

Gas Property Effects on Dropsizes of Simulated Fuel Sprays

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Two-phase flow in pneumatic two-fluid fuel nozzles was experimentally investigated to determine the effect of gas properties on liquid-jet breakup in sonic-velocity gas flow. Dropsizes were obtained for the following atomizing gases: nitrogen, argon, carbon dioxide, and helium. The ratio of liquid-jet diameter to Sauter mean diameter (SMD) D_o/D_{32} was correlated with aerodynamic and liquid-surface forces based on the product of the Weber and Reynolds number $WeRe$ and gas-to-liquid density ratio ρ_g/ρ_l . To correlate characteristic dropsizes with breakup forces produced by using different atomizing gases, a molecular-scale dimensionless group was derived, $\rho_l V^3/g\mu_g$. As a result, a semiempirical correlating expression was obtained that can be used in the design of fuel injectors for gas turbine and rocket combustors. This expression for liquid-jet breakup in two-fluid atomizer shows that $D_{32} \sim (\rho_g V_c)^{-1.33}$, where $\rho_g V_c$ is gas mass-flux at sonic velocity, and this agrees well with atomization theory for liquid-jet breakup in high velocity gas flow. Also, it was found that at the same gas mass-flux $\rho_g V_c$, helium was considerably more effective than nitrogen in producing small droplet sprays with SMDs in the order of 5 μm . This was attributed to the high acoustic velocity of helium.

Nomenclature

- b = dropsizes parameter in Nukiyama-Tanasawa expression, cm
 c = dropsizes parameter in Rosin-Rammler expression, cm
 D_c = characteristic drop diameter measured for entire spray, cm
 D_i = diameter of i th drop, cm
 $D_{v,5}$ = volume median drop diameter, cm
 D_{31} = volume-linear mean drop diameter, $(i^{nD_i^3}/i^{nD_i})^{0.5}$
 D_{32} = Sauter mean drop diameter, $i^{nD_i^3}/i^{nD_i}$, cm
 k = correlation coefficient for Eq. (1)
 k' = correlation coefficient for Eq. (3)
 N_n = exponent for Nukiyama-Tanasawa dropsizes distribution expression
 N_r = exponent for Rosin-Rammler dropsizes distribution expression
 n = number of droplets
 R = gas constant, 8.31×10^7 erg
 Re = Reynolds number, $D_o \rho_g V_c / \mu$
 V = fluid velocity, cm/s
 v = volume fraction of droplets with diameters less than or equal to x
 W = weight flow of fluid, g/s
 We = Weber number, $D_o \rho_g V_c^2 / \sigma$
 x = droplet diameter in dropsizes distribution expression, cm
 μ = absolute viscosity, g/cm s
 ρ = fluid density, g/cm³
 σ = surface tension of liquid relative to air, dynes/cm

Subscripts

- c = acoustic
 g = gas
 l = liquid
 m = molecular
 o = orifice
 w = water

Introduction

LIQUID-FUELED gas turbine and rocket combustor performance can be markedly improved with two-fluid fuel nozzles capable of producing large numbers of small fuel droplets, i.e., fuel sprays that have a large liquid surface-area to volume ratio. This improvement in combustor performance is due to the fact that large surface-area sprays yield high vaporization and burning rates. The very small droplets produced by this type of atomizer vaporize fast enough so that it may also be used to form premixed-prevaporized fuel-air mixtures suitable for application in catalytic combustors.

In Ref. 1, it was found that it was necessary to sample the spray at a distance of 2.2 cm axially downstream of the injector orifice to avoid the loss of very small droplets due to vaporization. Also, as reported in Ref. 2, an investigation was previously conducted using four differently sized two-fluid nozzles. It was found that reciprocal Sauter mean diameter (SMD) D_{32}^{-1} , could be correlated with the product of the Weber number, Reynolds number, and gas-to-liquid density ratio raised to the 0.44 power as follows: $D_{32}^{-1} \sim (WeRe \rho_g/\rho_l)^{0.44}$. This relationship shows that $D_{32} \sim V_c^{-1.33}$ where V_c is acoustic gas velocity. The exponent agrees with that predicted by atomization theory for liquid-jet breakup in high velocity gas flow.

Numerous investigators have studied the effect of fluid properties on liquid-jet atomization. Some of their results are given in Refs. 3–5. Of all the fluid properties that affect atomization, it was found in Ref. 2, that acoustic mass-flux $\rho_g V_c$ had the greatest effect on the fineness of atomization obtained with two-fluid nozzles. However, at present, the independent effect of gas density ρ_g on spray dropsizes has not been very well established in the literature as indicated in Refs. 6 and 7. Therefore, in the present study, the effect of gas density on spray dropsizes was investigated. To accomplish this, acoustic gas-velocity was held constant while gas density was varied over a gas mass-flux range of 6 to 50 g/cm²-s. In addition, a wide range of acoustic gas-velocities was investigated by using four different atomizing gases having molecular weights ranging from 4 to 44. The gases used were helium, nitrogen, argon, and carbon dioxide.

In the present study, two-phase flow in fuel nozzles was experimentally investigated to determine the effect of acoustic gas-velocity and mass-flux on characteristic spray dropsizes produced by liquid-jet breakup in high velocity gas flow. Characteristic dropsizes were measured with a scattered-light scanner developed at the NASA Lewis Research Center.⁸ The sprays were sampled at a distance of 2.2 cm downstream of the

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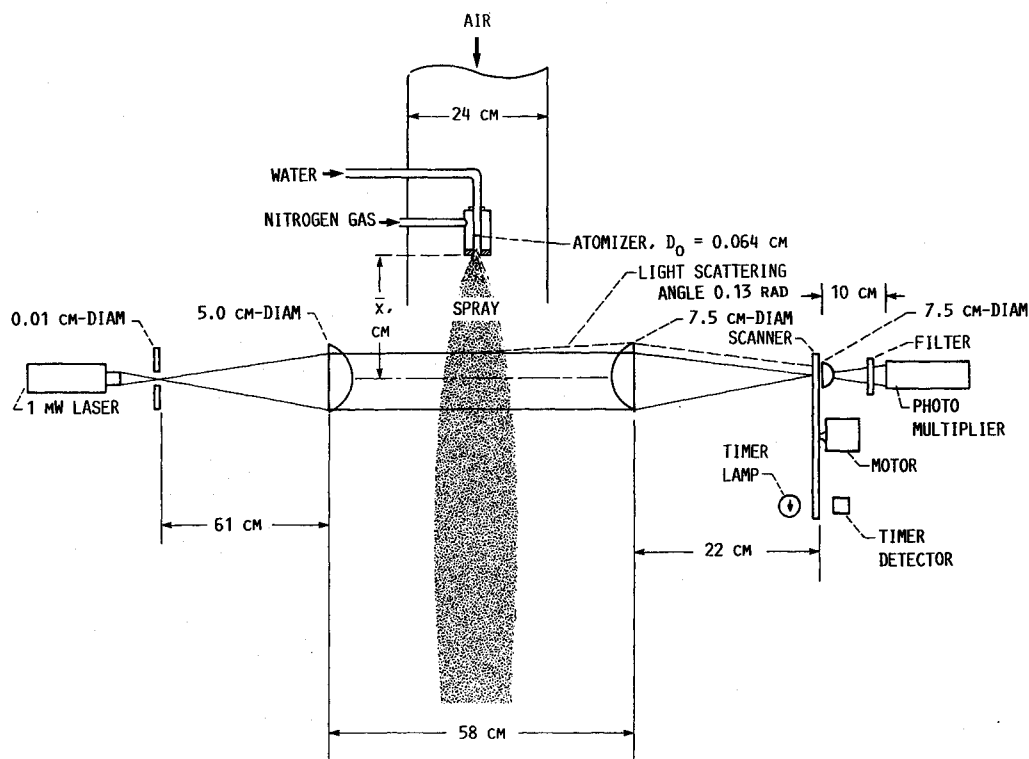


Fig. 1 Atmospheric pressure test section and optical path of scattered-light scanner.

fuel-nozzle orifice to minimize the loss of small droplets due to vaporization and dispersion. The sprays were injected into a low velocity (5 m/s) stream to aid in transporting very small droplets through the laser beam. Small-droplet sprays with Sauter mean diameters varying from 3 to 30 μm were produced by the atomization of small-diameter liquid jets in the regime of aerodynamic-stripping, i.e., high-velocity gas flow. Liquid and gas pressures were varied from 0.2 to 1.0 MPa.

Apparatus and Procedure

A two-fluid atomizer was mounted horizontally in the open duct as shown in Fig. 1. Air supplied at ambient temperature (293 K) passed through the 24 cm i.d. test section before being exhausted to the atmosphere. The test section was 1 m in length, and the airflow rate in the test section was measured with a 5.08 cm diam orifice. To aid in transporting small droplets through the laser beam, an airstream velocity of 5 m/s was maintained in the test section.

Four pneumatic two-fluid atomizers were fabricated according to the diagram illustrated in Fig. 2 with orifice diameters ranging from 0.32 to 0.56 cm. The atomizer was operated over pressure ranges of 0.2 to 1.0 MPa for both water and the atomizing gas. Sprays were injected downstream into the air-flow just upstream of the duct exit. The sprays were sampled at a distance of 2.2 cm downstream of the atomizer.

Water at a temperature of 298 K, measured with an iron-constantan thermocouple, was axially injected into the air-stream by gradually opening a control valve until the desired flow rate of 3.15 g/s was obtained as indicated by a turbine flowmeter. The atomizing gas was then turned on, and weight flowrate was measured with a 0.51 cm diam sharp-edge orifice. After the air, atomizing gas and water flowrates were set, the Sauter mean drop diameter was measured with the scattered-light scanner to characterize each spray. Exponents for the Rosin-Rammler and Nukiyama-Tanasawa droplet distribution expressions were also determined using the scattered-light scanner.

The optical system of the scattered-light scanner shown in Fig. 1 consists of a laser beam expander with a spatial filter,

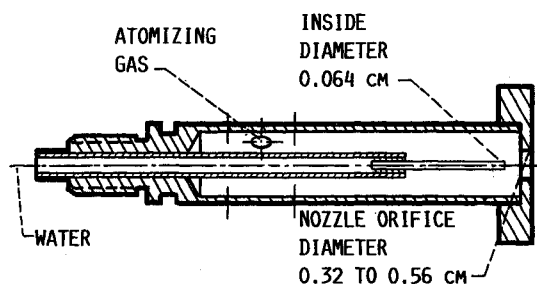


Fig. 2 Diagram of pneumatic two-fluid atomizer.

rotating scanning slit, and a detector. Using a 4.4 by 1.9 cm laser beam, the instrument measures scattered light as a function of scattering angle by repeatedly sweeping a variable-length slit in the focal plane of the collecting lens. The data obtained is scattered-light energy as a function of the scattering angle relative to the laser beam axis. This method of particle size measurement is similar to that given in Ref. 9.

In Ref. 10, it was found that measurements of points on a plot of scattered-light energy normalized to the maximum energy and plotted against scattering angle can be used to determine the SMD, the volume median, the volume linear, and the 75% volume diameters as illustrated in Fig. 3. The dispersion of the size distribution is also determined from the points on the plot shown in Fig. 3. Also, it should be noted that this method of determining characteristic drop diameters and dispersion of droplets can be used independent of the particle size distribution function as discussed in Ref. 10. For a typical measurement, the scan is repeated 60 times per s to average out any temporal variations in the energy curve.

Spray pattern effects were minimized by measuring characteristic drop diameters using the entire spray. Reproducibility using this technique was within $\pm 5\%$. Calibration was accomplished with five sets of monosized polystyrene spheres having diameters of 8, 12, 25, 50, and 100 μm . Since the present sprays were sampled very close to the atomizer orifice, they contained a relatively high number-density of very small drops. As a result, the light-scattering measurements required correction for multiple scattering as described in Ref. 11.

Dropsizes measurements were also corrected to include Mie scattering theory when very small droplet diameters, i.e., $< 10 \mu\text{m}$, were measured.

Experimental Results

Four atomizing gases, i.e., nitrogen, argon, carbon dioxide, and helium, were used in two-fluid fuel nozzles to study the effect of atomizing-gas density on spray dropsizes. To demonstrate this effect, several dimensionless groups were investigated.

Effect of Atomizing-Gas Mass-Flux on Spray Dropsizes

The reciprocal SMD D_{32}^{-1} was plotted against atomizing-gas flowrate per unit area as shown in Fig. 4. From this plot, the following relationship is obtained for the four atomizing gases, helium, nitrogen, argon, and carbon dioxide:

$$D_{32}^{-1} = k(W_g/A_o)^{1.33} \quad (1)$$

where k is a correlation coefficient that is a function of the gas used to atomize water jets. Equation (1) can be rewritten in terms of gas mass-flux as follows:

$$D_{32}^{-1} = k(\rho_g V_g)^{1.33} \quad (2)$$

Values of the correlation coefficient k for each atomizing gas are given in Table 1.

The four atomizing gases show good agreement with atomization theory,¹² which predicts reciprocal SMD to be directly proportional to gas velocity raised to the 1.33 power. This exponent also agrees well with the results previously reported in Refs. 1 and 2 and the value of 11.5 obtained for the coefficient k is in good agreement with that reported in Ref. 8 for two-fluid atomizers using nitrogen gas.

A comparison of k values clearly shows the marked improvement that is obtained in fineness of atomization when

a low-density gas such as helium is used as the atomizing gas for two-fluid fuel nozzles operating at acoustic gas velocities. The attainment of a large liquid-surface area per unit volume of liquid, i.e., large values of reciprocal SMD D_{32}^{-1} , with the use of helium is attributed to the low molecular weight and therefore high acoustic-velocity of helium. On the other hand, the higher molecular weights and lower acoustic velocities of argon and carbon dioxide make them much less efficient as atomizing gases for two-fluid fuel nozzles operating at acoustic gas velocities.

Correlation of Normalized Reciprocal SMD with Dimensionless Groups

In the study of liquid-jet breakup in high-velocity nitrogen gas flow that is reported in Ref. 1, it was found that the reciprocal of the normalized SMD $(D_{32}/D_o)^{-1}$ could be directly correlated with the product of the Weber and Reynolds numbers $WeRe$ multiplied by the gas-to-liquid density ratio ρ_g/ρ_l as follows:

$$D_o/D_{32} = k'(WeRe \rho_g/\rho_l)^{0.44} \quad (3)$$

where $WeRe = D_o^2 \rho_g^2 V_c^3 / \mu_l \sigma$ and V_c is the acoustic velocity of the gas. Atomization data obtained for the four atomizing gases are shown in Fig. 5. From the slope of the plots, a correlation coefficient k' was determined for each atomizing gas and values of k' are recorded in Table 1.

Effect of Atomizing-Gas Properties on Liquid-Jet Breakup

The primary objective of this investigation was to study liquid-jet breakup in two-fluid atomizers by using four different atomizing gases and to correlate reciprocal Sauter mean diameter D_{32}^{-1} with atomizing-gas properties. As shown in Fig. 5, the product of the Weber and Reynolds numbers and the density ratio do not give a single correlating expression. In order to accomplish the objective of this study, the normalized

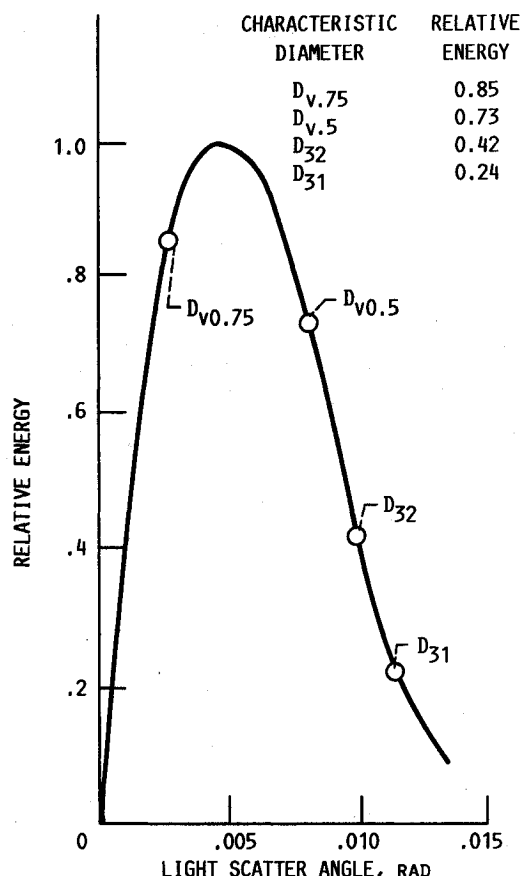


Fig. 3 Typical scattered-light energy curve with four characteristic diameters.

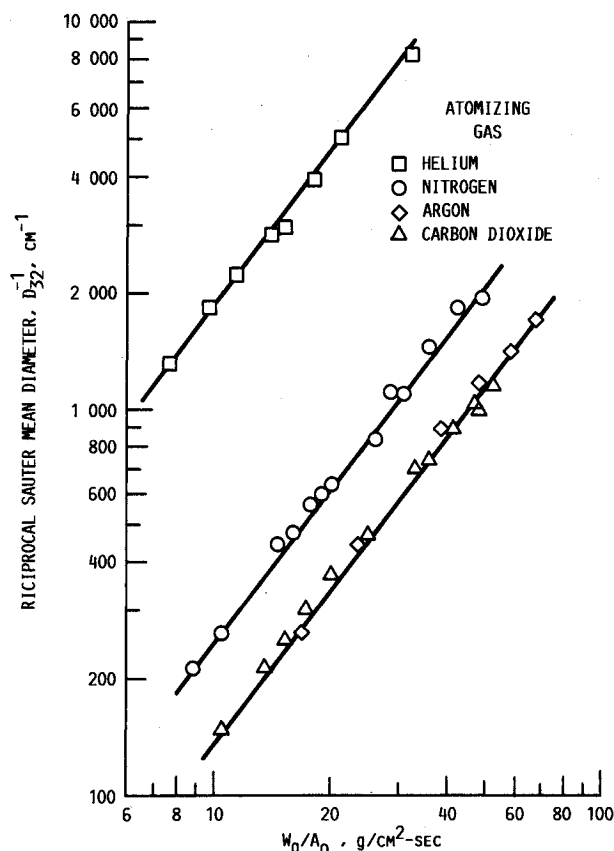
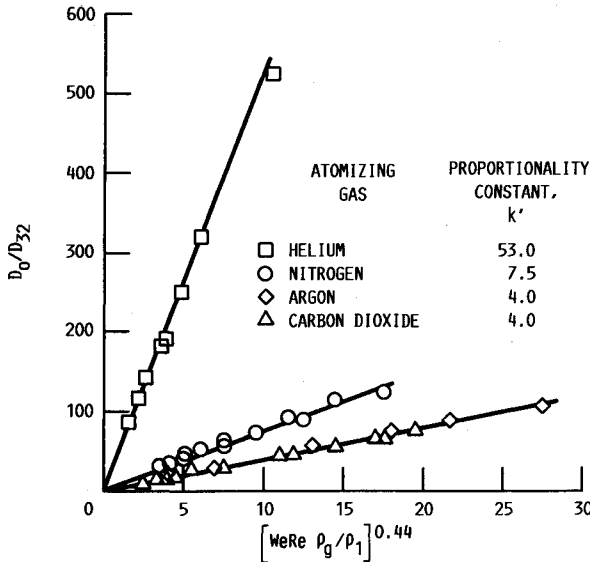


Fig. 4 Variation of reciprocal SMD with gas flowrate per unit area W_g/A_o at a liquid flowrate of 3.15 g/s, and Mach 1 gas flow.

Table 1 Correlation coefficients for atomizing gases

Atomizing gas	Correlation coefficients	
	k , Eq. (1)	k' , Eq. (3)
He	86.5	53.0
N ₂	11.5	7.5
Ar	6.3	4.0
CO ₂	6.3	4.0

**Fig. 5** Correlation of SMD D_{32} with dimensionless group $WeRe$ and fluid density ratio.

reciprocal Sauter mean diameter D_o/D_{32} produced by liquid-jet breakup with two-fluid atomizers is also assumed to be a function of the rms velocity of the gas molecules V_m the acceleration of gas molecules due to gravity g , atomizing-gas viscosity μ_g , and liquid density ρ_l . Using dimensional analysis, the following expressions are obtained:

$$D_o/D_{32} = f(V_m, \mu_g, \rho_l, g) \quad (4)$$

where $V_m = \sqrt{3RT_g/M_g}$.¹² By rewriting Eq. (4), there results

$$D_o/D_{32} = f(\rho_l)^a (V_m)^b (g)^c (\mu_g)^d \quad (5)$$

The preceding equation is then expressed in terms of the mass-length-time system (where T is time; M , mass; and L , length) to give

$$\frac{D_o}{D_{32}} = f\left(\frac{M}{L^3}\right)^a \left(\frac{L}{T}\right)^b \left(\frac{L}{T^2}\right)^c \left(\frac{M}{LT}\right)^d \quad (6)$$

so that for

$$M, 0 = a + d$$

$$T, 0 = -b - 2c - d$$

$$L, 0 = -3a + b + c - d$$

which may be written as

$$a = -d$$

$$b = -2c - d = -3d$$

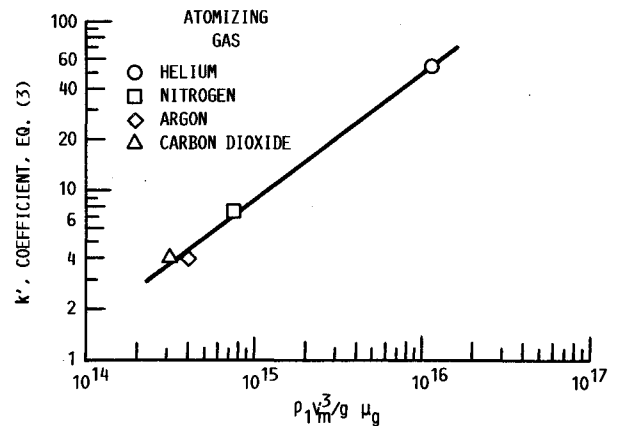
$$c = 3a - b + d$$

Substitution of these values into Eq. (5) gives

$$D_o/D_{32} = f(\rho_l V_m^3 / g \mu_g)^{-d} \quad (7)$$

Table 2 Effect of physical properties on reciprocal SMD, at Mach 1 gas flow

Source	Relationship
Gas-phase properties	
Present study	$D_{32}^{-1} \sim V_c^{1.33}, \rho_g^{1.33}, \mu_g^{-0.75}, M_g^{-0.46}, V_m^{2.25}$
Ref. 12 theory	$D_{32}^{-1} \sim V_g^{1.33}, \rho_g^{0.67}, \mu_g^0, M_g^0, V_m^0$
Liquid-jet properties	
Present study	$D_{32}^{-1} \sim \rho_l^{0.31}, \mu_l^{-0.44}, \sigma^{-0.33}$
Ref. 12 theory	$D_{32}^{-1} \sim \rho_l^{0.33}, \mu_l^{-0.67}, \sigma^{-0.33}$
Other terms	
Present study	$D_{32}^{-1} \sim D_o^{-0.2}, g^{-0.75}$
Ref. 12 theory	$D_{32}^{-1} \sim D_o^0, g^0$

**Fig. 6** Correlation of proportionality coefficient k' with dimensionless group $\rho_l V_m^3 / g \mu_g$.

To obtain a general correlating expression for the four atomizing gases, the correlation coefficient k' is plotted against $\rho_l V_m^3 / g \mu_g$. From the slope of this plot shown in Fig. 6, the following relationship is obtained:

$$k' \sim (\rho_l V_m^3 / g \mu_g)^{0.75} \quad (8)$$

where the exponent $-d$, derived from dimensionless analysis, is equal to 0.75. Since this exponent is fairly large, the variables μ_g , ρ_l , V_m , and g have a very important effect on the liquid-jet breakup process. Microgravity studies are needed in which g is varied to determine if the exponent 0.75 is correct for g .

To obtain a single correlating coefficient for the atomizing gases, values of D_o/D_{32} are plotted against the product of the dimensionless groups given in Eqs. (3) and (8), as shown in Fig. 7. Thus the following expression is obtained for the four atomizing gases:

$$D_o/D_{32} = 4.33 \times 10^{-11} (WeRe \rho_g / \rho_l)^{0.44} (\rho_l V_m^3 / g \mu_g)^{0.75} \quad (9)$$

Since $WeRe(\rho_g / \rho_l) = D_o^2(\rho_g V_c)^3 / \mu_l \rho_l \sigma$, it is evident that the reciprocal Sauter mean diameter is proportional to $V_m^{2.1}$, $\rho_l^{0.31}$, $\mu_g^{-0.75}$, and gas molecular weight raised to the -0.46 power. For the liquid properties, D_{32}^{-1} is proportional to $\mu_l^{-0.44}$, $\sigma^{-0.44}$, and $\rho_l^{0.31}$. The liquid-property exponents give fairly good agreement with those predicted by atomization theory,¹² as shown in Table 2. Therefore Eq. (9), although it was derived for water-jet breakup, should give fairly good results in predicting fuel-jet breakup in Mach 1 gas flow with two-fluid nozzles.

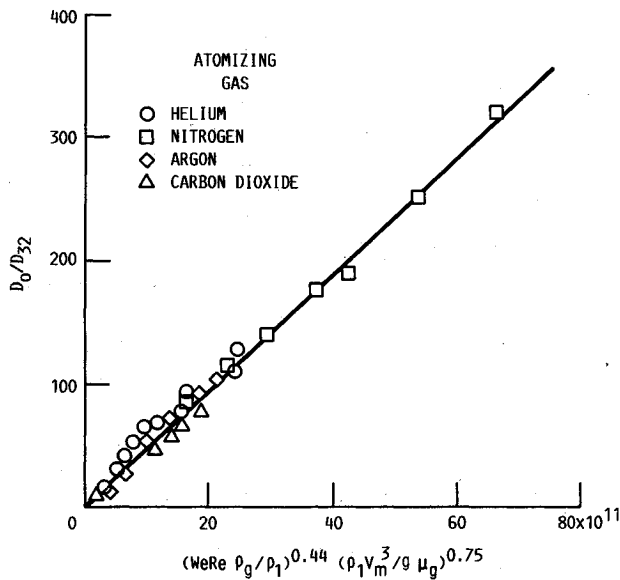


Fig. 7 Correlation of normalized reciprocal SMD with dimensionless groups.

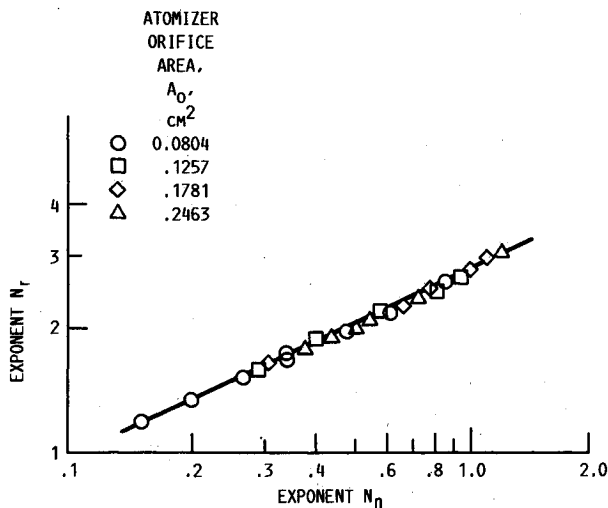


Fig. 8 Correlation of Rosin-Rammler and Nukiyama Tanasawa exponents N_r and N_n , respectively.

Correlation of Exponents for Dropsizes Distribution Expressions

The scattered-light scanner gave data for the exponent N_r , which appears in the Rosin-Rammler expression as follows¹³:

$$\frac{dv}{dx} = \frac{N_r x^{N_r-1}}{c N_r} e^{-(x/c)^{N_r}} \quad (10)$$

Data were also obtained for the exponent N_n , which appears in the Nukiyama-Tanasawa expression as follows¹³:

$$\frac{dv}{dx} = \frac{b^{6/N_n}}{\Gamma(6/N_n)} x^5 e^{-bx^{N_n}} \quad (11)$$

From a plot of the data obtained with the four atomizers, as shown in Fig. 8, the following relation was determined:

$$N_r = 2.8 N_n^{0.45} \quad (12)$$

which is the same as that derived in Ref. 2. Thus it was found that the relation between exponents N_n and N_r was not appreciably affected when the atomizing-gas molecular weight was varied from 4 to 44.

Conclusions

From the correlating expressions derived in this study, it is evident that

1) The effect of atomizing-gas density ρ_g on spray droplet size is the same as that of acoustic velocity V_c , i.e., $D_{32}^{-1} \sim (\rho_g V_c)^{1.33}$.

2) The rms gas molecular-velocity V_m and acoustic mass-flux $\rho_g V_c$ have the greatest effect of all gas- and liquid-phase properties on the process of liquid-jet breakup in high-velocity gas flow.

3) The reciprocal SMD D_{32}^{-1} produced with two-fluid atomizers was considerably greater for helium in comparison with nitrogen at the same gas mass-flux. The superior performance of helium gas as compared with that obtained with nitrogen is attributed to the relatively high acoustic and rms molecular velocities of helium.

Appendix: Characteristic Dropsizes of Liquid Fuel-Sprays Simulated by Water-Jet Breakup in High-Velocity Gas Flow

Values of liquid properties given in Table A1 were used in Eq. (9) to calculate reciprocal Sauter mean diameters for JP-5 and n-octane fuel-sprays. These are plotted against gas mass-flux in Fig. A1. Two sets of plots are presented. The elevation of the upper set over the lower one shows the effect on spray

Table A1 Liquid-jet physical properties at 20°C and values of k for Eq. (1)

Liquid	Physical properties			Values of k for atomizing gases	
	$\mu_l \times 10^2$, poises	σ , dynes/cm	ρ_l , g/cc	N ₂	He
Water	10.10	72.8	1.00	11.5 ^a	86.5 ^a
JP-5	15.80	28.5	0.68	12.7 ^b	95.3 ^b
n-Octane	5.42	21.8	0.82	24.2 ^b	181.7 ^b

^aExperimental. ^bCalculated.

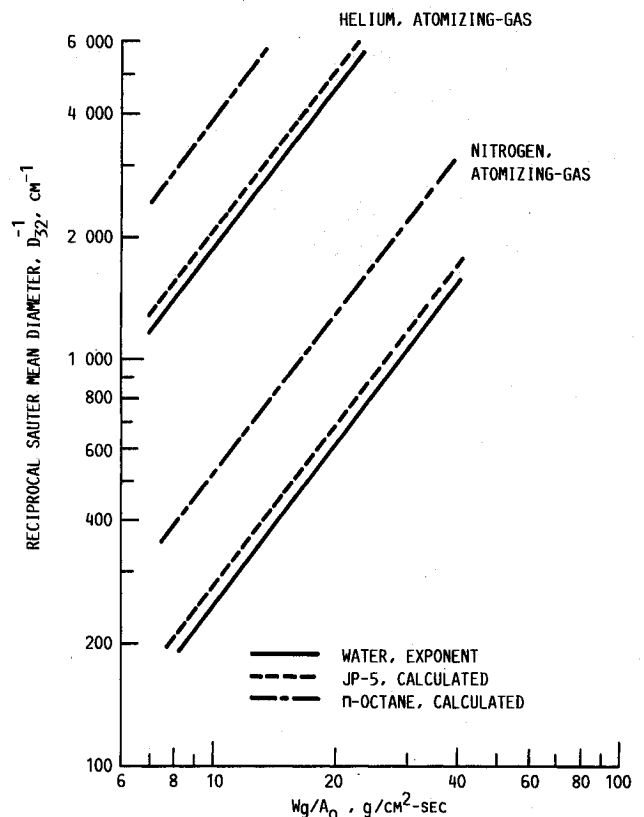


Fig. A1 Comparison of reciprocal SMDs for water with fuel-spray calculated values, at Mach 1 gas flow.

surface-area that is obtained, according to Eq. (9), when helium gas is used in two-fluid atomizers instead of nitrogen gas. From these plots, values of k were calculated and are recorded in Table A1.

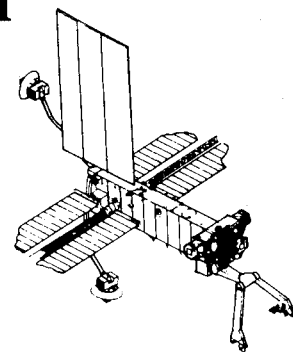
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