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Characteristics of Sprays Produced by Coaxial Airblast Atomizers

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Measurements of droplet size, velocity, and liquid flux were made in sprays produced by a coaxial airblast atomizer using a phase Doppler anemometer. The atomizer comprised a liquid jet with an exit diameter varied between 1.1–2.3 mm, positioned in the center of a gaseous annular stream. The characteristics of the preburner sprays of the main engine of the Space Shuttle were simulated by using water and air, replacing liquid oxygen and hydrogen, respectively. The sprays covered a range of Weber numbers at the exit of the nozzle from 200 to 3500, of gas-to-liquid momentum ratio from 2 to 110, velocity ratio from 10 to 85, mass flow rate ratio from 0.2 to 1.3, liquid jet Reynolds numbers from 1×10^4 to 5.5×10^4, and gaseous jet Reynolds numbers from 9×10^4 to 1.9×10^5. Reduction of the diameter of the liquid tube was found to improve the atomization and reduce the width of sprays with similar gas-to-liquid velocity ratios. The presence of a converging nozzle at the exit of the gaseous jet improved the atomization and increased the rate of spread of sprays with a gas-to-liquid velocity ratio up to around 50, but had no effect for higher velocity ratios. Recess of the liquid tube by two and three liquid tube diameters increased the rate of spread of the sprays and reduced the atomization for the straight and converging gaseous jet exit nozzle.

Introduction

THE atomization of liquid oxygen by a high-velocity coaxial hydrogen stream is required in the preburner of the main engine of the Space Shuttle (SSME), and the characteristics of the sprays can influence the operation. The combustion stability of rocket engines has been shown to depend on the geometry of the coaxial injectors and on the gaseous and liquid injection velocity.[1] Also, the ignition of the mixture during the startup process of the preburner can be delayed with combustion occurring even in the first and second stage blades of the gas turbine or the turbopump dome,[2] causing cracks on housings, sheetmetal, nozzles, and blade shunks. Therefore, it is important to be able to control the droplet sizes and the spray width of coaxial airblast atomizers, since both parameters affect the evaporation of the oxidizer and its mixing with the fuel and can limit combustion efficiency.[3]

The characteristics of sprays produced by airblast atomizers have been reviewed,[4,5] and the results summarized by empirical correlations between the mean diameters of the sprays and the parameters affecting atomization such as velocity, density, viscosity, and surface tension of the gas, and the liquid and nozzle geometry. It is common for the above parameters to be expressed in terms of the nondimensional numbers, exit Weber number, Reynolds numbers of the gas and the liquid jet, ratios of gas-to-liquid velocities, mass flow rates, and the momentum fluxes (these are defined as footnotes of Table 1). Most of these sprays were characterized by their spray angle and mean droplet size averaged over the spray, rather than local values, which makes it difficult to evaluate the effect of each parameter, with the consequences that empirical correlations cannot be expected to reproduce the spray characteristics over a wide range of conditions.

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Early work on sprays produced by coaxial airblast injectors was performed by droplet capture and imaging techniques[6] and hot wax freezing,[7] but accuracy was limited and the more recent optical nonintrusive sizing techniques have allowed more accurate and detailed measurements. Laser diffraction provides the droplet mean diameter averaged over the line of sight of the laser beam and has been used to show that the Sauter mean diameter increases with the radial distance from the axis of the spray,[8] but such measurements can be misleading if they are not deconvoluted to provide local size information[9] and do not provide the droplet velocity. Interferometric techniques, based on visibility and intensity, measure the local size and velocity,[4] but with limited accuracy of the size measurements, particularly for the smaller droplets in the sprays. The phase Doppler anemometer provides local characteristics with high spatial resolution and has been used successfully to characterize sprays produced by coaxial injectors.[10–14] For exit Weber numbers up to 200 and liquid jet Reynolds numbers up to 4500, the radial distribution of the Sauter mean diameter has been shown to have two maxima—at the center and towards the spray boundary[10]—in contrast to the single maximum at the spray boundary.[8] Sprays produced from nozzles with gas and liquid flow rates close to those of rocket engines have maximum values of mean diameter close to their axis of symmetry.[11,13]

Although the effect of the geometry of the nozzle has been examined previously,[11,14] the spray conditions were limited, as summarized in Table 1, and the effect of the recess of the exit of the liquid tube upstream of the exit of the gaseous jet, e.g., remains unclear. The present investigation examines the effect of the nozzle geometry on the local size and velocity characteristics of coaxial atomizer sprays using a phase Doppler instrument. The effects of the liquid tube diameter, the liquid tube recess, and a convergence at the exit of the gaseous jet have been examined over a wide range of conditions, similar to those of the injectors in the preburner of the SSME, and are summarized in Table 1. The effects of the increased density of the gaseous fuel and the supercritical nature of the liquid oxidizer of the SSME will be examined at a later stage.

Experimental Arrangement

The airblast atomizer of Fig. 1a was constructed and operated at atmospheric pressure with air replacing the hydro-

Table 1 Parameters of experiments with coaxial atomizers using phase Doppler anemometer

Parameters	Sankar et al.[11]	Zaller and Klem[14]	Eroglu and Chigier[10]	This work	Preburner sprays of the SSME
Liquid jet diameters, o.d./i.d., D_l, mm	3.2/2.54	3.18/1.32	1.262/0.971	2.95/2.3 1.47/1.11	3.76/2.26
Gaseous jet i.d., D_{gas}, mm	3.81	5.56	10.36	8.95	4.93
Gas jet velocity,[a] U_{gas}, m/s	Pressure drop available, 206 – 686 KPa	121 – 324	64.8 – 158.7	155 – 315	366
Liquid jet velocity,[b] U_{liquid}, m/s	3.12	2.2 – 7.3	1.1 – 4.5	7.6 – 20	30.5
Gas-to-liquid velocity ratio[c]	——	22.1 – 148	14.4 – 144	10 – 85	12
Gas-to-liquid momentum ratio[d]	——	8.8 – 246	——	2 – 110	10.6
Gas-to-liquid mass flow rate ratio[e]	——	0.4 – 1.67	2 – 20.3	0.2 – 1.3	0.84
Exit Weber number[f]	——	290 – 2,228	2 – 200	200 – 3,500	745,000
Reynolds number, liquid jet[g]	9.3×10^3	$3.4 \times 10^3 - 1.1 \times 10^4$	$1.1 \times 10^3 - 4.4 \times 10^3$	$1 \times 10^4 - 5.5 \times 10^4$	4.8×10^5
Reynolds number, gaseous jet[h]	——	$4.5 \times 10^4 - 1.2 \times 10^5$	$3.7 \times 10^4 - 9.1 \times 10^4$	$9 \times 10^4 - 1.9 \times 10^5$	2.1×10^6

[a]Averaged over the area of the annulus. [b]Averaged over the area of the liquid tube. [c]U_{gas}/U_{liquid}. [d]$\rho_g A_{gas} U_{gas}^2/\rho_l A_{liquid} U_{liquid}^2$, where ρ is density and A_{gas} is the area of the annulus. [e]$\rho_g A_{gas} U_{gas}/\rho_l A_{liquid} U_{liquid}$. [f]$\rho_g U_{rel}^2 D_l/\sigma$, where $U_{rel} = U_{gas} - U_{liquid}$, and σ is the surface tension. [g]Based on U_{gas} and D_{gas}. [h]Based on U_{liquid} and D_l.

gen, and water replacing the liquid oxygen of the SSME. A central tube provided the liquid to the nozzle and consisted initially of a 10-mm-diam tube which reduced to an o.d. of 2.95 mm, with an i.d. of $D_l = 2.3$ mm (0.090 in.), and with length-to-diameter ratio 22; a second internal tube with an o.d. of 1.47 mm and an i.d. of $D_l = 1.1$ mm with a length-to-diameter ratio of 45 was also used. The exit of the liquid tube could be adjusted to be in the plane of the exit of the gaseous jet or recessed.

The gas flow rate was supplied to the nozzle by four gas inlets with their axes normal to that of the nozzle (Fig. 1a). Flow straighteners were used to remove residual swirling motion and ensure axisymmetric flow. Since swirl is one of the parameters affecting atomization, four additional tangential inlets could provide swirling gas flow, but were not used during the reported work. The gaseous flow was accelerated by a conical contraction before the exit of the nozzle to reduce possible flow asymmetries. As shown in Fig. 1b, nozzles with straight and converging exits could be attached at the exit of the gaseous jet with a diameter of 8.95 mm, resulting in annular widths of 3 and 3.74 mm when the liquid jet tube with an o.d. of 2.95 and 1.47 mm was used. The length of the straight part of the nozzle was 18 mm, and the converging nozzle had a half-angle of 28 deg and a length of 23.5 mm.

The gas flow rate was provided by a compressor and metered separately by rotameters before passing to separate settling chambers from which four tubes supplied gas to the axial inlets of the arrangement of Fig. 1a. The liquid was pumped from a reservoir and the liquid flow rate to the nozzle was metered by a rotameter and adjusted by a valve in the return line of excess liquid to the reservoir. The liquid content of the spray was collected in a separate tank while an exhaust system removed the gas with the mist of small droplets. Flow straighteners were used at the top of the collection tank to ensure that the spray remained undisturbed by the exhaust system. The results of the following section are for sprays without swirling gas and over the range of operating conditions given in Table 1.

The velocity, diameter, and liquid flux of the droplets were measured by the phase-Doppler anemometer,[15,16] which was comprised of a transmission optical system based on rotating grating, and integrated receiving optical components with three photodetectors. The receiving optics were arranged to collect light at a forward scattering angle of 30 deg on the bisector plane of the two laser beams to ensure that refraction through the droplets dominated the light scattered by the droplets. The collected light was focused to the center of a 100-μm slit and passed through a mask with three evenly spaced rectangular apertures before reaching the three photodetectors. The optical arrangement allowed the measurement of droplet diameters up to 360 μm. The optical characteristics of the instrument are given in Table 2.

The measured size distributions and mean diameters at each point were based on at least 20,000 measurements, resulting in statistical uncertainties of less than 2%.[17] The representative diameters of the sprays were estimated from the temporal size distribution, which is related to the liquid flux, and is used by current prediction models to calculate the local spray characteristics.[19] The sizing resolution of the instrument was around 4 μm, as defined by the electronic circuit and the sizing response curve. The electronic circuit used a 500-MHz clock to count the time delays between Doppler signals and evaluate the phase shift, resulting in a 4-deg resolution of the phase measurement for a typical Doppler frequency of 6 MHz, which, after considering the sizing conversion factor of the instrument (Table 2), corresponds to 4 μm. This uncertainty increased to around 6 μm for droplets smaller than around 20 μm, due to oscillations of the sizing response curve.[15]

Droplet velocities were obtained in 60 size classes, with a 6-μm range in each class. The uncertainties were less than 1 and 4% for the mean and rms values, respectively, based on an average sample size of at least 1000 in each class for the smaller sizes, and around 2 and 6% at the larger droplets due to the smaller sample size. The smaller number of measurements in the larger droplet size classes was due to the low number density of large droplets in the spray.

The volume flux of the liquid droplets was measured by the fringe count technique,[20] and the uncertainty in the estimate of the probe volume is expected to be around 10%, since the main direction of the droplets was parallel to the spray axis. The main reason for systematic errors in the flux measurements is the rejection of measurements by the validation procedure of the instrument[18–20] due to attenuation of the laser beams and occurrence of multiple droplets in the probe volume. Integration of the measured radial profiles of liquid flux resulted in liquid flow rates lower than the value measured by the rotameter by around 50% at an axial distance of 120 mm from the nozzle exit. For this reason, the profiles of liquid flux were normalized with the local centerline. The measured radial profiles of the liquid flux had a maximum value at the center of the spray, and so the rate of spread of the sprays was evaluated using the flux half-width at each

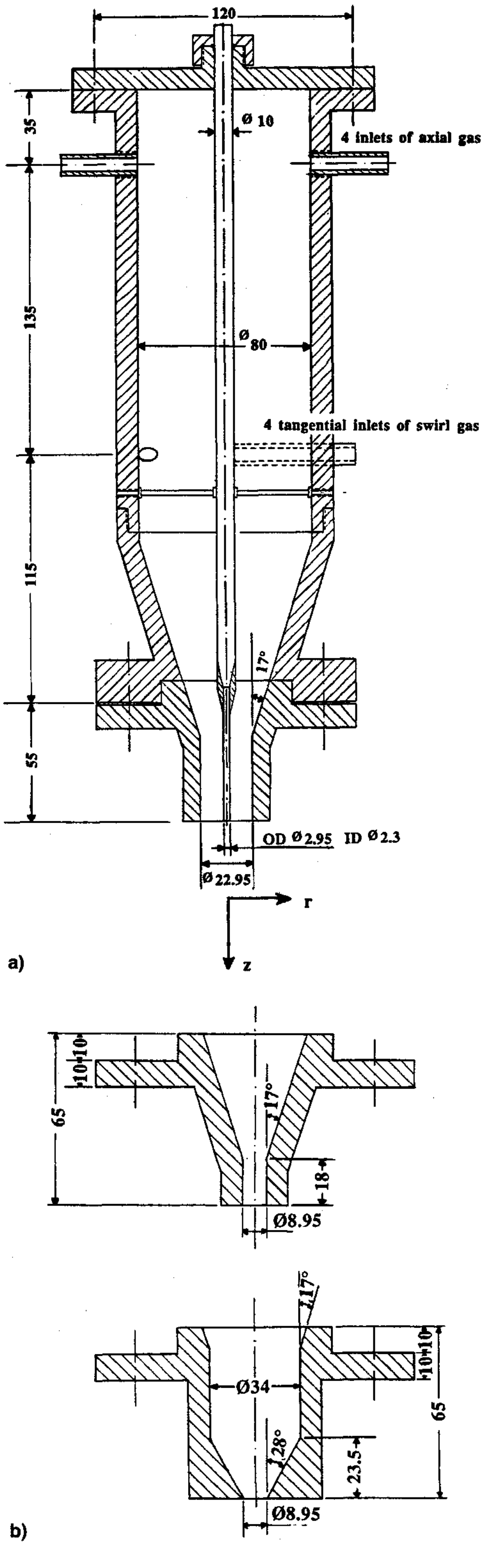

Fig. 1 Experimental arrangement of the coaxial atomizer: a) atomizer with 10-mm annular width and b) nozzles used for the coaxial atomizers with 3-mm annular widths with a straight and converging exit. Dimensions are in mm.

axial station from the nozzle, namely the radial position where the liquid flux was half the local value on the axis of the spray. The error of the rate of spread measurement was around 15%, as defined by the random error of the normalized flux profiles.

Results and Discussion

This section evaluates the effect of the diameter of the inner pipe, the existence of a converging nozzle at the exit of the gaseous jet, the influence of axial recess between the exit

Table 2 Optical characteristics of the phase Doppler anemometer

Transmitting optics	Receiving optics
Laser: He-Ne laser	Focal length of collimating lens, 500 mm
Operating power, 35 mW Wavelength, 632.8 nm	Location of receiving optics from forward scatter angle, 30 deg
Beam intersection angle, 3.024 deg	
Probe volume dimensions at e^{-2} intensity	Equivalent aperture at collimating lens
Length, 4.88 mm Diameter, 129 μm	Dimension of rectangular aperture, 67 × 10.6 mm Separation of aperture 1 and 2, 13.3 mm
Fringe spacing, 11.99 μm	Separation of aperture 1 and 3, 26.6 mm
Number of fringes, 11	
Frequency shift, 3 MHz	Spatial filter slit width, 100 μm
	Effective length of probe volume, 312.5 μm
	Phase angle-to-diameter conversion factor for channels 1 and 3, 0.973 μm/deg

planes of the inner and outer pipes on atomization, and the rate of spread and velocity characteristics of the sprays. The velocity characteristics of droplet sizes in the ranges 6–12 and 102–108 μm, referred to as 9 and 105 μm, respectively, are presented separately. These sizes were chosen because the smaller droplets followed the mean flow characteristics of the continuous phase, and the 105-μm droplets indicated the motion of the large droplets in the spray, which carry a large fraction of the volume flux and do not follow the gas flow. The mean Stokes number St_m, defined as the ratio of the mean gas flow time scale to the relaxation time of the droplets, characterizes the response of the droplets to the gas flow, and when larger or equal to unity indicates faithful response. The mean flow time scale was around 0.06 ms, defined as the ratio of the gaseous jet diameter of 8.95 mm to the area averaged gas velocity at the exit of the nozzle of around 150 m/s, and the relaxation time of the 9-μm droplets was around 0.1 ms, so that the mean Stokes number was of the order of 1 and indicates that the 9-μm droplets followed the mean flow velocity.

The size characteristics of the sprays will be compared in terms of the Sauter mean diameter on the axis of symmetry of the sprays close to the nozzle, so that the rate of spread of the sprays can have a limited effect on the local values of the mean diameters. The minimum axial distance from the nozzle exit was, however, limited by the ability of the phase Doppler anemometer to measure in the dense spray and the requirement of the existence of spherical droplets, and a distance of 80 mm was chosen as a compromise. The characteristics of sprays are examined on the basis of the exit Weber number and the gas-to-liquid velocity ratio, which define the velocity gradient along the interface of the two jets and the strain rate that the flame front would experience in reacting sprays. Since this work is related with the ability of the sprays to ignite in the preburner of the SSME, it is important to understand the characteristics of the sprays for constant strain rate, which could preclude ignition when larger than a critical value.

Effect of Liquid Tube Diameter

Figure 2a presents the radial variations of the axial velocity of the 9- and 105-μm droplet sizes of sprays produced by a coaxial atomizer with the gaseous jet diameter of 8.95 mm, the two inner tube diameters of 2.3 and 1.1 mm, and a gas-to-liquid velocity ratio (V.R.) of around 25 at a distance

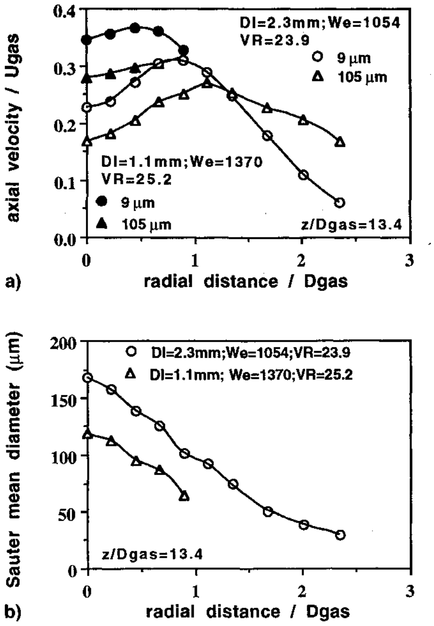

Fig. 2 Radial profiles of velocity and SMD: D_{gas} = 8.95 mm, and D_l = 2.3 and 1.1 mm for V.R. = 25 at an axial distance from the nozzle z/D_{gas} = 13.5: a) mean axial velocity of 9- and 105-μm droplets and b) Sauter mean diameter.

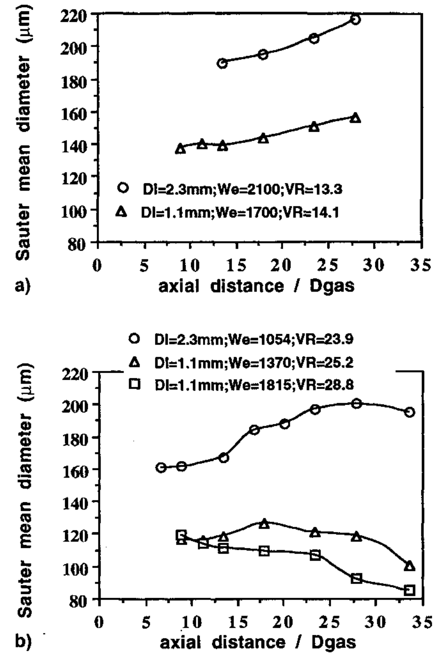

Fig. 3 Centerline development of the Sauter mean diameter: D_{gas} = 8.95 mm, and D_l = 2.3 and 1.1 mm for a) V.R. = 14 and b) V.R. = 25.

z/D_{gas} = 13.4 from the nozzle. The radial and axial distances from the axis and the exit of the nozzle, respectively, were normalized by the diameter of the gaseous tube D_{gas}, and the axial velocity of the droplets by the gas velocity averaged over the area of the annulus U_{gas} to allow comparison between sprays with different initial gas velocity. For the nozzle with D_l = 2.3 mm, the low velocity of the 9-μm droplets close to the axis of symmetry indicates the reduced gas entrainment in the central part of the spray due to the presence of the liquid jet, whereas the 105-μm droplet velocity was lower than that of the gas phase because of their delayed response to the gas phase. The gas velocity was a maximum away from the center, at the shear layer between the liquid and the gaseous jet, and accelerated the few large droplets which reached there faster than at the center. The droplets of the spray produced by the nozzle with D_l = 1.1 mm accelerated faster, because the initial diameter of the liquid jet was smaller and allowed the liquid jet to break up faster than for the nozzle with D_l = 2.3 mm, and its effect on the gas phase flow at the central part was reduced. The droplets in the central part of the spray continued to accelerate with axial distance from the exit, so that downstream of z/D_{gas} = 13.4 the velocity minimum at the central part of the spray disappeared. The small droplets moved faster than the larger droplets up to the shear layer of the gas jet, and then decelerated faster than the larger droplets as the gas jet expanded and the gas velocity decreased, due to their better response to the continuous phase. The large droplets at the edge of the spray moved faster than the gas since they could not follow the continuous phase and maintained their upstream velocity for a larger distance. The relative velocity between the large droplets and the gaseous phase indicates the possibility of secondary atomization of the droplets, this information was absent in the results of the average velocity over all droplet sizes.[11,12,14] The local Weber number, based on the droplet Sauter mean diameter and the relative velocity, was around unity, lower than the critical Weber number value of 6 for breakup, and this has two consequences. First, measurements were obtained in a region of the spray where droplet breakup did not occur, and so most of the droplets are expected to be spherical and, second, higher values of the local Weber number are expected to occur closer to the nozzle, where the high relative velocity results in the secondary breakup of large droplets produced after the primary breakup of the liquid jet. The mean Stokes number of the large droplets has been shown to increase with the axial distance from the nozzle exit,[21] since the time scale of the mean gas phase flow increases, and suggests that the droplet response to the gas phase flow increases with the axial distance from the nozzle and explains the reduction of the relative velocity between small and large droplet sizes. However, the large droplets had straight trajectories determined by their initial conditions without responding to the gas phase turbulence.

Figure 2b shows that the radial variation of the Sauter mean diameter (SMD) of the spray had a maximum at the center and decreased with the radial distance. The shear at the interface between the fast moving gaseous jet and the liquid jet generated small droplets which dispersed faster away from the axis and surrounded the developing sprays. The larger droplets were generated at the center after the breakup of the liquid jet and remained there over a longer period of time. Comparison between the SMD of the sprays from the two nozzles shows that atomization improved by around 25% for V.R. ≈ 25 with D_l = 1.1 mm. The radial variation of the SMD indicates that the finding of Ref. 8 with a laser diffraction instrument (namely that the SMD was a minimum at the center), was probably caused by the averaging of the spray droplet diameters over the line of sight of the diffraction instrument. Also, the observation of two maxima in the radial distribution of the SMD, one at the center and one at the edge of the spray,[10] may be a characteristic of the near nozzle region at a low exit Weber number, which does not correspond to the sprays in the preburners of the SSME.

The centerline development of the SMD for the two nozzles and for V.R. of 14 and 25 (Fig. 3) indicates that the nozzle with D_l = 1.1 mm produced consistently smaller droplets by around 25%. The SMD along the centerline of the spray from the nozzle with D_l = 2.3 mm increased first, as the smaller droplets dispersed faster leaving larger droplets on the centerline, and then decreased again as the larger droplets also dispersed (Fig. 3b). This behavior was not observed for the nozzle with D_l = 1.1 mm (Fig. 3b), because the droplet sizes in these sprays were smaller and dispersed from the centerline earlier. The preferential spread of the droplets was supported also by the lower SMD outside the centerline (Fig. 2b). It should be noted that the corresponding exit Weber number

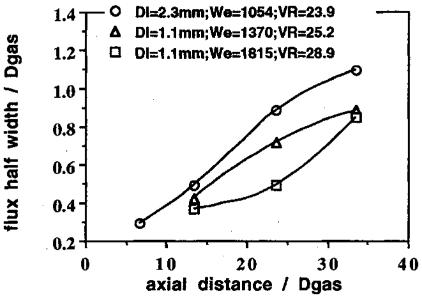

Fig. 4 Flux half-width of the sprays with the axial distance from the nozzle: D_{gas} = 8.95 mm, and D_l = 2.3 and 1.1 mm for V.R. = 25.

was larger for the large diameter liquid jet nozzle for V.R. = 14 (Fig. 3a), and when considered in isolation, this suggests better atomization for the large diameter liquid jet, in contrast to the observations of Fig. 3a. Thus, the influence of the exit Weber number on the spray characteristics was not as important as the other atomization parameters discussed in detail in another communication.[22] Comparison of Fig. 3a and 3b shows that the SMD increased with a decrease of the gas-to-liquid velocity ratio, so that the atomization reduced with the reduction of the gas-to-liquid velocity ratio, and this justifies the correlation between sprays produced by low gas-to-liquid velocity ratio nozzles and combustion instability.[1]

The flux half-width of the sprays normalized by the diameter of the gaseous jet (Fig. 4) indicates that the spray from the larger liquid jet tube was wider by around 20%, although the atomization reduced with the increase of the liquid tube diameter (Fig. 3b). For the nozzle with D_l = 1.1 mm, an increase of the gas-to-liquid velocity ratio by an increase of the gas flow rate reduced the rate of spread of the spray up to z/D_{gas} to around 24 (Fig. 4), although the atomization improved (Fig. 3b), and this effect has also been observed for the large liquid jet diameter nozzle.[13] Therefore, width and atomization characteristics cannot be improved at the same time for sprays with similar gas-to-liquid velocity ratio and reduced liquid tube diameter, or for sprays with increased gas-to-liquid velocity ratio and constant liquid tube diameter. There is a tradeoff between improving the atomization, which affects the vaporization of the oxidizer, and the rate of spread, which affects mixing of the fuel with the oxidizer. This result is unexpected, since finer droplets can follow the gas phase and disperse faster than the larger droplets, and it indicates that the spreading of the sprays for small distances from the nozzle is due to the initial velocity vectors of the larger droplets generated after the primary breakup of the liquid jet, rather than their dispersion due to their response to turbulence. The large droplets move along trajectories established by their initial velocity vector over larger radial and axial distances, while finer droplets follow the gas phase flow and are entrained initially towards the central part of the spray before dispersing from the centerline.

Summarizing the results, the effect of the reduction of the liquid jet diameter by around 50% was to improve the atomization of sprays with the same gas-to-liquid velocity ratio, but the width of the spray was reduced by the reduction of the liquid tube diameter up to a distance of $30D_{gas}$ from the nozzle. Reduction of the gas-to-liquid velocity ratio for constant liquid tube diameter reduced atomization.

Effect of Converging Gaseous Jet Exit

The effect of a convergence with a half-angle of 28 deg at the exit of the gaseous jet on the atomization and the rate of spread of the spray was examined with the nozzle of Fig. 1b. The gaseous jet diameter D_{gas} was 8.95 mm, and the liquid jet diameter D_l was 2.3 mm. The radial and axial distances from the nozzle and the flux half-width were normalized by the liquid jet diameter. The centerline development of the SMD for the converging and the straight exit nozzle (Fig. 5) indicates that the converging nozzle improved atomization by around 20 and 10% for gas-to-liquid velocity ratios of 23.9 and 41, respectively.

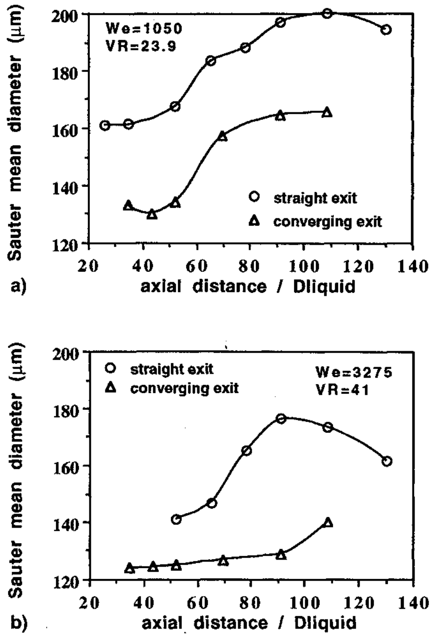

Fig. 5 Centerline development of the Sauter mean diameter: D_l = 2.3 mm with the straight and converging exit nozzle with D_{gas} = 8.95 mm: a) *We* = 1054 and V.R. = 23.9 and b) *We* = 3280 and V.R. = 41.

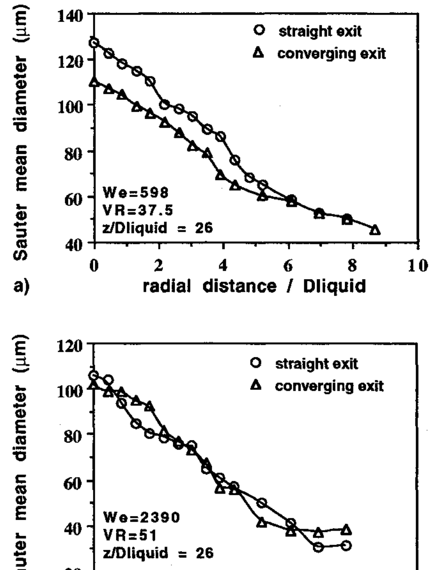

Fig. 6 Radial profiles of Sauter mean diameter: D_l = 2.3 mm with the straight and converging exit nozzle with D_{gas} = 8.95 mm at axial distance from the nozzle z/D_l = 26: a) *We* = 598 and V.R. = 37.5 and b) *We* = 2390 and V.R. = 51.

In order to understand the effect of low and high gas-to-liquid velocity ratio for the converging nozzle, the radial variation of the SMD and the axial velocity of the 9- and 105-μm droplets at a distance of z/D_l = 26 may be compared for the converging and straight nozzle. The SMD for a spray with V.R. = 37.5 was 10% lower on the axis as well as at the edge of the spray (Fig. 6a), whereas there was no difference between the spray size characteristics (Fig. 6b) for V.R. = 51. The experiments over the range of conditions indicated in Table 1 suggest that atomization improved with the converging nozzle for low gas-to-liquid velocity ratios, and the influence decreased with the increase of V.R. up to around 50 and was absent for larger values. The axial velocity charac-

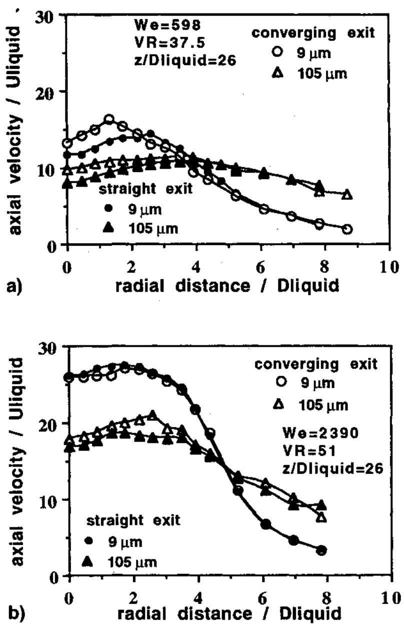

Fig. 7 Radial profiles of axial velocity of 9- and 105-μm droplets: D_l = 2.3 mm with the straight and converging exit nozzle with D_{gas} = 8.95 mm at axial distance from the nozzle z/D_l = 26: a) *We* = 598 and V.R. = 37.5 and b) *We* = 2390 and V.R. = 51.

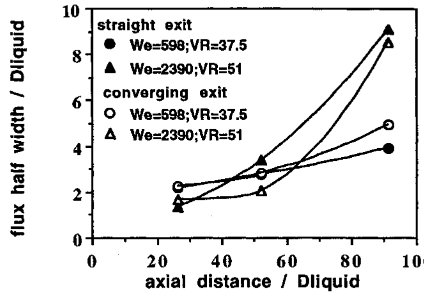

Fig. 8 Flux half-width of the sprays with the axial distance from the nozzle: D_l = 2.3 mm with the straight and converging exit nozzle with D_{gas} = 8.95 mm for *We* = 598, V.R. = 37.5 and for *We* = 2390, V.R. = 51.

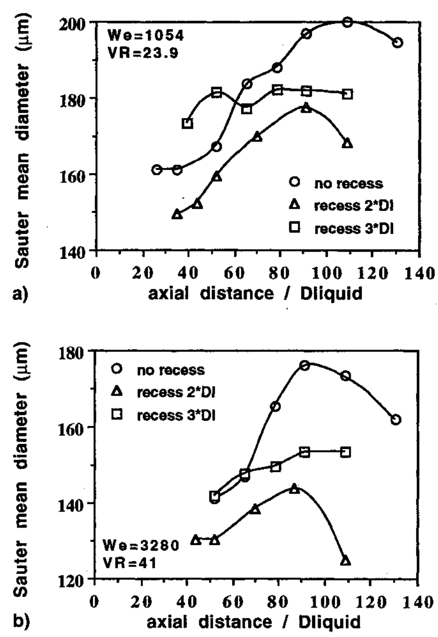

Fig. 9 Centerline development of the Sauter mean diameter: D_l = 2.3 mm with the straight exit nozzle with D_{gas} = 8.95 mm as a function of the liquid tube recess: a) *We* = 1054 and V.R. = 23.9 and b) *We* = 3280 and V.R. = 41.

teristics of sprays with the same V.R. (Fig. 7) show that the velocity in the central part increased with the converging nozzle relative to the straight exit nozzle for V.R. = 37.5, and there was no difference for V.R. = 51. Since the converging nozzle had a half-angle of 28 deg, the velocity vector at the exit of the nozzle should be inclined at the same angle towards the liquid jet which can break up faster for V.R. lower than around 50. For V.R. higher than 50, the shear between the gas and the liquid phase was sufficient to atomize without help from the directed gaseous jet.

Figure 8 shows that the flux half-width increased by around 20% for the converging nozzle for V.R. = 37.5, but, an increase in the gas-to-liquid velocity ratio above 50 reversed this effect close to the nozzle, although the widths of the sprays were similar for both nozzles at z/D_l = 90. It should be noted that both nozzles had lower rates of spread up to z/D_l = 50 for the higher velocity ratio, and this suggests that the high momentum of the gas phase jet close to the nozzle limited the spread of the finer droplets and, although the atomization was improved, the mixing of the fuel and oxidizer was reduced. This compromise between finer atomization of the liquid jet and mixing close to the nozzle can delay ignition close to the nozzle of the reacting sprays, but was less important far downstream, where the differences in the width of the spray became smaller as the droplets dispersed from the centerline.

Effect of Liquid Tube Recess

This effect will be examined for the straight and the converging nozzles separately.

Straight Gaseous Jet Exit Nozzle

Recesses of 0, 4.6, and 7 mm with the D_l = 2.3-mm-diam liquid jet tube were examined, corresponding to 0, $2D_l$, and $3D_l$, and the centerline development of the SMD of the sprays (Fig. 9) suggests that a recess of $2D_l$ improved atomization by around 15%, independent of the gas-to-liquid velocity ratio over a range from 20 to 41. Increasing the recess from $2D_l$ to $3D_l$ reduced atomization below that without recess and for V.R. = 23.9 (Fig. 9a). Improved atomization of the spray with the recess of the tube has been observed by other investigations,[11] and it was also found to improve the combustion stability of rocket engines,[1] which could also imply improved atomization. The improved atomization can be explained by the higher gaseous velocity at the initial interface between the liquid and the gaseous jet when the tube is recessed, because the confinement of the flow does not allow the gaseous jet to expand as it does at the exit. However, this explanation cannot support the observed reduction in the atomization when the recess increased more than $2D_l$, or similar findings of other investigation.[14] This conflicting effect on atomization can be explained by the radial variation of the SMD (Figs. 10a and 10b), which shows that for a tube recessed by $2D_l$, the mean diameters are lower at the center, but greater away from the axis from those without recess, and this effect was stronger for higher V.R. Thus, a recess of $2D_l$ resulted in more rapid dispersion of the larger droplets from the center and the observed differences in the centerline values of the SMD may be due to differences in droplet dispersion and rate of spread of the spray for each case, rather than improved atomization. With the recess of $3D_l$ the radial variation of SMD of Fig. 10 shows that the mean droplet sizes were larger everywhere in the spray, and this can only be explained by reduced atomization. The cumulative SMD calculated by integrating the radial profiles of the SMD of Fig. 10 over the cross-sectional plane weighted with the cross-sectional area of the corresponding ring and the flux at each radial position suggests that the effect of recess of the liquid tube was small and tended to reduce atomization.

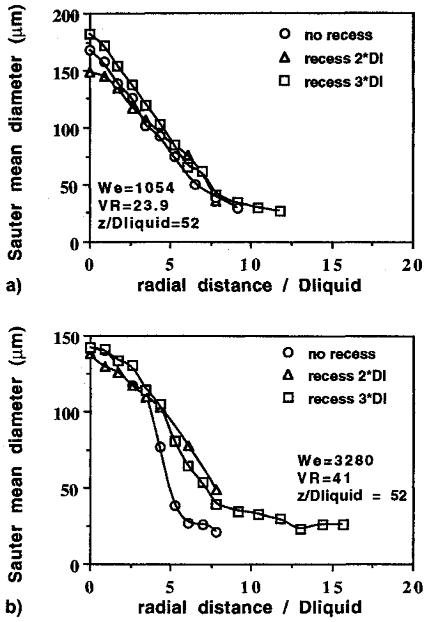

Fig. 10 Radial profiles of Sauter mean diameter: D_l = 2.3 mm with the straight exit nozzle with D_{gas} = 8.95 mm at axial distance from the nozzle z/D_l = 52 as a function of the liquid tube recess: a) *We* = 1054 and V.R. = 23.9 and b) *We* = 3280 and V.R. = 41.

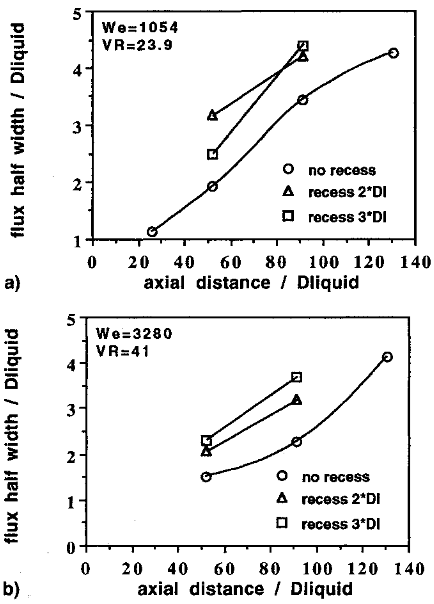

Fig. 11 Flux half-width: D_l = 2.3 mm with the straight exit nozzle with D_{gas} = 8.95 mm as a function of the liquid tube recess: a) *We* = 1054, V.R. = 23.9 and b) *We* = 3280, V.R. = 41.

The influence of the recess on the rate of spread (Fig. 11) shows that the flux half-width increased by around 40% for all the cases with a recess and for a V.R. between 20–41. This supports the argument of the previous paragraph, that the larger droplets dispersed faster from the centerline when the liquid tube was recessed, and justifies the centerline development and the radial profiles of the Sauter mean diameter (Figs. 9 and 10). This was probably caused by the breakup of the liquid jet upstream of the gaseous jet exit, so that droplets at the exit of the gaseous jet could be affected more by the sudden expansion than without recess, and dispersed faster from the center. Thus, the improved combustion stability observed with the liquid tube recessed[1] was due to the increased rate of spread rather than to improved atomization.

Converging Gaseous Jet Exit Nozzle

Figure 12 shows that the centerline SMD decreased with the recess of the 2.3-mm-diam liquid tube for the converging

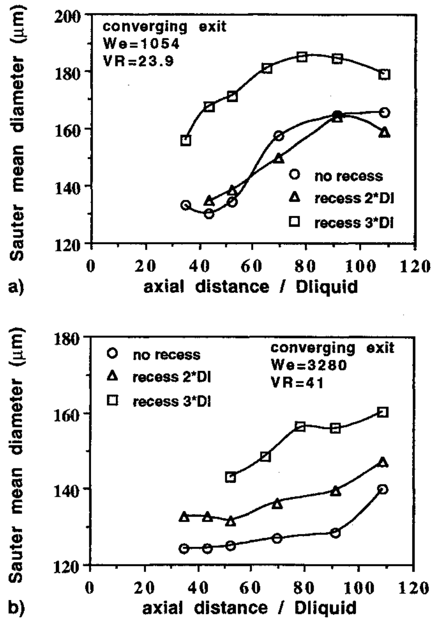

Fig. 12 Centerline development of the Sauter mean diameter: D_l = 2.3 mm with the converging exit nozzle with D_{gas} = 8.95 mm as a function of the liquid tube recess: a) *We* = 1054 and V.R. = 23.9 and b) *We* = 3280 and V.R. = 41.

gaseous jet exit. For V.R. = 23.9, the effect of recessing the tube by $2D_l$ was negligible and recess by $3D_l$ reduced atomization by around 15% (Fig. 12a). For V.R. = 41, the atomization was reduced by 10 and 15% for recesses of $2D_l$ and $3D_l$, respectively. Since the converging nozzle had a conical shape, recess of the liquid tube increased the corresponding area of the annulus of the gaseous jet at the plane of the exit of the liquid tube and, therefore, reduced the corresponding local area averaged gas velocity and gas-to-liquid velocity ratio at the exit of the liquid tube by three and four times for recesses of $2D_l$ and $3D_l$, respectively. Thus, recess of the liquid tube reduced atomization due to the reduction of the local gas-to-liquid velocity ratio at the plane of the exit of the liquid tube. However, the gas flow accelerated downstream of the exit of the recessed liquid tube due to the converging gaseous jet, and the gas velocity at the exit of the gaseous jet was only 10% lower than without recess, which explains the relatively small reduction in atomization.

Conclusions

The characteristics of sprays produced by coaxial airblast atomizers operating at atmospheric pressure with air and water have been measured by a phase Doppler anemometer. The results have shown the following:

1) For sprays with the same gas-to-liquid exit velocity ratio, a decrease in the diameter of the liquid tube by around 50% improved the atomization by around 25%, but decreased the width of the sprays by 20%.

2) For constant liquid tube diameter, atomization was improved by an increase of the gas-to-liquid velocity ratio, but the rate of spread close to the nozzle was reduced.

3) The use of a 28-deg half-angle converging nozzle at the exit of the gaseous jet improved atomization by around 20 and 10% for velocity ratios of 24 and 41, respectively, and the rate of spread by 20% for gas-to-liquid exit velocity ratios up to around 50 relative to the straight exit nozzle. For gas-to-liquid velocity ratios higher than 50, atomization was not improved, but the rate of spread of the sprays was reduced close to the nozzle.

4) The effect of recesses of $2D_l$ and $3D_l$ of the liquid tube with the straight exit nozzle did not affect atomization and improved the rate of spread by 40%. The improved mixing due to the increased rate of spread of the sprays is the likely

cause of the observed improvement in combustion stability in rocket engines with the recess of the liquid tube.

5) The effect of a liquid tube recess with the converging exit nozzle was to reduce atomization. The effect was larger for a gas-to-liquid velocity ratio higher than 40 for which atomization was reduced by 10 and 15% for recesses $2D_1$ and $3D_1$.

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References

[1]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, April 1966.

[2]Wang, T.-S., "Computational Analysis of the Three-Dimensional Steady and Transient SSME Fuel Preburner Combustor," *Proceedings of the IUTAM Symposium on Aerothermodynamics in Combustors* (Taipei, Taiwan), 1991, pp. VI.93–VI.95.

[3]Priem, R. J., and Heidman, M. F., "Vaporization of Propellants in Rocket Engines," *ARS Journal*, Vol. 29, Nov. 1959, pp. 836–842.

[4]Ferrenberg, A., Hunt, K., and Duesberg, J., "Atomization and Mixing Study," NASA CR-178751, Dec. 1985.

[5]Lefebvre, A. H., *Atomisation and Sprays*, Hemisphere, New York, 1989.

[6]Weiss, M. A., and Worsham, C. H., "Atomization in High Velocity Airstreams," *ARS Journal*, Vol. 29, April 1959, pp. 252–259.

[7]Burick, R. J., "Atomization and Mixing Characteristics of Gas/Liquid Coaxial Injector Elements," *Journal of Spacecraft and Rockets*, Vol. 9, May 1972, pp. 326–331.

[8]Caré, I., and Ledoux, M., "Study of an Air Blast Coaxial Atomizer: Experiments and Modelisation," *Proceedings of the 5th International Conference on Liquid Atomization and Spraying Systems (ICLASS)* (Gaithersburg, MD), 1991, pp. 763–770 (Paper 85).

[9]Cossali, E., and Hardalupas, Y., "Comparison Between Laser Diffraction and Phase Doppler Velocimeter Techniques in High Turbidity, Small Diameter Sprays," *Experiments in Fluids*, Vol. 13, Nov. 1992, pp. 414–422.

[10]Eroglu, H., and Chigier, N. A., "Initial Drop Size and Velocity Distributions for Airblast Coaxial Atomizers," *Journal of Fluids Engineering*, Vol. 113, Sept. 1991, pp. 453–459.

[11]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.

[12]Sankar, S. V., Wang, G., Brena de la Rosa, A., Rudoff, R. C., Isakovic, A., and Bachalo, W. D., "Characterisation of Coaxial Rocket Injector Sprays Under High Pressure Environments," AIAA Paper 92-0228, Jan. 1992.

[13]Hardalupas, Y., McDonald, H., and Whitelaw, J. H., "Two Fluid Mixing," *Advanced Earth-To-Orbit Propulsion Technology 1992*, NASA CP 3174, Vol. II, May 1992, pp. 63–72.

[14]Zaller, M. M., and Klem, M. D., "Coaxial Injector Spray Characterization Using Water/Air as Simulants," *Proceedings of the 28th JANNAF Combustion Meeting* (San Antonio, TX), 1991, pp. 1–9 (NASA TM 105322).

[15]Hardalupas, Y., "Experiments with Isothermal Two Phase Flows," Ph.D. Dissertation, Univ. of London, London, 1989.

[16]Hardalupas, Y., "Description of the Fluids Section 'Model 2' Phase Doppler Counter," Imperial College, Mechanical Engineering Dept., Rept. FS/90/29, Aug. 1990.

[17]Tate, R. W., "Some Problems Associated with the Accurate Representation of Drop-Size Distributions," *Proceedings of the 2nd International Conference on Liquid Atomization and Spraying Systems (ICLASS)* (Madison, WI), 1982, pp. 341–351.

[18]Bachalo, W. D., Rudoff, R. C., and Brena de la Rosa, A., "Mass Flux Measurements of a High Number Density Spray System Using the Phase Doppler Particle Analyser," AIAA Paper 88-0236, Jan. 1988.

[19]Dodge, L. G., Rhodes, D. J., and Reitz, R. D., "Drop-Size Measurement Techniques for Sprays: Comparison of Malvern Laser Diffraction and Aerometrics Phase Doppler," *Applied Optics*, Vol. 26, June 1987, pp. 2144–2154.

[20]Hardalupas, Y., and Taylor, A. M. K. P., "On the Measurement of Particle Concentration near a Stagnation Point," *Experiments in Fluids*, Vol. 8, Oct. 1989, pp. 113–118.

[21]Hardalupas, Y., Taylor, A. M. K. P., and Whitelaw, J. H., "Velocity and Particle Flux Characteristics of Turbulent Particle-Laden Jets," *Proceedings of the Royal Society of London*, Vol. A426, No. 1870, 1989, pp. 31–78.

[22]Hardalupas, Y., and Whitelaw, J. H., "Coaxial Airblast Atomizers," NASA Contract NAS8-38872, April 1993.