ability to vary the impingement distance in all three axes.

Due to the reactivity of the simulants, all parts in contact with the chemicals were fabricated from 316 stainless steel or Teflon. The components utilized for the fixture included an x-y-z transverse, an x-transverse, two stainless steel injector holders, and an aluminum back panel with incremental angle mounting plate, two rotameters, and four stainless steel chemical storage tanks.

The two rotameters were made by Aalborg and featured all-Teflon construction for parts in contact with the chemicals. The four stainless tanks were properties of the UCI Combustion Lab and were used to mix and feed the simulants. Five-gallon batches of simulants were generated for each sequence of tests. After any dye was used, the tanks and any connected piping required rinsing with acetone to remove the residual dye. The testing with fluorescence was conducted last to help reduce the number of times rinsing was required. The tanks were pressurized with nitrogen at a level sufficient to drive the liquid (90 psig). Pressure relief valves and vents were provided as safeguards against explosion.

As mentioned above, the desired parameters included varying the injector impingement angle from 50-90 °C. The strategy was to have one injector fixed at a 45° angle from the horizontal and the other injector varied between 45° and 85° from the horizontal (see Figure 2). A second requirement was for the tip of the nozzles to be located such that the impingement point was at 4-10 orifice diameter from the injector tip. Given the small size of the orifice (on the order of 0.010 in), the setup required precise alignment and positioning. The solution was to mount the injectors on precision translation stages. The fixed injector was mounted on a Newport ULTRAlign 462 single-axis stage and the mobile injector was mounted to a Newport ULTRAlign 462 multi-axis stage. Each stage allowed for

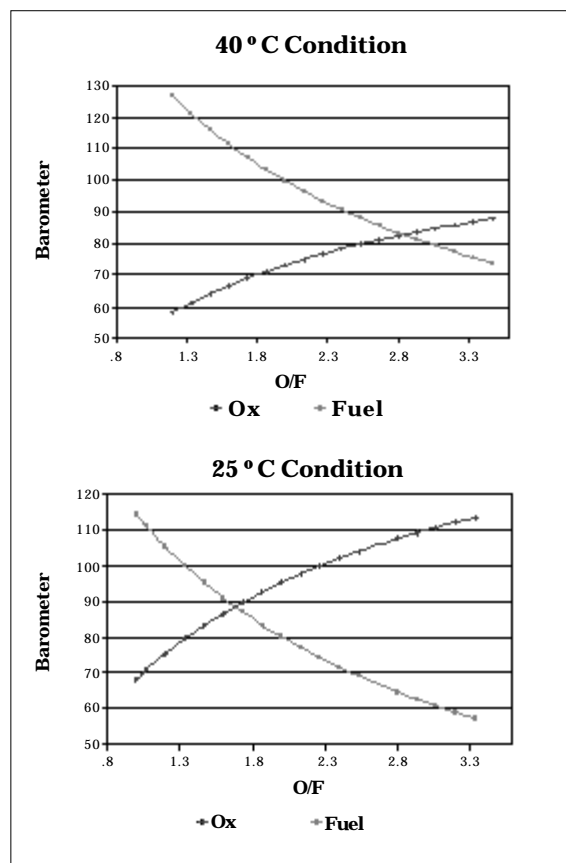
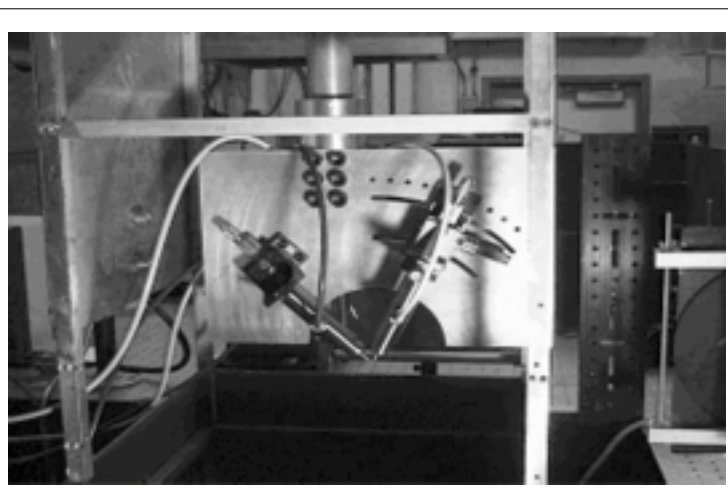
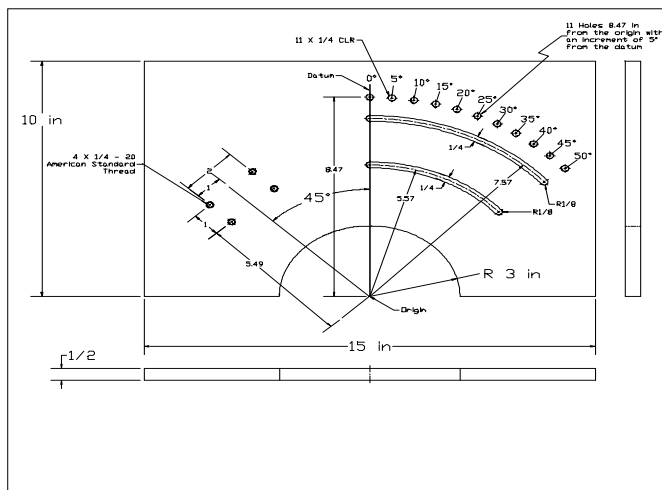


Figure 4 Rotameter calibration curve and settings versus O/F.

one inch of total travel and provided the necessary precision and ease of alignment. A high-magnification video camera was used to aid in the positioning and stand-off distance.

The arc cut below the injectors on the mounting plate was required for the application of optical diagnostics (see Figure 2 and Figure 3).



Figures 2 and 3

Schematic of mounting plate which illustrates the positioning of the injector at various angles and photo of the final setup.

The third requirement was to correctly meter the flows. Aalborg's all-Teflon rotameters were used. The calibration curves established for controlling the flow rate are presented in Figure 4. Note that the required O/F conditions provided by Kaiser Marquardt involved variation of both oxidizers and fuels.

### Diagnostics

Two non-intrusive diagnostics were utilized: high-speed video and Planar Laser Induced Fluorescence (PLIF). High-speed video was used to screen cases of optimal at-

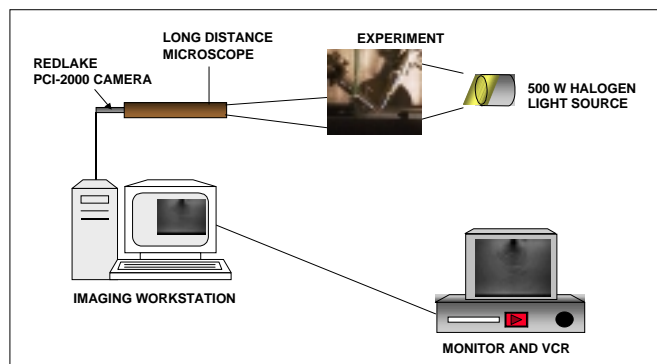


Figure 5

Overall setup for high magnification, high-speed imaging.

In addition to the qualitative results from the imaging, Planar Laser Induced Fluorescence (PLIF) was used to characterize the extent of mixing. In particular, with the setup utilized a 16-bit Thermoelectrically cooled CCD array) and the experience with this technique at the UCICL, it was expected that at least semi-quantitative results could be obtained.

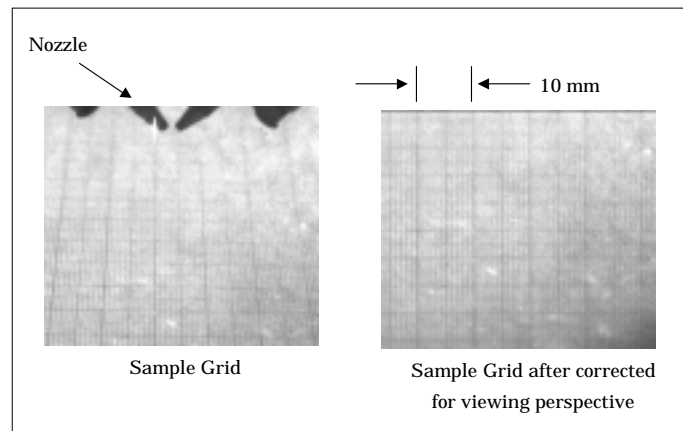


Figure 7

Illustration of the calibration grid image and subsequently corrected grid image.

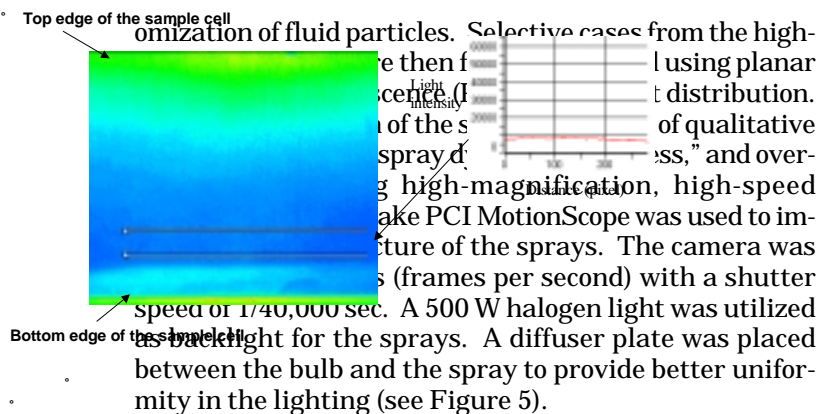


Figure 6

Setup for Planar Laser Induced Fluorescence (PLIF) diagnostic.

In the present study, mixing effectiveness was assessed by selectively dyeing the oxidizers or fuels and by using a selection of filters to isolate one from the other. With both streams dyed, the overall dispersion of material could be assessed. With just the fuels dyed, the dispersion of the fuels relative to the combined mixture could be assessed. One limitation of this strategy was the time-averaged behavior, which was acceptable for the present study. Fluorescein was used at a concentration of 0.0076 g/gal of simulant. This amount created an optically thin liquid that generated reasonable signal levels when excited by a 488 nm Ar<sup>+</sup> laser operated at 200 mW. A 16-bit TE-cooled intensified CCD array (Princeton Instruments) was used to detect the fluorescence. A low pass filter was used to cut off light scattering and background noises (see Figure 6).

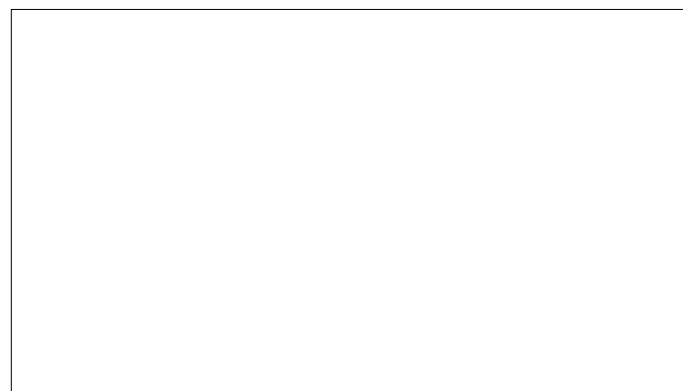


Figure 8

Laser sheet intensity profile (sheet traverses from bottom to top of cell).

A two-step process was used to make the images into semi-quantitative quality. First, the images were obtained at an oblique angle, as illustrated in Figure 6. To correct for this angle, a calibration image was obtained using a target with known geometry (Figure 7 illustrates the image obtained and the resultant corrected image).

The image was taken with a camera at an angle of  $29^\circ$ , so the image (on the left) formed a trapezoidal grid instead of square. A method called "Affined Transform" was used to reshape the image back into a square grid on the right image.

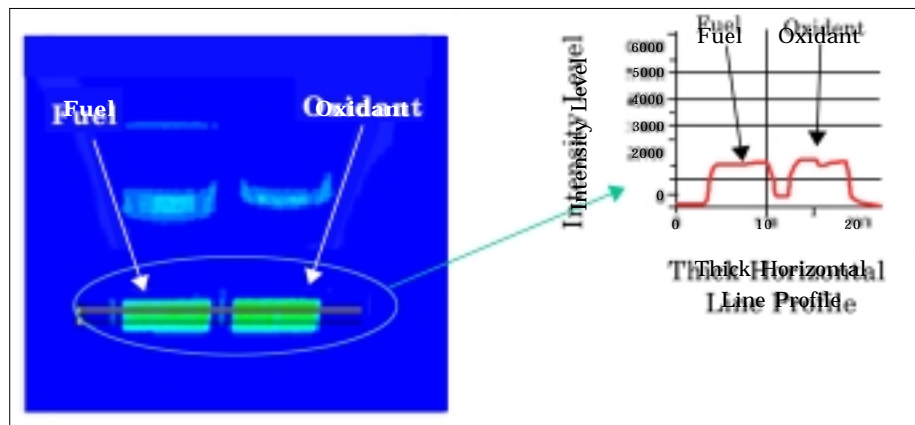


Figure 9

Comparison of fluorescence levels from fuels and oxidant simulants. A typical comparison of the measured intensity levels for the oxidizers and fuels simulants for the  $-40^\circ\text{C}$  case.

Next, the laser intensity profile was characterized. Since the fluorescence level was directly proportional to the incident light intensity, spatial variations of the intensity could lead to misinterpretation of the images. In the case of the Argon ion laser, a Gaussian intensity profile is an inherent feature of the light beam. In the present case, cylindrical lenses were selected to over-expand the beam relative to the focal length and diameter of a collimating lens. The result was that only the center portion of the beam, which featured little spatial variation, was utilized. Figure 8 illustrates the intensity profile of the laser sheet utilized. The locally bright regions along the very bottom of the cell were due to reflections.

In order to minimize secondary scattering, the laser was operated at very low power and weak dye concentrations were used. While additional steps can be taken to account for other sources of attenuation (Talley et al., 1997), they were not utilized in the present case.

The final issues addressed were the possible uncertainties introduced by significant mismatches in the concentration of dye in the fuels or oxidizers stream. In mixing the different simulants and introducing the dye, a solution was generated with 0.038 g fluorescein dye mixed into 5 gal-

lons of liquid. Despite the care taken in weighing the dye (which is in the form of a salt) and measuring the liquid volume, uncertainties present created opportunities for mismatches in dye concentration. Rather than assuming that the concentrations were similar, measurements of the sample were taken to generate a calibration factor (see Figure 9).

The results from Figures 7, 8, and 9 allowed for the viewing perspective, laser intensity variation, and relative dye concentration to be accounted for in the PLIF measurements.

Despite the care taken above, several key assumptions remained with respect to the use of PLIF in the present study. First, since the measured intensity was based on time spent in the excited light, differences in velocities between the cases could result in differences in intensity levels independent of the dye concentration. This effect was difficult to account for in the absence of detailed velocity measurements. Second, the diffusivity of the dye in the different liquid combinations, and the relative mixing time of the simulants compared to the actual liquids, had not been assessed. As a result, the images obtained cannot be considered quantitative.

Finally, although acetone was observed to dissolve the dye utilized, subsequent excitations resulted in minimal signal, indicating strong quenching. As a result, despite the careful selection of apparently appropriate liquids, PLIF results for the  $25^\circ\text{C}$  case were impossible with the simulants utilized.

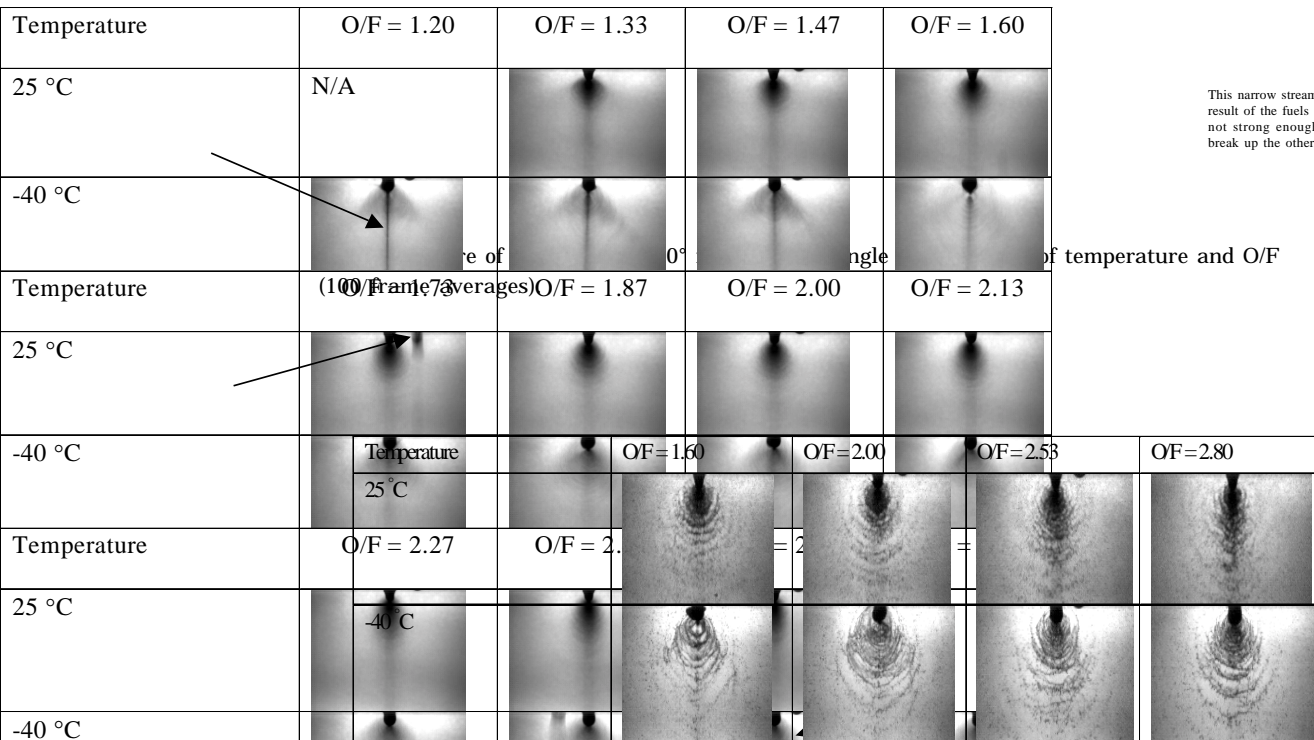
## Results

Kaiser Marquardt selected injectors with orifices of 0.0230 and 0.0168 inches in diameter for the oxidizers and fuels, respectively. These injectors were then characterized using high-speed video. They were then taken to Kaiser Marquardt for the hot fire tests. Later, they were returned to the UCICL, where the Planar Laser Induced Fluorescence (PLIF) studies were conducted.

This tail in the center is because of one liquid stream penetrating through the fan. ("blow through")

A Droplet form on the side of the injector

This is characteristic of a good spray. The fan is very wide and there is no center tail.



This narrow stream is the result of the fuels stream not strong enough to break up the other stream.

Figure 11 Spray structure of simulants for 90° impingement angle as a function of temperature and O/F (2/30,000 sec exposure)

Temperature	O/F = 3.03	O/F = 3.07	O/F = 3.20
25 °C			
-40 °C			

The effect of O/F is illustrated first for an impingement angle of 90°. Results are shown for both the 25 °C and -40 °C conditions. The following two types of results are shown: 1) time-averaged sequences of images, shown in Figure 10, and 2) single snapshot frames, shown in Figure 11.

The instantaneous behavior illustrates obvious ligaments and patterns in the dispersion of the material, which may be critical in the resulting performance. The images presented in Figure 10 show some distinct trends. In particular, there is a transition from a heavy central streak to a well-dispersed spray and then back to a heavy central streak as the O/F ratio increases. The heavy streak was associated with either the fuels or oxidizers stream as the momentum dominated. For the -40 °C case, this local heavy streak was minimized at O/F ratios between 2 and 2.8. This suggests that the dispersion, and possibly the mixing, were more optimal for O/F in this range (at least for the -40 °C cases).

The 25 °C case showed some similarity in behavior compared to the -40 °C case. However, the 25 °C case tended to produce more dispersion at lower O/F ratios compared to the -40 °C case. Of course, the higher viscosity associated with the colder liquids would delay breakup, and this was evident in the comparison of the images. The optimal range for the 25 °C case appeared at O/F ratios between 1.6 and 2.0.

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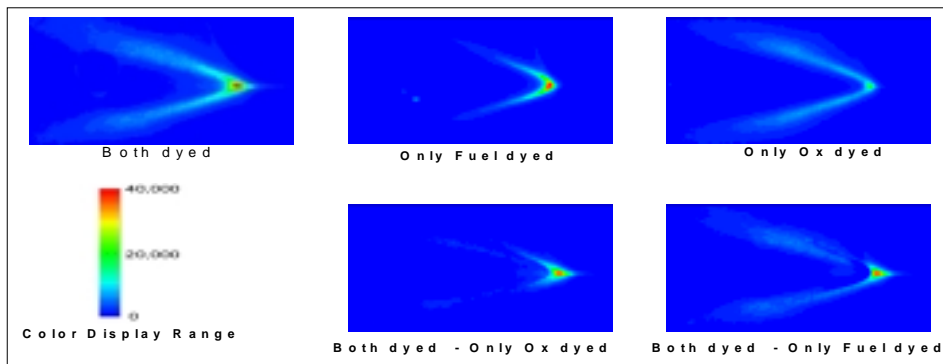


Figure 12

Comparison images for O/F 1.60. Due to the dynamic of this space, the result could be misleading and was not analyzed.

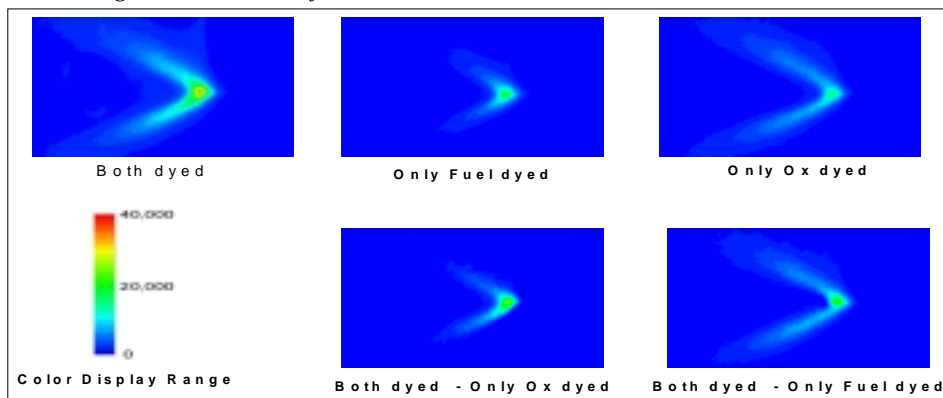


Figure 13

Comparison images for O/F 2.00. The image showed signs of good mixing. The oxidizers and fuels were located at relatively the same space and had similar intensity level.

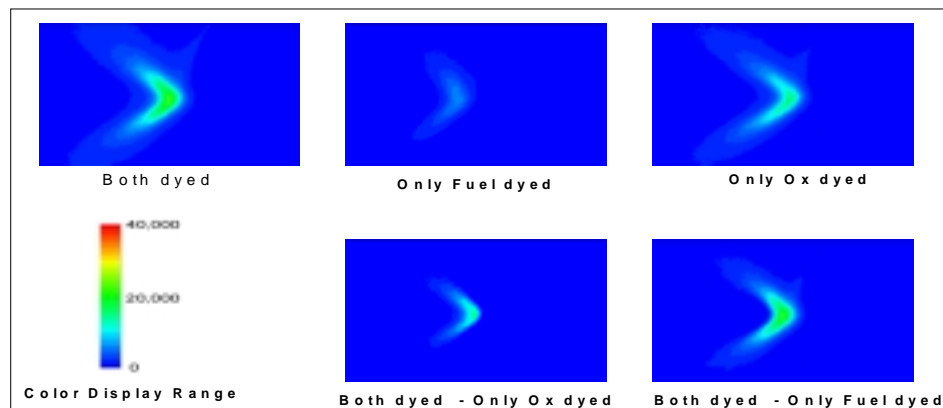


Figure 14

Comparison images for O/F 2.53. Oxidizers were in excess relative to fuels for this case.



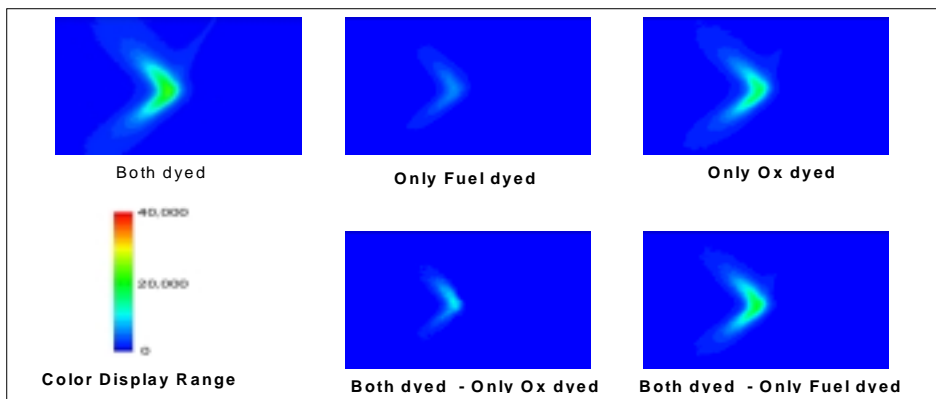


Figure 15

Comparison images for O/F 2.80. The light intensity level for the fuels was too low compared to the oxidizers.

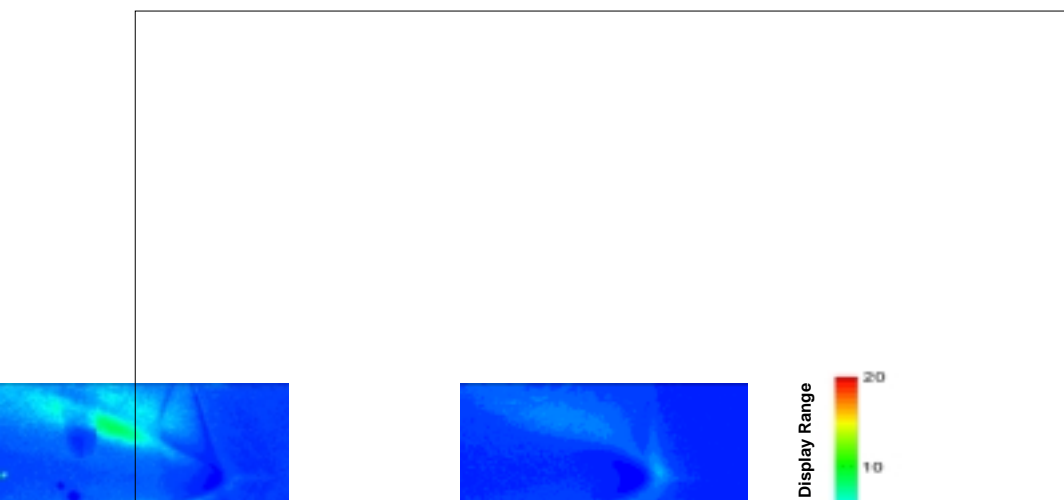
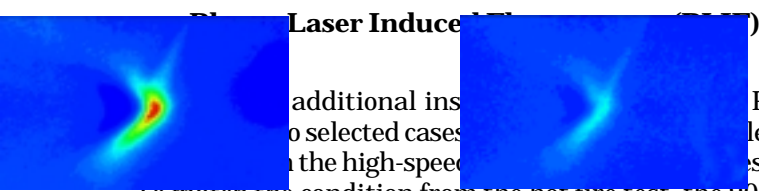


Figure 16

Results obtained by dividing oxidizers images by fuels images (Figures 12-15).  
 O/F = 1.60                      O/F = 2.00



additional ins... PLIF  
 to selected cases... selected  
 at the high-speed... results.  
 O/F = 1.60                      O/F = 2.00  
 To match the condition from the not pure test, the 90° impingement angle was selected. Further, the O/F range was limited between 1.6 to 2.80 for the -40 °C case. Although great care and thought were given to the selection of test liquids, the results from the acetone were impossible to obtain.

In order to reduce errors, great care was also taken to match the dye concentrations in the oxidizer's and fuel's streams. As a quality check, tests were conducted with: 1) both streams dyed, and 2) with either fuels or oxidizers stream dyed. Figures 13-16 show the comparison of the combinations of images. Ideally, if the image with only the fuels dyed is subtracted from the image with both streams dyed, the result should resemble the image with only the oxidizers' stream dyed. In Figures 12-15, a com-

parison between the two images on the right side of the upper row and the two images on the bottom row should reveal very similar structure.

Figure 12 shows the results for the O/F = 1.6 case. It was noted in the visualization of this particular case that the spray would “flap” back and forth, jumping from a small angle fan to a large angle fan and vice versa. As a result of the inherent dynamics associated with this condition, the comparisons shown in Figure 12 could be misleading.

The results displayed in Figures 13-15 were much more consistent. Visually, the fan remained relatively similar throughout the test. Some differences were noted between the upper and lower rows that were attributed to experimental errors and dynamics in the sprays. However, since the overall trends and appearances were consistent, the images could, in principle, be utilized to assess mixing. If the fuels and oxidizers were dispersed equally, the pattern of images of the fuels and oxidizers should occupy the same space within the image. In comparing the various cases shown, it became apparent that the fuels and the oxidizers have significantly different patterns of dispersion, indicating that the mixing was far from perfect.

Several steps were taken to further the analysis. The first involved dividing the oxidizers image by the fuels image. This was a good way to represent the O/F ratio throughout the image's field of view. Figure 16 shows the results of this exercise. The results appeared inconsistent. A portion of the inconsistency could be due to the fact that the PLIF measurement was an indication of the mass of material present per unit area. As a result, droplets with higher velocities had inherently less signal intensity. Since the flow rates of oxidizers and fuels were both changing when the O/F ratio changed, this could introduce an effect that had not been accounted for, thereby generating inconsistencies in the results. Also, since the noise levels were essentially constant throughout the image, signal to noise ratios at the edges of the sprays were inherently reduced.

Setting these issues aside, the results shown in Figure 16 suggest that the O/F 2.00 had a more uniform O/F ratio over the area of interest.

## Summary

An experimental study of atomization, mixing performance, and basic spray structures was conducted for unlike doublet injectors for use with liquid fuels. Two methods of study were used: 1) High speed Video (HSV), and 2) Planar Laser Induced Fluorescence (PLIF). Using High Speed Video, the optimum atomization and the finest droplets occurred between an O/F ratio of 1.87 and 2.67 for the -40 °C case and an O/F ratio of 1.33 to 2.13 for the 25 °C case. Second, cases between 1.60 and 2.80 for the -40 °C case were selected for further testing using PLIF. The case that offered the best mixing with a reasonable well-atomized spray had an O/F ratio of 2.00, which corresponds to a Reynold number ratio for the oxidizers and fuels flow of 6.35.

Since the injector diameter and fluid viscosity were held constant, it was possible to use the ratio of the Reynold number as a scaling parameter between the cold flow test and hot fire tests at Kaiser Marquart. Using Reynolds ratio scaling, optimal hot fire test performance was achieved for the -40 °C case when the ratio of Reynold numbers for the ox and fuels streams was 6.35 (O/F of 2.00). Optimum performance for both cold flow and hot fire test occurred at a Reynold ratio of 6.35 (O/F of 2.00), suggesting that the cold flow test could be used to identify optimum firing conditions.

## Conclusion

This project, based on a novel scaling strategy (viscosity-matching of actual propellants), coupled with data obtained from using high speed video (HSV) and Planar Laser Induced Fluorescence (PLIF) techniques, was successful in predicting the optimum oxidizers to fuels (O/F) ratio for a -40 °C rocket launch, which is the condition found on Mars surface. By applying these techniques, the engine designer can save a significant sum of money by narrowing the optimum O/F ratio to a few points. The results then can be confirmed with a relatively small number of expensive hot fire tests. Although there appears to be great potential for applying HSV and PLIF for scaled conditions to predict optimum performance, more research must be conducted before these techniques can be used. Independent of the quantitative results, the HSV methods provide tremendous insights into the basic phenomena occurring and give the designer additional information regarding design strategies. For example, the results illustrate complex dynamics, stream break ups, and mixing processes. In summary, these advanced diagnostic methods have resulted in a key strategy for providing information regarding the basic physical processes that occur in a complex rocket engine system. Moreover, this project has resulted in an inexpensive method to test rocket fuels under conditions mimicking those on the surface of Mars.

## Acknowledgements

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