IN-20
58240
P-10

NASA Technical Memorandum 105322

Coaxial Injector Spray Characterization Using Water/Air as Simulants

Michelle M. Zaller
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Mark D. Klem
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Prepared for the
28th JANNAF Combustion Meeting
San Antonio, Texas, October 28—November 1, 1991

NASA

Coaxial Injector Spray Characterization Using Water/Air as Simulants

Michelle M. Zaller
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

Mark D. Klem
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

Quantitative information about the atomization of injector sprays is required to improve the accuracy of computational models that predict the performance and stability of liquid propellant rocket engines. An experimental program is being conducted at the NASA Lewis Research Center to measure drop size and velocity distributions in shear coaxial injector sprays. In the first phase of this program, a phase/Doppler interferometer is used to obtain drop size data in water/air shear coaxial injector sprays. Droplet sizes and axial component of droplet velocities are measured at different radii for various combinations of water flow rate, air flow rate, injector liquid jet diameter, injector annular gap, and liquid post recess. Sauter mean diameters measured in the spray center 51 mm (2.0 in) downstream of the liquid post tip range from 28 to 68 μm, and mean axial drop velocities at the same location range from 37 to 120 m/s (120 to 390 ft/s). The shear coaxial injector sprays show a high degree of symmetry; the mean drop size and velocity profiles vary with liquid flow rate, post recess, and distance from the injector face. The drop size data can be used to estimate liquid oxygen/hydrogen spray drop sizes by correcting property differences between water/air and liquid oxygen/hydrogen. The detailed velocity and local drop size data produced in this test program using a variety of geometry, recess, and flow rate parameters can provide validation for recently developed multi-dimensional atomization models.

INTRODUCTION

Obtaining measurements of drop sizes produced by liquid propellant rocket injector sprays has been identified by the JANNAF Liquid Rocket Combustion Instability Panel[1] and the JANNAF Performance of Solid and Liquid Rockets Panel[2] as critical to improving the accuracy of computational models that predict the performance and stability margin of liquid propellant rocket engines. These panels found that drop size predictions made by available atomization models were grossly inaccurate, did not take into account liquid oxygen post recess, and often required correction using cold flow test data. Wide variation in the drop size predictions by existing models has been reported to exist.[3] Recess of the liquid post in coaxial injectors has been shown to increase performance,[4] but drop size correlations do not take into account the recess geometry and no conclusive atomization data has shown the effect of recess. The panels recommended the acquisition of detailed quantitative atomization data to aid development of more mechanistic atomization models. Improving atomization models was determined to be important because the drop size and velocity distributions produced at the completion of atomization are the initial conditions for vaporization, mixing, and reaction calculations. Without detailed spray drop size and velocity measurements, accurate liquid rocket engine performance and stability predictions cannot be made. Making accurate performance and stability predictions would contribute to reducing the expensive testing performed in engine development programs, avoiding combustion instabilities, and optimizing the efficiency of new engines.

Efforts have been made by several investigators to determine the drop sizes produced by shear coaxial rocket injectors, and experiments have been conducted on airblast atomizers with geometries similar to shear coaxial injectors. Extensive literature surveys are given by Ferrenberg[5] and Lefebvre.[6] Early work was performed using hot wax freezing or droplet capture techniques: these intrusive techniques could not be used to measure particle velocities. Holography was applied non-intrusively to measure drop sizes in rocket engines, but was not used to measure droplet velocities. Drop sizes obtained using holography had large uncertainties due to the limited number of drops counted at each test condition. Ferrenberg[5] conducted an extensive study of coaxial injectors using a visibility/intensity droplet sizing interferometry (V/I DSI) technique. This technique was capable of simultaneously measuring droplet sizes and velocities. The study was limited by the inability of the V/I DSI to reliably measure drop sizes below 18 μm, handle a wide droplet velocity range, or make measurements in dense sprays. Gomi[7] applied a laser diffraction technique to coaxial injector sprays: velocities could not be measured with this technique, and only spatially averaged drop sizes at a few radial locations were obtained. Sankar[8] used a Phase/Doppler Particle Analyzer to make coaxial injector spray measurements of drop size and velocity with high spatial resolution; however, gas velocity, liquid flow rate, and injector geometry were not varied extensively in those tests.

A test program was initiated at NASA Lewis Research Center to obtain the detailed atomization data required to improve current modeling capability.[3] The first phase of the test program was intended to provide an estimate of the capabilities of the droplet sizing instrumentation, and provide detailed mappings of the drop sizes produced by water/air coaxial injector sprays as a function of liquid and gas flow rates and injector geometry. The second phase of the test program was proposed to obtain drop size and velocity measurements in confined liquid nitrogen/helium coaxial injector sprays. Confining the spray will permit the effect of varying chamber pressure to be examined, and the use of liquid nitrogen/helium will closely simulate the fluid properties of liquid oxygen/hydrogen. The third phase of the test program was proposed to obtain drop size data in a LOX/hydrogen rocket engine using the same single element coaxial injector. The results of the first phase of the test program are presented here.

The physics of atomization are quite complex. Detailed and accurate models of the atomization process have not been developed to the point where they can reliably predict drop sizes resulting from the injection process. Therefore, drop size and velocity measurements, as well as local gas velocity measurements, obtained in operating combustors using non-intrusive techniques, are required to validate atomization models and improve modeling capabilities.[9,10] Unfortunately, the hostile environment of rocket engine combustors has prevented detailed measurements of drop size and velocity from being taken. Due to the lack of hot firing rocket combustor atomization data, modelers use other methods to estimate the drop sizes occurring in the hot firing engine. One such method is to use equations with adjustable parameters that have been calibrated by forcing the overall performance predictions to agree with actual performance measurements. Another method is to use drop size correlations derived from cold flow test results that have been adjusted to take fluid property differences into account. The cold flow data presented in this paper can be used in this one-dimensional method if the property differences between water/air and liquid oxygen/hydrogen are taken into account. The wealth of detailed velocity and local drop size data produced from this test program using a variety of injector geometries, liquid post recesses, and flow rate parameters will provide validation data for more sophisticated, multi-dimensional atomization models. This test program has contributed detailed shear coaxial rocket injector drop size and velocity data to existing atomization databases, and has provided the first clear evidence of the effect of liquid post recess on the spray drop size and velocity profiles.

EXPERIMENTAL SETUP

A single element shear coaxial injector was used for these tests (Figure 1). This injector element has an interchangeable post and face plate, allowing the gas and liquid exit areas to be varied. The injector dimensions used for these tests are listed in Table 1. These geometries were selected to satisfy the hot fire LOX/hydrogen injector design for a 311 N (70 lbf) thrust injector.[3] Water flowed through the center orifice, and air through the annulus. The injector was sprayed into ambient air: no attempt was made to confine the spray. Both gas and liquid flow rates and velocities were varied. The data were taken using sufficiently low gas flow rates to avoid choking at the injector exit. Conducting tests with the gas gap unchoked allows the atomizing gas velocity to be varied, and more closely simulates the unchoked gas flow in a hot firing engine. The liquid flow rates were reduced from the injector design flow rates to correspond to the gas flow rates. Air and water flow rates were measured with rotameters. The water flow rate uncertainty was computed to be ±2% (95% confidence level), and the air flow rate uncertainty, ±5% (95% confidence level).

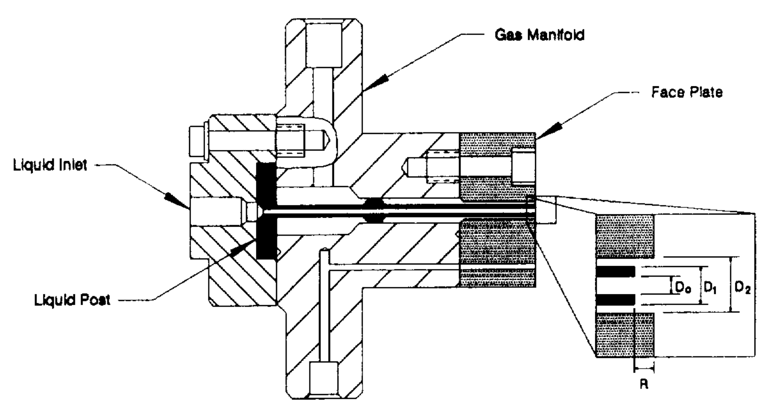

Figure 1. Shear Coaxial Injector Design

Table I. LeRC Modular Coaxial Injector Configurations

Configuration	No. 1	No. 2	No. 3	No. 4
D_2, mm (in)	5.56 (.219)	5.16 (.203)	5.16 (.203)	5.16 (.203)
D_1, mm (in)	3.18 (.125)	3.18 (.125)	3.18 (.125)	3.18 (.125)
D_o, mm (in)	1.32 (.052)	1.32 (.052)	1.98 (.078)	2.54 (.100)
R, mm (in)	0 (0)	variable	variable	variable

A phase/Doppler interferometer (PDI)[11] was used to make simultaneous measurements of droplet size and one droplet velocity component in the shear coaxial injector sprays. Phase/Doppler instruments are single particle counters that extract size and velocity measurements from the light scattered by each drop that passes through the probe volume formed by intersecting laser beams. The PDI included transmitting and receiving fiber optic links. The receiver was located at 30° to collect the forward-scattered light. A Berglund-Liu monodisperse droplet generator was used to calibrate the sizing capability of the PDI. The system was calibrated by adjusting the software parameters until two different sizes of monodisperse droplet streams were measured to within ±2%. A single optical configuration was employed for all tests. The selected optical configuration provided a total size measurement range capability of 2.0-230 μm. The transmitter focal length used was 170 mm, with a beam separation of 9.0 mm, and receiver focal length, 300 mm.

An Aerometrics Doppler Signal Analyzer (DSA) was used to process the signals. The DSA is a frequency domain processor that permits size and velocity measurements to be taken in high number density sprays at very low signal-to-noise ratio levels. The DSA filters were set to allow velocity measurements from 0-250 m/s (0-820 ft/s) to be made. Since the DSA was used in conjunction with a fiber optic receiver, the bias in the size measurements due to variations in the signal phase measured by each detector needed to be zeroed out. A "calibration" laser diode included with the DSA was used to equalize the phase measured by the photomultiplier tubes. This calibration was repeated approximately once every 100 test runs.

The effect of sample size on the mean drop sizes was determined by taking several measurements at one spray location while varying the number of valid samples collected. The mean drop sizes varied widely for small sample sizes. As the sample size was increased, the standard deviation of the mean drop sizes reached a minimum at a sample size of 6000. Larger sample sizes did not lower the standard deviation further, so a sample size of 6000 valid drops was selected for all the tests.

The symmetry of the drop size and velocity distribution profiles at an axial location of 50.8 mm (2.0 in) was examined by traversing the probe volume along four radii of the spray separated by 90°. Variations in mean drop sizes taken at the same radial location were as high as ±20% at a 95% confidence level. However, the PDI drop size measurement variation at any given location in the spray taken at different times was determined to be ±15% at a 95% confidence level. This implies the sprays could be fairly symmetrical, since much of the asymmetry could have been caused by the variation in measurement repeatability. Several data sets were obtained by traversing across a diameter of the spray; since these data sets exhibited a high degree of symmetry, the remaining tests were conducted by traversing along only half the spray diameter.

Repeatability of the mean drop size measurements was determined to be affected largely by the photomultiplier tube (PMT) gain. The effect of the PMT gain on the measurements was examined by taking data at one spray location using different high voltages on the photomultiplier tubes. Mean drop sizes decreased almost linearly with increasing PMT sensitivity, giving no indication of an appropriate PMT gain selection. It was decided to select the PMT high voltage that produced the maximum valid data rate (valid number of drops accepted divided by the time required to acquire the data). The valid data rate reached a maximum value as the PMT gain was varied, but only in the higher number density region of the spray. Typical valid data rates in the spray center exceeded 13,000 Hz. Beyond a radius of 12.7 mm (0.5 in), no method was found to improve the drop size measurement repeatability. Therefore, the drop size measurement uncertainty was large at the edge of the spray, and data obtained beyond 12.7 mm (0.5 in) radius have been omitted. By discarding the data at the spray edge, and maximizing the data rate as a criterion for selecting the PMT high voltage, measurement repeatability was improved to ±10% (95% confidence level) for the Sauter mean diameter.

RESULTS

Sauter mean diameters and drop mean axial velocities are presented for Configuration 1 (see Table 1) as a function of radius for one water flow rate of 0.0032 kg/s (0.007 lb/s) and three air flow rates of 0.0027, 0.0041, and 0.0055 kg/s (0.006, 0.009, and 0.012 lb/s) in Figures 2a and 2b. Mean drop sizes decrease with increasing air flow rate, in agreement with observations made by numerous investigators.[13-20] The largest increase in Sauter mean diameter (SMD) appears as the air flow rate increases from 0.0027 kg/s (0.006 lb/s) to 0.0041 kg/s (0.009 lb/s). SMD values at the edge of the spray were not observed to be minimum values. In tests performed by Sankar,[8] minimum SMD values did occur at the spray edge. Gomi[7] measured a slight increase in mean drop sizes at the edges of shear coaxial injector sprays. Well defined peaks occur in the SMD at the spray center for air flow rates of 0.0041 and 0.0055 kg/s (0.009 and 0.012 lb/s). For an air flow rate of 0.0027 kg/s (0.006 lb/s), the SMD profile is very flat in the spray center, indicating that the air flow rate influences the shape of the drop size profiles. In Figure 2b, the mean axial drop velocities reached maximum values at the spray center. The velocity for all three flow rates approaches the same value of 10.0 m/s (32.8 ft/s) at radius of 12.7 mm (0.5 in). Velocity profiles for all three air flow rates reach a definite peak at the centerline, but the peak velocities decrease with decreasing air flow rate. Since the centerline velocities get smaller as air flow rate decreases, while the outer velocities remain constant, the velocity profiles flatten as air flow rates are reduced. While there is a large reduction in SMD from 0.0027 kg/s (0.006 lb/s) to 0.0041 kg/s (0.009 lb/s) air flow rate, the drop velocities do not show a similarly large increase. The observed change in drop size corresponding to a regular increase in velocity at the centerline indicates a nonlinear relationship between the drop sizes and the drop velocities as a function of injected gas flow rate.

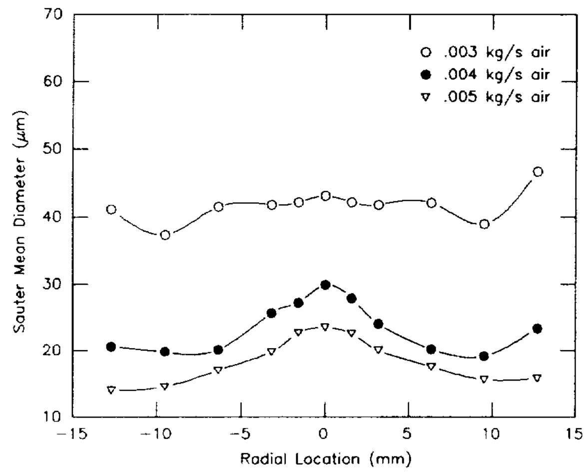

Figure 2a. Effect of varying air flow rate on Sauter mean diameter as a function of radius. Water flow rate is 0.003 kg/s; Configuration 1.

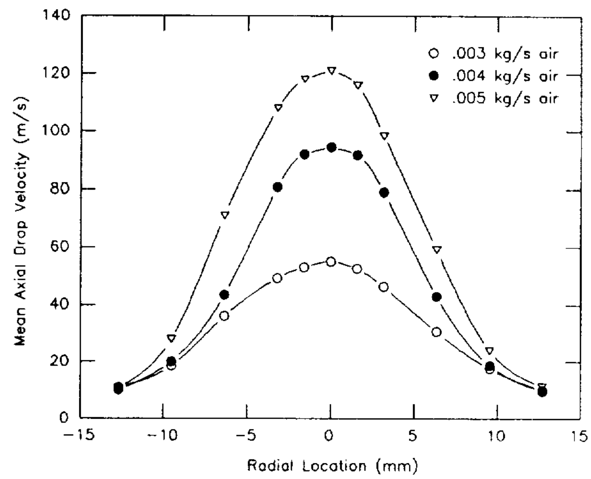

Figure 2b. Effect of varying air flow rate on mean axial drop velocity as a function of radius. Water flow rate is 0.003 kg/s; Configuration 1.

SMD data and drop mean axial velocities are presented in Figures 3a and 3b for a higher water flow rate of 0.0073 kg/s (0.016 lb/s), the same air flow rates of 0.0027, 0.0041, and 0.0055 kg/s (0.006, 0.009, and 0.012 lb/s), and the same injector geometry. Again, SMD decreases with increasing gas velocity, and the largest SMD values occur in the spray center. The SMD curves have prominent peaks in the center; they are not as flat as the drop size curves in Figure 2a. An unexpected feature of these tests is the undeveloped, diffuser-like velocity profile, where the drops in the spray center do not have the highest average velocity. This effect becomes more pronounced as the air flow rate is increased, as can be seen in the drop velocity curve measured at the 0.0027 kg/s (0.006 lb/s) air flow rate.

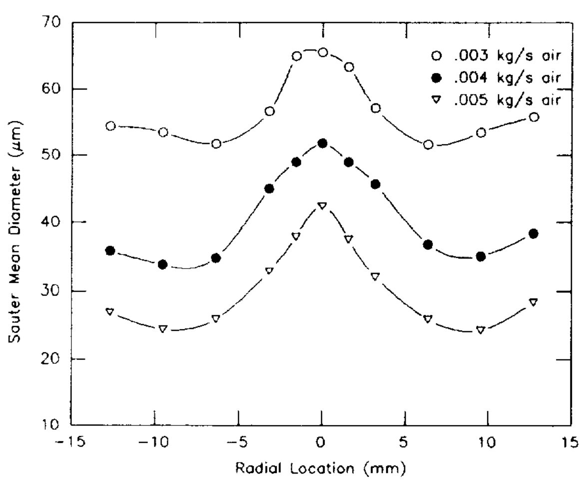

Figure 3a. Effect of varying air flow rate on Sauter mean diameter as a function of radius. Water flow rate is 0.007 kg/s; Configuration 1.

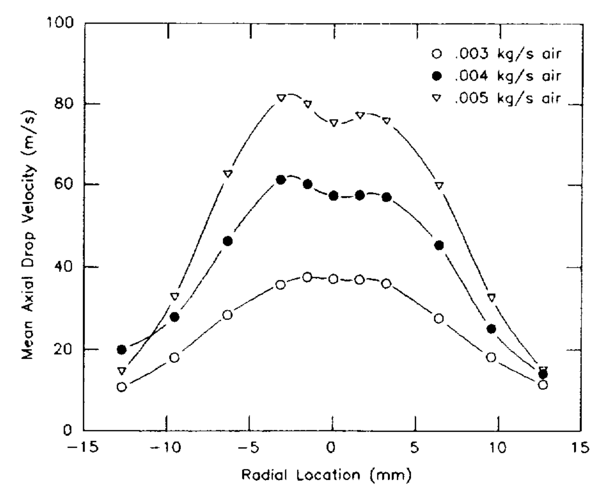

Figure 3b. Effect of varying air flow rate on mean axial drop velocity as a function of radius. Water flow rate is 0.007 kg/s; Configuration 1.

Figures 4a and 4b illustrate the effect on SMD and velocity of varying water flow rates while keeping the air flow rate constant at 0.0041 kg/s (0.009 lb/s). The shapes of these SMD curves are similar to those in Figures 2a and 3a. The spacing between the SMD curves is fairly uniform, with the gradient near the spray center increasing with increasing water flow rate. Mean drop velocity curves are similar to those in Figures 2b and 3b. Changes in water flow rate do not appear to have much effect on the drop velocities beyond 6.4 mm (0.25 in) radius. From the centerline to 6.4 mm (0.25 in) radius, there are drastic differences in the curve shapes. The shapes of the drop velocity curves change from having a peak in the center, to being flat in the center, to exhibiting a dip in the center as the water flow rate is increased. These variations in the velocity curve shapes are postulated to be the result of effectively moving the measurement point closer to the region of primary breakup. As the water flow rate is increased, the liquid jet persists farther downstream. Since the measurement plane is maintained at the same axial location for all the tests, the jet breakup point moves closer to the measurement plane. As the distance between the measurement plane and the liquid jet breakup point is decreased, the high velocity gas has less time to accelerate the drops recently formed from the low velocity liquid jet, causing these drops to have a lower mean velocity. In agreement with this hypothesis, the drop velocities at the centerline are indeed observed to decrease as the water flow rate is increased (Figure 4b).

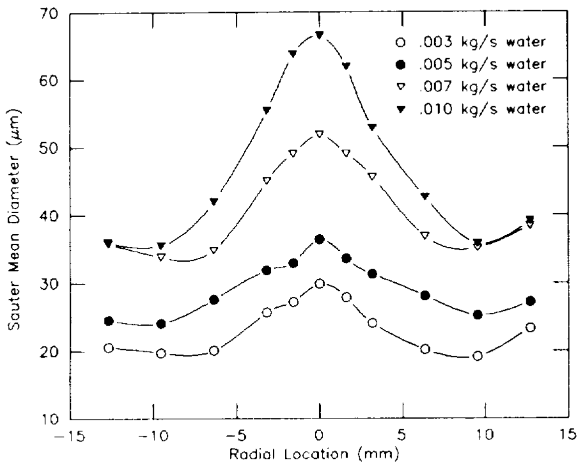

Figure 4a. Effect of varying water flow rate on Sauter mean diameter as a function of radius. Air flow rate is 0.004 kg/s; Configuration 1.

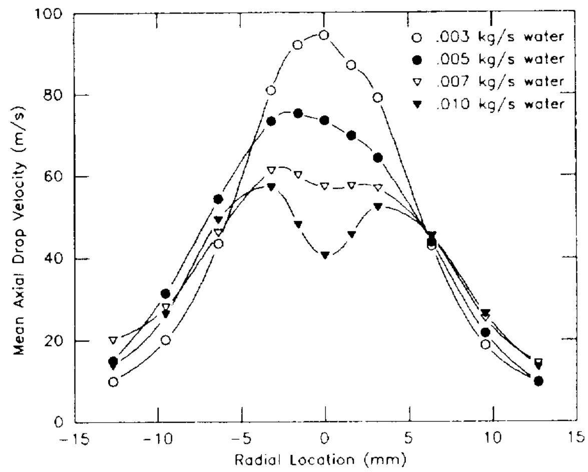

Figure 4b. Effect of varying water flow rate on mean axial drop velocity as a function of radius. Air flow rate is 0.004 kg/s; Configuration 1.

The effect of increasing liquid post recess on the drop size and velocity distributions was examined using three different injector configurations. The post was recessed in increments of 1.6 mm (0.062 in) from 0.0 to 6.4 mm (0.0 to 0.25 in). All the results presented in Figures 5, 6, and 7 were conducted using a water flow rate of 0.005 kg/s (0.012 lb/s) and an air flow rate of 0.004 kg/s (0.008 lb/s). The liquid orifice diameters used for the data presented in Figures 5, 6, and 7 were 1.3 mm (0.052 in), 2.0 mm (0.078 in), and 2.5 mm (0.100 in), respectively. In every case, as the post recess was increased, the Sauter mean diameters measured at the center increased. At the same time, drop sizes measured at 12.7 mm (0.5 in) radius decreased with increasing recess, with the exception of the 6.4 mm (0.25 in) recess case. Therefore, the general effect of increasing post recess was to increase the slope of the mean drop size profile. A composite mean drop size was calculated for each case by weighting the drop sizes measured at each radial location by the relative area of a ring at the radial sample location, the local valid data rate, and the local average drop velocity. The composite mean drop sizes were also observed to increase with increasing post recess.

The observed increase in mean drop size with increasing post recess was unexpected. Previous experiments have shown that the impact of liquid post recess on the drop sizes produced by coaxial injector sprays to be unclear or negligible. Burick[12] reported that recessing the LOX post typically increased mean drop sizes for post recesses of less than twice the post diameter. This is in agreement with the data presented here, since this study found increased drop sizes for post recesses less than twice the post diameter. Falk[14] found that recessing the liquid post had very little effect on mean drop sizes; however, only one test with a recessed post was conducted in that study. Gomi[7] observed very slight differences in drop sizes between cases with zero recess and cases with a post recess equal to three post diameters. Sankar[8] showed that increasing post recess had a variable effect on drop sizes; however, Sankar[8] did not characterize the error in the drop size measurements, so the variation in mean drop size due to post recess may have been less than the measurement uncertainty, masking any clear effect of post recess. Other evidence has indicated that recessing the liquid post might produce smaller mean drop sizes. Hot firing tests have shown that increased post recess leads to improved combustion efficiency.[4] It was assumed that improved atomization (producing smaller drops) was a factor in the observed increase in performance. However, larger mean sizes were observed in these water/air tests, implying that some difference between cold flow and hot firing testing, such as burning in the cup formed by the liquid post recess, may have significant impact on the drop size distributions in hot firing rocket engines.

The mean drop sizes shown in Figures 6a and 7a are nearly identical, indicating that the effect of changing the liquid jet diameter had very little influence on the drop sizes for these cases. In Figure 5a, the reduced jet diameter has produced an increase in mean drop size, presumably due to the increase in liquid velocity, as compared with Figures 6a and 7a. The influence of post recess on the mean drop sizes was greatest in Figure 7a, which had the largest liquid jet diameter and the lowest liquid velocity, while Figure 5a (smallest diameter liquid jet and highest liquid velocity) shows a reduced effect of recess on the mean drop size. For all cases with post recess, the drop velocity maximum did not occur at the centerline (Figures 5b, 6b, and 7b). In the cases without post recess, the drop velocities did peak at the spray center. Similar drop velocities were measured in all the cases with liquid post recess, despite the differences in liquid injection velocities.

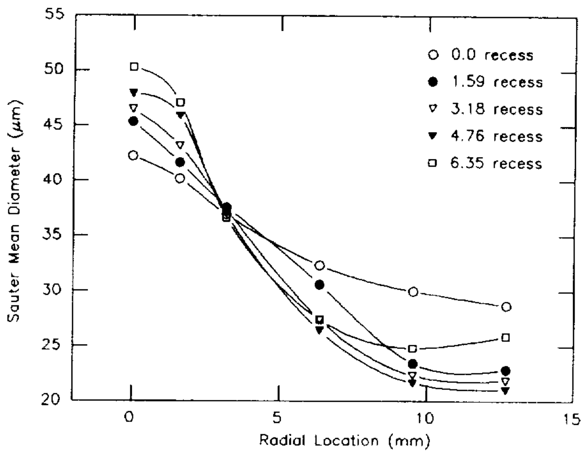

Figure 5a. Effect of liquid post recess on Sauter mean diameter. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 2.

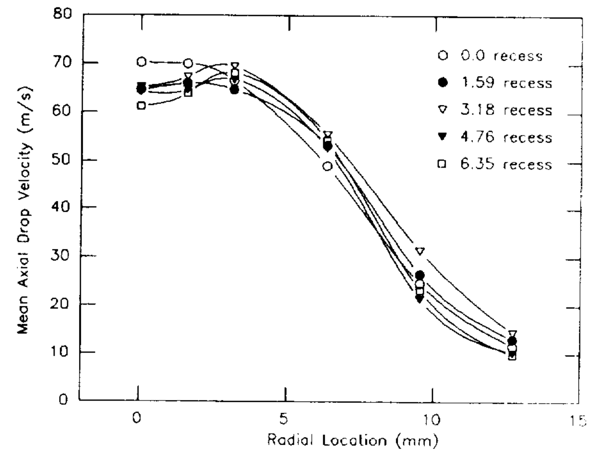

Figure 5b. Effect of liquid post recess on mean axial drop velocity. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 2.

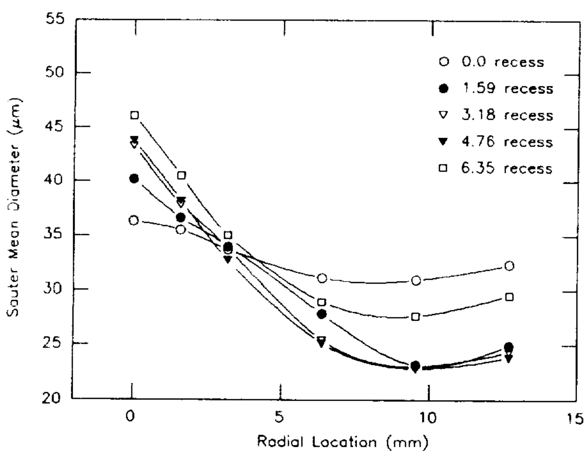

Figure 6a. Effect of liquid post recess on Sauter mean diameter. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 3.

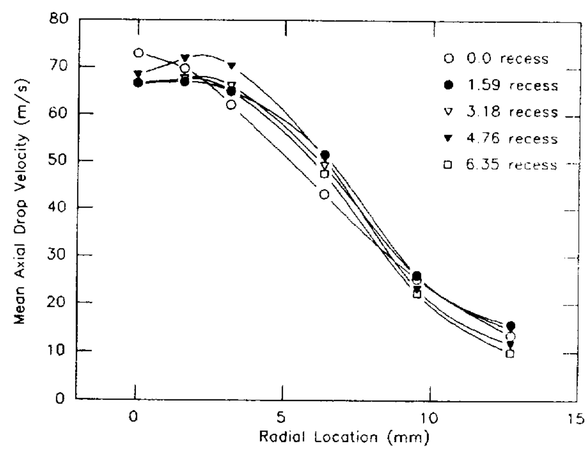

Figure 6b. Effect of liquid post recess on mean axial drop velocity. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 3.

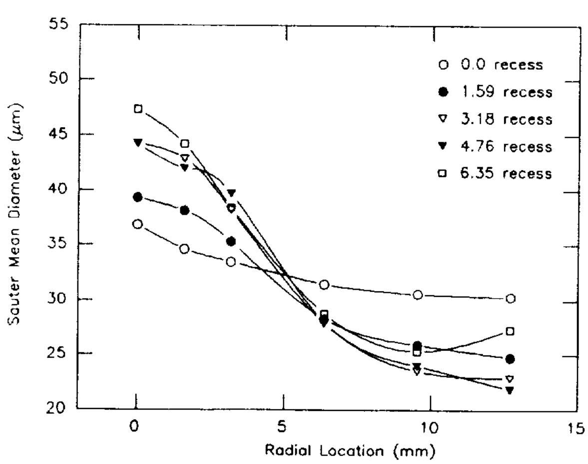

Figure 7a. Effect of liquid post recess on Sauter mean diameter. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 4.

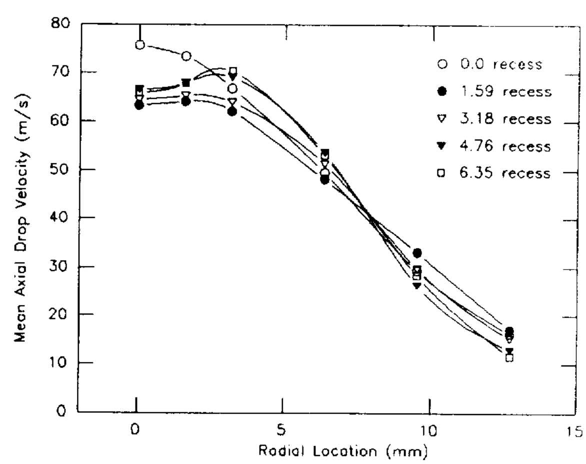

Figure 7b. Effect of liquid post recess on mean axial drop velocity. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 4.

The spray characteristics at different axial locations were examined using injector configuration 3. For the results shown in Figures 8a and 8b, the water flow rate was maintained at 0.005 kg/s (0.012 lb/s), and air flow rate, at 0.004 kg/s (0.008 lb/s). Drop size and velocity profiles were measured for one test case at axial locations from 51 mm (2.0 in) to 19 mm (0.75 in) in decrements of 6.4 mm (0.25 in). The drop size data presented in Figure 8a do not show a clear effect of axial location on the drop size. The standard deviations of the mean drop size values at every radial location are less than the uncertainty (due to random error) in the measurements; therefore, it is concluded that the variation in drop size with axial location for this case is small. As the measurement plane was moved closer to the injector face, the spray radius decreased, making it impossible to obtain data beyond 6.4 mm (0.25 in) radii for all the axial locations tested. The velocity measurements (Figure 8b) have less uncertainty than the drop size measurements, and the effect of varying the axial location on the shape of the velocity profiles is more evident. As would be expected, the velocity profiles become flatter as axial distance is increased. At 51 mm (2.0 in), 44 mm (1.8 in) and 38 mm (1.5 in) from the injector face, the velocity profiles reach a maximum at 0.0 radius. For axial locations of 32 mm (1.2 in) and 25 mm (1.0 in), the velocity values at 0.0 radius and 1.6 mm (.062 in) are nearly the same. Finally, for the velocity profile obtained 19 mm (.75 in) downstream, the velocity peaks at 1.6 mm (.062 in) radius. This data supports the theory that drops in the spray center closer to the liquid jet breakup region have lower velocity than drops farther downstream.

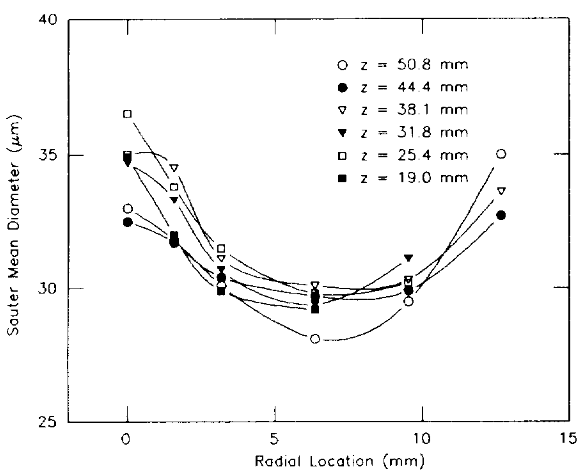

Figure 8a. Effect of varying axial location on Sauter mean diameter. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 3.

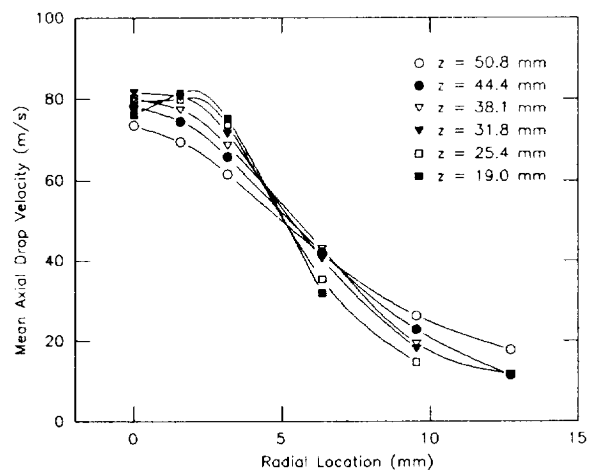

Figure 8b. Effect of axial location on mean axial drop velocity. Water flow rate 0.005 kg/s; air flow rate 0.004 kg/s; Configuration 3.

Detailed values of drop size and velocity data are listed for several cases in Appendix A. The local SMD and drop mean axial velocity are presented for radial positions from 12.7 mm (0.5 in) to the centerline. Flow rates are varied within each injector configuration to show the effect of varying gas and liquid flow rates on Sauter mean diameters and drop velocities. In order to compare the data presented here with results obtained by other investigators, composite Sauter mean diameters were calculated for each test condition. The best approach would be to weight the mean drop sizes by the volume flux and area of a representative ring at each radial location. Unfortunately, the data presented by Sankar[8] demonstrated that the volume flux data as measured by a phase/Doppler instrument in dense coaxial injector sprays did not conserve spray mass, and therefore, were unreliable. As an alternative, a composite SMD was calculated using a weighting method based on the relative area of a ring at the radial sample location, the local valid data rate, and the local average drop velocity. This method summed the products of area, data rate, and velocity. The local products were multiplied by the local SMD and divided by the sum to produce fractions of the composite SMD. The fractions were summed to produce the composite SMD.

Composite values of SMD for the data presented in Appendix A are plotted against some of the commonly used correlations[13-20] in Figure 9. Some of these correlations are for airblast atomizers, but the geometries are generally similar to shear coaxial injectors. Figure 9 clearly shows that there is a wide variation (greater than 20:1) in the predicted drop sizes. The composite mean drop sizes calculated from these tests falls in the middle of the correlation predictions. Although there is much scatter in each curve and there are large errors in the quantitative values, the general slopes of the points for each model do have the same slope as the data. The composite SMD was used because these correlations cannot predict the detailed spatial information produced in this test program. These correlations also were not compared to the data obtained with the recessed configurations because they cannot account for variations in liquid post recess.

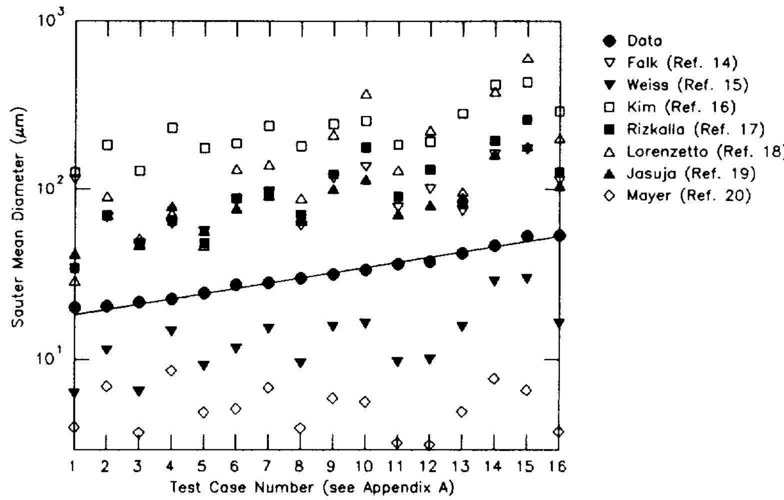

Figure 9. Comparison of Correlations with Data

CONCLUDING REMARKS

A phase/Doppler instrument was used to measure the drop sizes and drop velocities in shear coaxial injector water/air sprays. The phase/Doppler technique, in conjunction with a frequency domain signal processor, was found to be capable of making simultaneous drop size and velocity measurements in very high number density sprays. The injector geometry, as well as the gas and liquid flow rates, were varied. The shear coaxial injector sprays generally exhibited a high degree of radial symmetry. Increasing gas flow rate or decreasing liquid flow rate caused smaller drops to be produced. For the higher liquid flow rates used in these tests, the drop size reached a maximum near the spray center; at lower liquid flow rates, mean drop sizes were larger at the edges of the spray. The drop velocity distribution reached a maximum at the spray centerline for test cases with reduced liquid flow rates. For cases with increased liquid flow rate, decreased axial distance from the injector face, or increased post recess, the mean drop velocity at the spray centerline was not the maximum velocity. Recessing the injector post caused the drop sizes measured at the centerline, as well as the composite mean drop sizes, to increase. Since hot fire data have shown increased combustion efficiency as post recess is increased, it is possible that processes not present in cold flow tests have significant influence on drop size distributions produced by shear coaxial injectors. This indicates the inadequacy of cold flow testing alone, and demonstrates that additional atomization studies are needed in hot firing engines to fully characterize reacting sprays.

It has been shown that existing model predictions vary widely. The data presented here fell in the middle of the predicted sizes. Drop size correlations currently in use are limited in their ability to account for variations in injector geometry. This test program has produced detailed velocity and local drop size data for water and air that can be used by modelers to produce more mechanistic models. The next logical step is to examine drop sizes in vaporizing and reacting sprays to determine the influences of these processes on shear coaxial injector atomization.

REFERENCES

1. Jensen, R. J.: A Summary of the JANNAF Workshop on Liquid Rocket Engine Combustion Driven Instability Mechanisms. 26th JANNAF Combustion Meeting, Vol. 2, D. L. Becker, ed., CPIA-PUBL-529-VOL-2, Chemical Propulsion Information Agency, Laurel, MD, 1989, pp. 273-288.

2. Gross, K. W.: Liquid Engine Jet Atomization Workshop Report. 24th JANNAF Combustion Meeting, Vol. 2, D. L. Becker, ed., CPIA-PUBL-476-VOL-2, Chemical Propulsion Information Agency, Laurel, MD, 1987, pp. 351-353.

3. Zaller, M.: LOX/Hydrogen Coaxial Injector Atomization Test Program. NASA CR-187037, Oct. 1990.

4. Wanhainen, J. P.; Parish, H. C.; and Conrad, E. W.: Effect of Propellant Injection Velocity on Screech in 20,000-Pound Hydrogen-Oxygen Rocket Engine. NASA TN D-3373, 1966.

5. Ferrenberg, A.; Hunt, K.; and Duesberg, J.: Atomization and Mixing Study. (RI/RD85-312, Rocketdyne; NASA Contract NAS8-34504), NASA CR-178751, 1985.

6. Lefebvre, A. H.: Airblast Atomization. Prog. Energy Combust. Sci., vol. 6, pp. 233-261, 1980.

7. Gomi, H.: Pneumatic Atomisation with Coaxial Injectors: Measurements of Drop Sizes by the Diffraction Method and Liquid Phase Fraction by the Attenuation of Light. NAL-TR-888T, Technical Report of National Aerospace Laboratory, 1986.

8. Sankar, S. V.; Brena de la Rosa, A.; Isakovic, A.; and Bachalo, W. D.: Liquid Atomization by Coaxial Rocket Injectors. AIAA Paper 91-0691, Jan. 1991.

9. Ferrenberg, A. J.; and Varma, M. S.: Atomization Data for Spray Combustion Modeling. AIAA Paper 85-1316, July 1985.

10. Dodge, L. G.; and Schwalb, J. A.: Fuel Spray Evolution: Comparison of Experiment and CFD Simulation of Nonevaporating Spray. ASME Paper 88-GT-27, June 1988.

11. Bachalo, W. D.; and Houser, M. J.: Phase/Doppler Spray Analyzer for Simultaneous Measurements of Drop Size and Velocity Distributions. J. Optical Eng., vol. 23, no. 5, 1984, pp. 583-590.

12. Burick, R. J.: Atomization and Mixing Characteristics of Gas/Liquid Coaxial Injector Elements. J. Spacecraft, vol. 9, no. 5, May 1972, pp. 326-331.

13. Falk, A. Y.; and Burick, R. J.: Injector Design Guidelines for Gas/Liquid Propellant Systems. NASA CR-120968, 1973.

14. Falk, A. Y.: Coaxial Spray Atomization in Accelerating Gas Stream. NASA CR-134825, 1973.

15. Weiss, M. A.; and Worsham, C. H.: Atomization in High Velocity Airstreams. ARS J., vol. 29, no. 4, Apr. 1959, pp. 252-259.

16. Kim, K. Y.; and Marshall, W. R., Jr.: Drop-Size Distributions from Pneumatic Atomizers. AICHE J., vol. 17, no. 3, May 1971, pp. 575-584.

17. Rizkalla, A. A.; and Lefebvre, A. H.: Influence of Liquid Properties on Airblast Atomizer Spray Characteristics. J. Eng. Power, vol. 97, no 2, Apr. 1975, pp. 173-179.

18. Lorenzetto, G. E.; and Lefebvre, A. H.: Measurements of Drop Size on a Plain-Jet Air Blast Atomizer. AIAA J., vol. 15, no. 7 July 1977, pp. 1006-1010.

19. Jasuja, A. K.: Plain-Jet Airblast Atomization of Alternative Liquid Petroleum Fuels Under High Ambient Air Pressure Conditions. ASME Paper 82-GT-32, Apr. 1982.

20. Mayer, E.: Theory of Liquid Atomization in High Velocity Gas Streams. ARS J., vol. 31, no. 12, Dec. 1961, pp. 1783-1785.

Appendix A

Detailed Drop Size and Velocity Data for Several Cases

Case No.	Injector Config.	Water Flow (kg/s)	Air Flow (kg/s)	Composite SMD (μm)	Sauter Mean Diameter (μm)						Mean Axial Drop Velocity (m/s)					
1	2	.003	.005	20.2	18.4	17.9	17.4	22.6	25.3	27.9	11.4	30.7	57.7	105	120	121
2	1	.005	.005	20.5	20.3	17.4	19.5	22.9	25.3	26.9	15.5	38.5	67.8	88.5	93.1	93.4
3	2	.005	.005	21.7	19.7	19.2	21.7	25.6	27.0	29.8	13.7	30.6	60.1	82.2	84.5	83.5
4	1	.003	.004	22.5	20.6	19.8	20.1	25.7	27.2	29.9	10.0	20.1	43.5	80.9	92.0	94.4
5	2	.003	.004	24.4	24.6	21.8	23.5	25.1	28.8	33.3	10.8	22.1	46.9	75.2	85.9	88.9
6	1	.007	.005	27.3	26.9	24.4	25.9	32.9	37.9	42.4	14.8	32.9	62.5	81.5	79.9	75.3
7	1	.005	.004	27.9	24.6	24.1	27.6	31.9	32.9	36.4	15.0	31.5	54.4	73.4	75.2	73.5
8	2	.005	.004	29.9	30.8	27.1	29.4	32.3	36.9	39.3	12.1	25.6	47.1	64.0	67.2	67.0
9	1	.007	.004	31.3	39.5	29.4	29.9	36.4	39.1	43.0	20.1	28.1	46.2	61.2	60.1	57.3
10	1	.010	.004	33.4	34.7	26.9	30.7	43.5	54.9	66.4	13.8	26.3	49.3	57.2	48.0	40.5
11	2	.007	.004	36.0	32.8	32.3	36.8	45.7	50.4	51.5	13.7	28.7	47.4	55.5	52.5	50.9
12	2	.010	.004	37.2	36.4	35.5	34.5	44.0	54.1	62.1	14.2	29.3	51.3	52.7	43.2	36.8
13	2	.003	.002	41.7	47.5	44.1	40.4	41.7	42.4	43.1	11.8	18.8	30.8	45.6	49.7	51.5
14	1	.005	.003	46.2	56.0	47.4	44.2	46.8	52.1	52.7	11.5	17.0	29.4	43.0	46.4	47.3
15	1	.007	.003	52.9	54.4	53.4	51.7	56.7	64.9	65.5	10.9	18.2	28.5	35.8	37.6	37.2
16	2	.005	.002	53.5	62.7	50.6	53.3	55.1	56.3	59.2	11.5	17.2	29.5	39.0	42.6	43.6
Radial Location (mm)					12.7	8.3	6.4	3.2	1.6	0.0	12.7	8.3	6.4	3.2	1.6	0.0

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		Technical Memorandum

4. TITLE AND SUBTITLE

Coaxial Injector Spray Characterization Using Water/Air as Simulants

5. FUNDING NUMBERS

WU-506-42-72

6. AUTHOR(S)

Michelle M. Zaller and Mark D. Klem

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-6681

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-105322

11. SUPPLEMENTARY NOTES

Prepared for the 28th JANNAF Combustion Meeting, San Antonio, Texas, October 28—November 1, 1991. Michelle M. Zaller, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3-25266). Mark D. Klem, NASA Lewis Research Center. Responsible person, Michelle M. Zaller, (216) 977-7469.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 20 and 15

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Quantitative information about the atomization of injector sprays is required to improve the accuracy of computational models that predict the performance and stability of liquid propellant rocket engines. An experimental program is being conducted at the NASA Lewis Research Center to measure drop size and velocity distributions in shear coaxial injector sprays. In the first phase of this program, a phase/Doppler interferometer is used to obtain drop size data in water/air shear coaxial injector sprays. Droplet sizes and axial component of droplet velocities are measured at different radii for various combinations of water flow rate, air flow rate, injector liquid jet diameter, injector annular gap, and liquid post recess. Sauter mean diameters measured in the spray center 51 mm (2.0 in.) downstream of the liquid post tip range from 28 to 68 μm, and mean axial drop velocities at the same location range from 37 to 120 m/s (120 to 390 ft/s). The shear coaxial injector sprays show a high degree of symmetry; the mean drop size and velocity profiles vary with liquid flow rate, post recess, and distance from the injector face. The drop size data can be used to estimate liquid oxygen/hydrogen spray drop sizes by correcting property differences between water/air and liquid oxygen/hydrogen. The detailed velocity and local drop size data produced in this test program using a variety of geometry, recess, and flow rate parameters can provide validation for recently developed multi-dimensional atomization models.

14. SUBJECT TERMS

Liquid atomization; Spray characteristics; Coaxial nozzles; Drop size

15. NUMBER OF PAGES	16. PRICE CODE
10	A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	