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Cryogenic Spray Vaporization in High-Velocity Helium, Argon and Nitrogen Gasflows

Robert D. Ingebo
Lewis Research Center
Cleveland, Ohio

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CRYOGENIC SPRAY VAPORIZATION IN HIGH-VELOCITY HELIUM, ARGON AND NITROGEN GASFLOWS

Robert D. Ingebo
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

Effects of gas properties on cryogenic liquid-jet atomization in high-velocity helium, nitrogen and argon gasflows were investigated. Volume median diameter, $D_{v.5e}$, data were obtained with a scattered-light scanning instrument. By calculating the change in spray dropsize, $-\Delta D^2_{v.5}$, due to droplet vaporization, it was possible to calculate $D_{v.5c}$ from the expression, $-\Delta D^2_{v.5} = D^2_{v.5e} - D^2_{v.5c}$. $D^2_{v.5c}$ is the unvaporized characteristic dropsize formed at the fuel-nozzle orifice. $D^2_{v.5c}$ was normalized with respect to liquid-jet diameter, D_o, to give the dimensionless ratio $D_o/D^2_{v.5c}$. It was then correlated with several dimensionless groups to give the following expression:

$$\frac{D_o}{D_{v.5c}} = k_c\left(\mathrm{WeRe}\frac{\rho_g}{\rho_\ell}\right)^{0.44}\left[\left(\frac{\rho_\ell V_m^3}{g\mu_g}\right)\left(\frac{T_g}{T_o}\right)\right]^{0.75}$$

where k_c is a proportionality constant, WeRe is the product of Weber and Reynolds number, ρ_g/ρ_ℓ is the fluid density ratio, and $\rho_\ell V_m^3/g\mu_g$ is a molecular-scale group derived in this study to correlate the original characteristic dropsize, $D_{v.5c}$, with atomizing forces produced by the three atomizing gases. This expression, for the volume median diameter of cryogenic LN_2 sprays, correlates dropsize $D_{v.5c}$ with aerodynamic and liquid-surface forces so that it can be readily determined in the design of multiphase-flow propellant injectors for rocket combustors.

Nomenclature

A_o	fuel nozzle orifice area, cm^2
a	acceleration, cm/sec^2
C_d	drag coefficient
D_o	liquid-jet diameter, cm
$D_{v.5}$	volume median drop diameter, cm
k	correlation coefficient for Eq. (1)
k′	correlation coefficient for Eq. (7)
k″	correlation coefficient for Eq. (12)
Nu	heat-transfer Nusselt number, based on $D_{v.5e}$
n	exponent for Eq. (1)
Re	Reynolds number based on $D_{v.5e}$
T_o	ambient airflow temperature, 293 K
t	vaporization time, sec
V_c	acoustic velocity, cm/sec
W	weight flow of fluid, g/sec
We	Weber number based on $D_{v.5e}$
x	axial downstream spray sampling distance
μ	absolute viscosity, g/cm sec
ρ	fluid density, g/cm^3
σ	surface tension relative to air, dyne/cm

Subscripts

c	calculated
d	droplet
e	experimental
f	film
g	gaseous nitrogen, GN_2
ℓ	liquid nitrogen, LN_2
o	orifice

Introduction

The performance of liquid-fuel atomizers in gas turbine and rocket engines can be markedly improved when fuel-spray surface areas are increased. This will give a corresponding increase in droplet vaporization and burning rates. Previous water spray studies reported in Ref. 1 have shown that two-fluid fuel nozzles can produce large numbers of very small drops, i.e., sprays with large surface-area-to-volume ratios. Small fuel droplets produced with this type of atomizer, vaporize rapidly so that it can even be used to form premixed-prevaporized fuel-air mixtures suitable for catalytic combustors. In the case of rocket combustors, the two-fluid propellant nozzle is used quite extensively, i.e., in the main engines of the space shuttle.

In studying sprays produced with two-fluid fuel nozzles, Ref. 1, dropsize measurements were made close to the fuel-nozzle orifice to avoid the loss of very small water droplets due to vaporization. However, in the present study of highly volatile liquid-jet breakup, it was necessary to determine effects of droplet vaporization and acceleration on dropsize measurements, in order to calculate original unvaporized spray dropsize and compare it with that predicted by atomization theory. This is due to the fact that LN_2 jets injected into high-velocity gasflow will quickly breakup into large numbers of very small drops, i.e., in the order of 1 to 10 μm. Some of the very small drops vaporized completely before passing through the laser beam, which was located at a distance of 1.2 cm downstream of the fuel nozzle orifice. As a result, only measurements of partially vaporized sprays could be obtained experimentally. In order to compare results of this study with atomization theory, the initially unvaporized value of $D_{v.5c}$ was determined by means of the following expression: $D^2_{v.5c} = D^2_{v.5e} - \Delta D^2_{v.5}$. Droplet vaporization and acceleration rates were calculated by using heat-transfer and drag coefficient expressions derived in Ref. 2. Values of $\Delta D^2_{v.5c}$ could then be calculated and used to determine original values of $D_{v.5c}$ that existed before vaporization had occurred.

Cryogenic sprays with relatively large surface-areas per unit volume are desirable since they produce rapid fuel spray vaporization and efficient combustion in rocket combustors. In order to calculate increases in the efficiency of a fuel spray combustion process, vaporization and burning rate expressions are needed to compute changes in the surface-area of a vaporizing fuel spray. Such mathematical expressions were investigated in the present study of LN_2 jets breaking up in He, N_2 and Ar gasflows. This information is needed to develop fuel-spray combustion models. Also, wide ranges of liquid fuel and atomizing-gas properties need to be investigated, so that fuel-spray combustion models can be directly applied to develop more efficient fuel atomizers, improve combustor performance and reduce exhaust emissions.

In the present investigation of vaporizing LN_2 sprays, measurement of $D_{v.5e}$ were made in the presence of relatively high thermal gradients. The atomizing gases, i.e., He, N_2 and Ar, were at room temperature, 293 K, whereas LN_2 droplet surface temperatures were near the boiling point of LN_2, 77 K. As a result, heat transfer across the gas-film had a driving potential ΔT, of 216 K. This is considerably higher than that encountered in the study of water sprays, as discussed in Ref. 1. In that study, the effect of vaporization on dropsize measurements of water sprays was negligible, when measurements were made very close to the fuel nozzle orifice. However, in the present study of LN_2 sprays, the droplets vaporized quite rapidly.

The effects of atomizing-gas mass flux and gas velocity on spray dropsize have been studied by numerous investigators as reported in Refs. 1-7. Atomization theory predicts that the characteristic dropsize, D_c, is proportional to V_g^n, where $n = -1.33$. However, as shown in Table I, exponents determined by various investigators varied from -1.00 to -1.33. This disagreement can be attributed to the effect of droplet vaporization on dropsize measurements, when they were taken relatively far downstream of the atomizer orifice. This was shown to be true for water sprays, as reported in Ref. 1, when sampling distance downstream of the atomizer was increased from 2.2 to 6.7 cm. As a result, the exponent for V_g decreased from -1.33 to -1.00.

To determine effects of atomizing-gas properties on LN_2 jet breakup in high-velocity gasflows of He, N_2 and Ar, the characteristic dropsize $D_{v.5}$ of the cryogenic sprays was measured with a scattered-light scanner developed at NASA Lewis Research Center by Buchele, Ref. 8. LN_2 sprays were sampled at a distance of 1.2 cm downstream of the fuel nozzle to minimize losses of very small droplets due to vaporization. Values of $D_{v.5e}$ varied from 3 to 30 μm and measurements were made at an atomizing-gas temperature of 293 K.

Apparatus and Procedure

In a two-fluid fuel nozzle, helium, nitrogen and argon gasflows were used to breakup liquid-nitrogen, LN_2, jets as shown in Fig. 1. The atomizer was mounted at the center line of the 24-cm diameter duct and operated over LN_2 and atomizing-gas pressure ranges of 0.2 to 1.0 MPa.

LN_2 sprays were injected downstream into the airflow, just upstream of the duct exit, and sampled at a distance of 1.2 cm downstream from the atomizer orifice to the center line of the 4.4- by 1.9-cm laser beam. The two-fluid nozzle was fabricated according to the diagram illustrated in Fig. 2. LN_2 at a temperature of 77 K was axially injected into the airstream by gradually opening the control valve until the desired flowrate of 51 g/sec 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 diameter sharp-edge orifice. After atomizing gas and LN_2 flowrates were set, the volume median diameter, $D_{v.5e}$, was measured with the scattered-light scanner.

The optical system of the scattered-light scanner shown in Fig. 3 consisted of a laser beam expander with spatial filter, rotating scanning-slit and a detector. 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 described in Ref. 9. According to Buchele,[8] measurements of scattered-light energy normalized by the maximum energy and plotted against scattering angle can be used to determine the volume median diameter, $D_{v.5e}$. Also, this method of determining characteristic dropsize and dispersion of dropsize can be used independent of particle size distribution function, according to Buchele.[8] For a typical measurement, the scan is repeated 60 times per second to average out any temporal variations in the energy curve.

Spray pattern effects were minimized by measuring $D_{v.5e}$ for the entire cloud of droplets. The instrument was calibrated with five sets of monosized polystyrene spheres having diameters of 8, 12, 25, 50 and 100 μm. Since the sprays were sampled very close to the atomizer orifice, they contained a relatively high number-density of very small droplets. As a result, the light-scattering measurements required correction for multiple scattering as described in Ref. 10. Also, dropsize measurements were corrected to include Mie scattering theory when very small drop diameters, i.e., 10 μm, were measured. Reproducibility tests showed that experimental measurements agreed within ± 5 percent. Background effects due to severe gas-density gradients were negligible due to taking background readings with a high-temperature atomizing gas flowing through the nozzle and thereby obtaining corrected light-scattering curves for measuring the spray dropsize.

Experimental Results

Measurements of the volume median diameter were obtained by sampling the entire LN_2 spray cross section with the laser beam center line located at a distance of 1.2 cm downstream of the fuel nozzle orifice, as shown in Fig. 3. Partially vaporized droplets traveled a distance of 2.0 cm through the scattered-light scanner laser beam. However, some of the very small droplets were completely vaporized before they could exit the laser beam. As a result, measurements of $D_{v.5e}$ were obtained for partially vaporized LN_2 sprays. Thus, it was necessary to calculate the change in dropsize, $\Delta D^2_{v.5}$, in order to determine the initially unvaporized spray dropsize, $D_{v.5c}$, that was formed at the fuel-nozzle orifice.

Variation of $D_{v.5e}$ With Atomizing-Gas Flowrate

Experimental values of $D_{v.5e}$ obtained with the scattered-light scanner are plotted against atomizing-gas flowrate, W_g, as shown in Fig. 4. High-velocity gasflows were used and LN_2 jet breakup occurred primarily in the regime of aerodynamic stripping. No indication of secondary breakup of droplets was observed, since the low gas-velocity regime of capillary wave breakup of liquid jets was not investigated. From the plot shown in Fig. 4, the following expression was obtained for reciprocal $D_{v.5e}$:

$$D^{-1}_{v.5e} = k_e W^n_g \tag{1}$$

Values of the proportionality constant k_e and exponent n are given in Table II, for the three atomizing gases helium, nitrogen and argon, respectively. The following expression was obtained for nitrogen gasflow: $D^{-1}_{v.5e} = 275\ W^{1.11}_n$, where values of $D^{-1}_{v.5e}$ and W_n are expressed as cm^{-1} and g/sec, respectively.

The value of n = 1.11 is considerably less than that of 1.33 predicted by atomization theory, for liquid-jet breakup in high-velocity gasflow. This discrepancy is attributed to the loss of very small vaporizing LN_2 drops, before dropsize measurements could be completed with the scattered-light scanner. In the present study, results agree better with theory than those reported in Ref. 11, since an allowance is made for the effect of droplet vaporization on dropsize measurements of highly volatile sprays. This effect was not accounted for in Ref. 11 and although the dropsize data did appear to agree with theory, the proportionality constant k was too low to adequately characterize an initially unvaporized spray. As a result, the study in Ref. 11 did not take into account the fact that very small drops could be completely vaporized before passing through the laser beam.

Droplet Acceleration

Effects of droplet vaporization rate on experimental values of $D_{v.5e}$ were determined by calculating vaporization time, t, as based on the velocity V_d for characteristic dropsize $D_{v.5e}$. Time, t, was calculated for a distance of 2.2 cm, i.e., from nozzle orifice to downstream edge of laser beam, as shown in Fig. 3.

Volume median drop velocity, V_d and acceleration, a, of liquid nitrogen droplets were calculated using the following momentum balance, as given in Ref. 8:

$$m_d a = \frac{1}{2}\rho_g A_d \left(V_g - V_d\right)^2 C_d \tag{2}$$

where m_d and A_d are mass and area of dropsize $D_{v.5e}$, respectively; i.e., $m_d = \rho_\ell \pi D^3_{v.5e}/6$. C_d is the drag coefficient based on characteristic length, $D_{v.5e}$.

Rewriting Eq. (2) in terms of ΔV_d^2, over the distance Δx, the following relationship is obtained:

$$\frac{\Delta V_d^2}{\Delta x} = \frac{3\rho_g\left(V_g - V_d\right)^2}{2\rho_\ell D_{v.5e}} C_d \tag{3}$$

where $C_d = 27\ Re^{0.84}$, as given in Ref. 2, and Re is based on characteristic dropsize, $D_{v.5e}$.

Deceleration of atomizing gases helium, nitrogen and argon into a low-velocity airflow was determined as follows. Gas velocity at the nozzle orifice was equal to the acoustic velocity, V_c. Values of V_g used to solve Eq. (3) were calculated at downstream distances of x = 5 and 10 cm, respectively, and plotted in Fig. 5. Values of V_g are based on data given in Ref. 12 and plotted in Fig. 5 for comparison. The percent deceleration of the atomizing gas was assumed to be approximately the same in both cases, since the two-fluid nozzles used in Ref. 12 and the one used in the present study are very similar in design.

To determine acceleration of LN_2 droplets characterized by $D_{v.5e}$, values of V_d^2 were calculated by numerically integrating Eq. (3) and plotting V_d^2 against downstream distance, x, as shown in Fig. 6. Vaporization time, t, was calculated from this plot by means of the expression $\Delta t = x/V_d$. Calculated values of Δt for a given distance Δx are given in Table III, along with calculated Reynolds numbers averaged over the distance Δx and values of $D_{v.5e}$. Atomizing-gas transport properties used in calculating vaporization times are given in Table IV.

Cryogenic Spray Vaporization Rate

Spray vaporization rates, as based on characteristic dropsize, $D_{v.5e}$, were calculated using the heat-balance expression: $dm_d/dt = hA\ \Delta T/H_t$, where h is the heat-transfer coefficient and A is spray surface-area based on $D_{v.5e}$. $\Delta T = T_g - T_d$ and $H_t = H_v + C_p\ \Delta T$. H_v is the latent heat of vaporization of LN_2 and C_p is the specific heat of nitrogen vapor. To determine vaporization rate in terms of droplet surface-area changes with time, the heat-balance was rewritten as follows:

$$\frac{-D_{v.5}^2}{\Delta t} = \frac{4k_g\ \Delta T\ Nu}{\rho_\ell H_t} \tag{4}$$

where k_g and ρ_ℓ are gas thermal conductivity and liquid density, respectively. Previous fuel droplet studies reported in Ref. 2 used a high-speed droplet tracking camera to determine vaporization rates of jet-A fuel, n-octane, benzene, acetone, water and several other liquids. In that study, it was found that Nu = 2 + 0.303 $Re^{0.6}$, where Nu is the Nusselt number and Re = $\rho_g\ D_{v.5e}\ \Delta V/\mu_g$. ΔV is the velocity difference averaged over incremental distance Δx. Vaporization rate calculations are based on characteristic diameter $D_{v.5e}$. Atomizing-gas viscosity and thermal conductivity are evaluated at the average gas-film temperature, i.e., $T_f = \frac{1}{2}(T_g - T_\ell)$. LN_2 droplet surface temperatures were assumed to be close to the boiling point, 77 K, as droplets were being accelerated and partially vaporized. Latent heat of vaporization of LN_2 was evaluated at 77 K and the specific heat of nitrogen vapor was evaluated at the average gas-film temperature T_f.

The initial unvaporized volume median diameter squared, $D_{v.5}^2$, was calculated from experimental measurements of $D_{v.5e}^2$ and values of $-\Delta D_{v.5}^2$ obtained from Eq. (4), by means of the following expression:

$$-\Delta D_{v.5}^2 = D_{v.5c}^2 - V_{v.5e}^2 \tag{5}$$

Calculated values of $D_{v.5c}^2$ were correlated with atomizing-gas flowrate, W_g, as shown in Fig. 7, and the following expression was obtained:

$$D_{v.5c}^{-1} = 264\ W_g^{1.33} \tag{6}$$

when nitrogen gas was used to atomize the LN_2 jets. Comparing Eq. (6) with Eq. (1), which gave $D_{v.5e}^{-1} = 275\ W_g^{1.11}$ for nitrogen gasflow, shows that values of k_e and k_c are nearly the same. However, the value of exponent n for the partially vaporized sprays is considerably less, i.e., 1.11 as compared with 1.33 given in Eq. (6). This indicates a marked effect of droplet vaporization on dropsize measurements and also shows good agreement of calculated values of n with atomization theory,[13] which predicts n = 1.33, for liquid jet breakup in high-velocity gasflow. The agreement of Eq. (6) with theory indicated the fact that a characteristic dropsize for the initial spray, $D_{v.5c}$ can be computed by using heat-transfer and drag coefficient expressions reported in Ref. 2.

Correlation of $D_o/D_{v.5c}$ With Dimensionless Force Ratios

Values of $D_{v.5c}$ were normalized with respect to LN_2-jet diameter, D_o, and plotted against the product of We, Re and ρ_g/ρ_ℓ, i.e., the Weber number, Reynolds number and fluid-density ratio, respectively, as shown in Fig. 8. The following expression was derived:

$$\frac{D_o}{D_{v.5c}} = k_c'\left(WeRe\frac{\rho_g}{\rho_\ell}\right)^{0.44} \tag{7}$$

where WeRe is the ratio of aerodynamic to LN_2-jet surface forces, i.e., liquid viscosity and surface tension. The fact that three plots are shown in Fig. 8 indicates that coefficient k_c' is also a function of some other physical properties of the three atomizing gases.

Effect of Atomizing-Gas Properties on LN_2-Jet Breakup

In the present study of LN_2-jet breakup in two-fluid fuel nozzles, the main objective was to derive a single correlating expression for $D_o/D_{v.5c}$ that would be valid for a wide variety of atomizing gases. Figure 8 shows the product of the Weber and Reynolds numbers and the fluid-density ratio do not give a single correlating expression. Therefore, to accomplish this study's objective, the normalized volume median diameter ratio, $D_o/D_{v.5c}$, as produced by liquid jet atomization in two-fluid fuel nozzles is also assumed to be a function of: the rms gas molecular velocity, V_m, liquid density, ρ_ℓ, gas viscosity, μ_g, and to be normalized with respect to acceleration of the gas molecules due to gravity, g. As a result, by means of dimensionless analysis, the following expressions were derived:

$$\frac{d_o}{D_{v.5c}} = f\left(V_m, \mu_g, \rho_\ell, g\right) \tag{8}$$

where $V_m = (3RT_g/M_g)^{0.5}$,[14] Eq. (8) may be rewritten as:

$$\frac{D_o}{D_{v.5}} = f(\rho_\ell)^a (V_m)^b (g)^c (\mu_g)^d \tag{9}$$

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

$$\frac{D_o}{D_{v.5}} = \left[\frac{M}{L^3}\right]^a \left[\frac{L}{T}\right]^b \left[\frac{L}{T^2}\right]^c \left[\frac{M}{LT}\right]^d \tag{10}$$

As a result:

$$M;0 = a + d$$

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

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

which gives:

$$a = -d$$

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

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

Substitution of these values into Eq. (9) gives:

$$\frac{D_o}{D_{v.5}} = f\left(\frac{\rho_\ell V_m^3}{g\mu_g}\right)^{-d} \tag{11}$$

In order to derive a correlating expression for He, N_2 and Ar, as atomizing gases for two-fluid fuel nozzles, the correlation coefficient, k′ is plotted against $\rho_\ell V_m^3/g\mu_g$. From the slope of the plot shown in Fig. 3, the following relationship is obtained:

$$k_c'' \sim \left(\frac{\rho_\ell V_m^3}{g\mu_g}\right)^{0.75} \tag{12}$$

and the exponent −d, derived from dimensionless analysis, is shown to equal 0.75. Since this exponent is fairly large, the variables μ_g, ρ_ℓ and V_m have considerable effect on the liquid-jet breakup process.

To obtain a single correlating coefficient for the three atomizing gases, values of $D_o/D_{v.5c}$ are plotted against the dimensionless groups given in Eqs. (7) and (12), as shown in Fig. 10. Thus, the three atomizing gases gave the following expression:

$$\frac{D_o}{D_{v.5c}} = 5.70\times10^{-11}\left(\mathrm{WeRe}\frac{\rho_g}{\rho_\ell}\right)^{0.44}\left(\frac{\rho_\ell V_m^3}{g\mu_g}\right)^{0.75} \tag{13}$$

In a previous study reported in Ref. 15, it was found that the effect of normalized atomizing-gas temperature T_g/T_o on $D_{v.5c}^{-1}$ could be expressed as follows:

$$\frac{D_o}{D_{v.5c}} = 9\left(\mathrm{WeRe}\frac{\rho_g}{\rho_\ell}\right)^{0.44}\left(\frac{T_g}{T_o}\right)^{1.25}$$

which shows $D_{v.5c}^{-1} \sim T_g^{1.25}$. Equation (13) indicates $D_{v.5c}^{-1} \sim (\rho_\ell V_m^3/g\mu_g)^{0.75} \sim T_g^{0.53}$, since $\mu_g \sim T_g^{0.8}$. Thus, $(\rho_\ell V_m^3/g\mu_g)^{0.75}(T_g/T_o)^{0.72} \sim T_g^{1.25}$. Since the exponents 0.75 and 0.72 are practically the same, Eq. (13) may be rewritten as follows:

$$\frac{D_o}{D_{v.5c}} = 5.7\times10^{-11}\left(\mathrm{WeRe}\frac{\rho_g}{\rho_\ell}\right)^{0.44}\left[\left(\frac{\rho_\ell V_m^3}{g\mu_g}\right)\left(\frac{T_g}{T_o}\right)\right]^{0.75} \tag{14}$$

where the correlation, 5.7×10^{-11} remains the same, since $T_o = T_g$ in the present study. Also, it was found that since $WeRe(\rho_\ell/\rho_g) = D_o^2(\rho_g V_c)^3/\mu_\ell \rho_\ell \sigma$; $D_{v.5c}^{-1}$ is proportional to $V_c^{1.33}$, $V_m^{2.25}$, $\rho_\ell^{0.31}$ and gas molecular weight raised to the -0.46 power. For the liquid properties. $D_{v.5c}^{-1}$ is proportional to $\mu_\ell^{-0.44}$, $\sigma^{-0.44}$ and $\rho_\ell^{0.31}$. The liquid-property exponents give relatively good agreement with those predicted in Ref. 13 from atomization theory for liquid-jet breakup in high-velocity gasflow.

Concluding Remarks

In working with cryogenic sprays such as LN_2, it is difficult to obtain reproducible data on dropsize measurements, unless the liquid temperature is kept well below the boiling point and the hydrodynamic pressure drop across the fuel nozzle is low enough to prevent flash boiling during the formation of a cryogenic spray. A reproducibility of dropsize data of ±5 percent was obtained by adhering to the above mentioned requirements for studying LN_2-jet breakup in sonic velocity gasflow.

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TABLE I.—ATOMIZING-GAS VELOCITY EXPONENT, n, LIQUID-JET BREAKUP IN HIGH-VELOCITY GASFLOW

Source	Exponent, $-n$
Adelberg, Theory[13]	1.33
Present study, $x = 2.2$ cm	1.33
Kim and Marshall[3]	1.14
Lorenzetto and Lefebvre[4]	1.00
Nukiyama and Tanasawa,[5] $x = 5$ to 25 cm	1.00
Weiss and Worsham[6]	1.33
Wolf and Anderson[7]	1.33

TABLE II.—EQUATIONS (1) AND (2) COEFFICIENTS AND EXPONENTS

Atomizing gas	Partially vaporized LN_2 spray,[a] experimental		Original unvaporized LN_2 spray,[b] calculated	
	k_e	n_e	k_c	n_c
Helium	1125	1.16	1911	1.33
Nitrogen	275	1.11	263	1.33
Argon	222	1.08	162	1.33

[a] $D_{v.5e}^{-1} = k_e W_g^n$.
[b] $D_{v.5c}^{-1} = k_c W_g^n$.

TABLE III.—VAPORIZATION TIME, Δt, AND REYNOLDS NUMBER FOR $D_{v.5e}^{-1}$

Atomizing gas	W_g, g/sec	$D_{v.5e}^{-1}$, cm^{-1}	$\Delta t \times 10^4$, sec	Re
Helium	1.00	1125	1.35	15.2
Nitrogen	4.54	1650	1.44	35.3
Argon	5.43	1370	1.52	31.4

TABLE IV.—ATOMIZING-GAS TRANSPORT PROPERTIES, AT $T_f = 188$ K AND $W_g = 4.54$ g/sec

Atomizing gas	$V_c \times 10^{-4}$, cm/sec	$\mu_f \times 10^4$, g/cm sec	$k_f \times 10^5$, cal/sec sq cm, °C/cm
Helium	9.10	1.98	26.3
Nitrogen	3.43	1.25	4.2
Argon	2.87	1.10	2.85

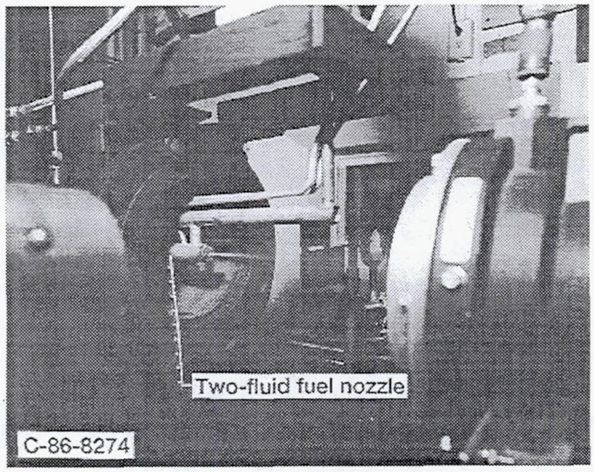

Figure 1.—Apparatus and auxiliary equipment.

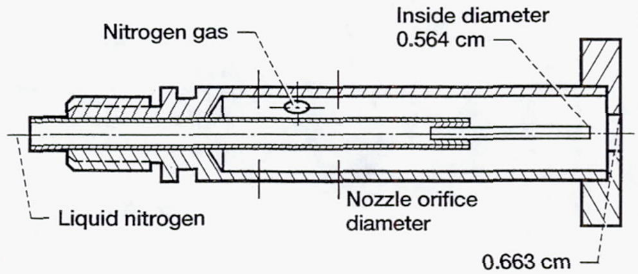

Figure 2.—Diagram of pneumatic two-fluid atomizer.

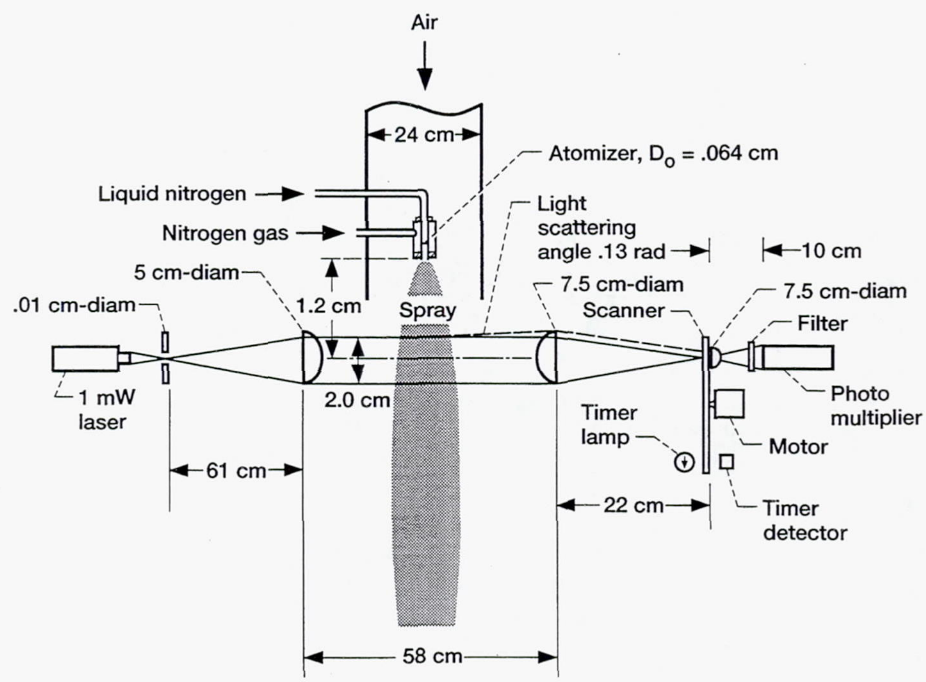

Figure 3.—Atmospheric pressure test section and optical path of scattered-light scanner.

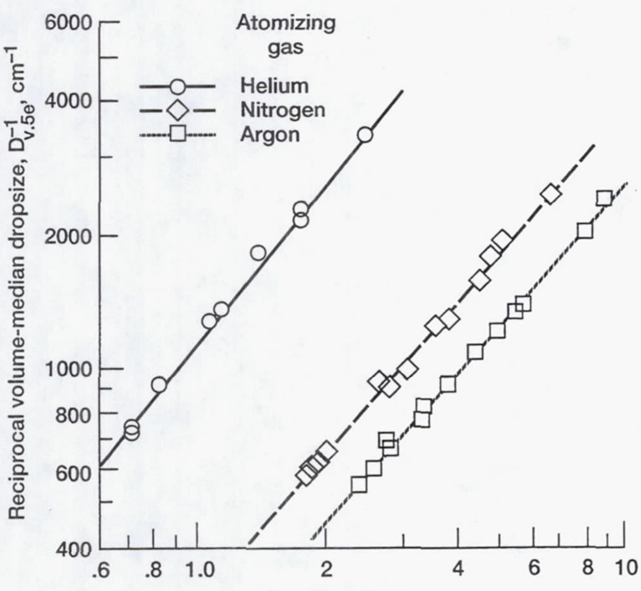

Figure 4.—Effect of atomizing-gas flowrate on experimentally determined reciprocal volume-median dropsize, $D_{v.5e}$.

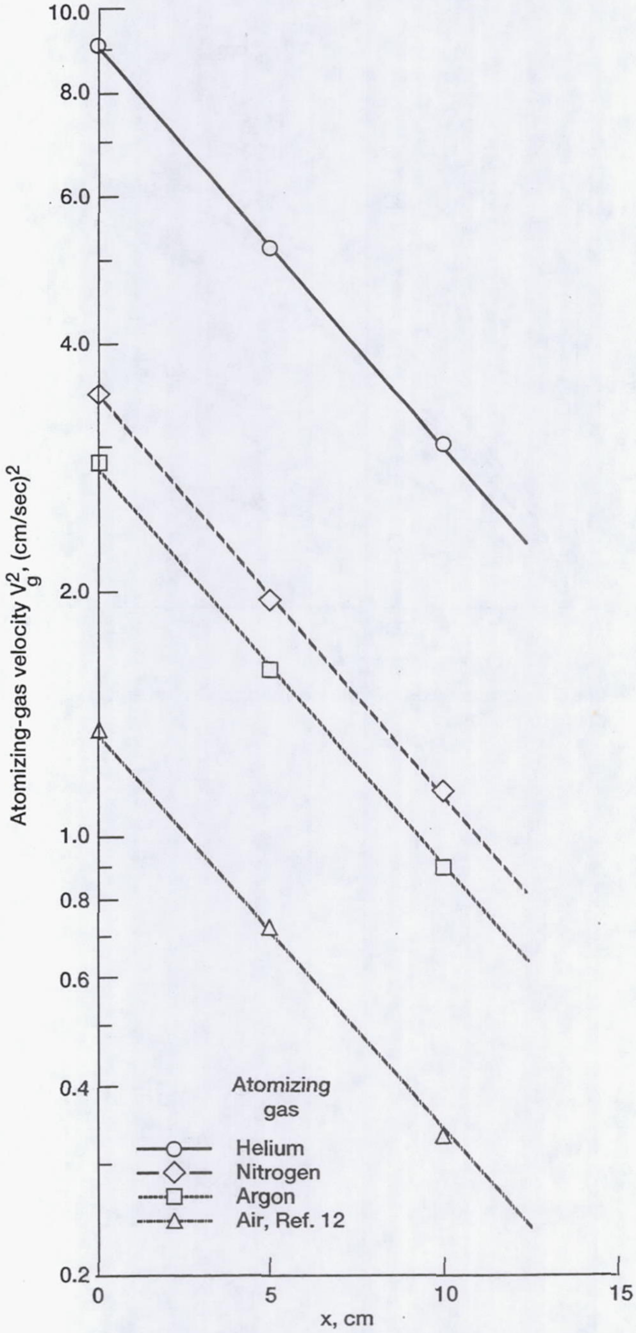

Figure 5.—Deceleration of atomizing-gases downstream of fuel-nozzle orifice. At x = 0, $V_g = V_c$.

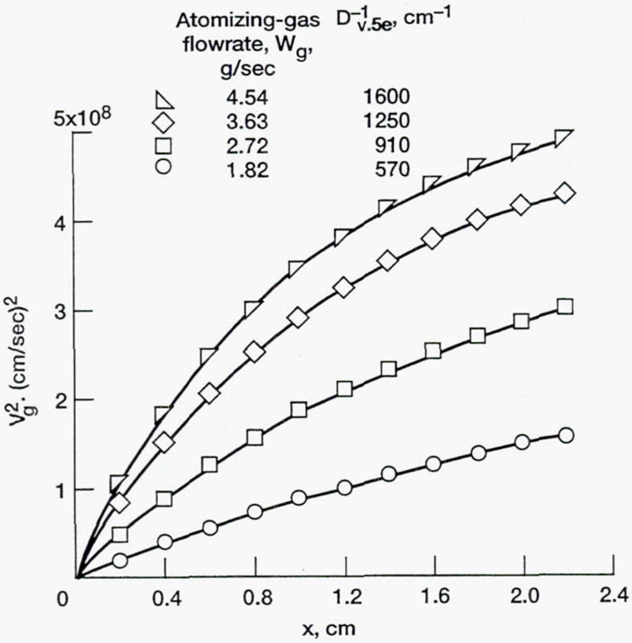

Figure 6.—Acceleration of volume-median dropsize, $D_{v.5e}$, in nitrogen gasflow.

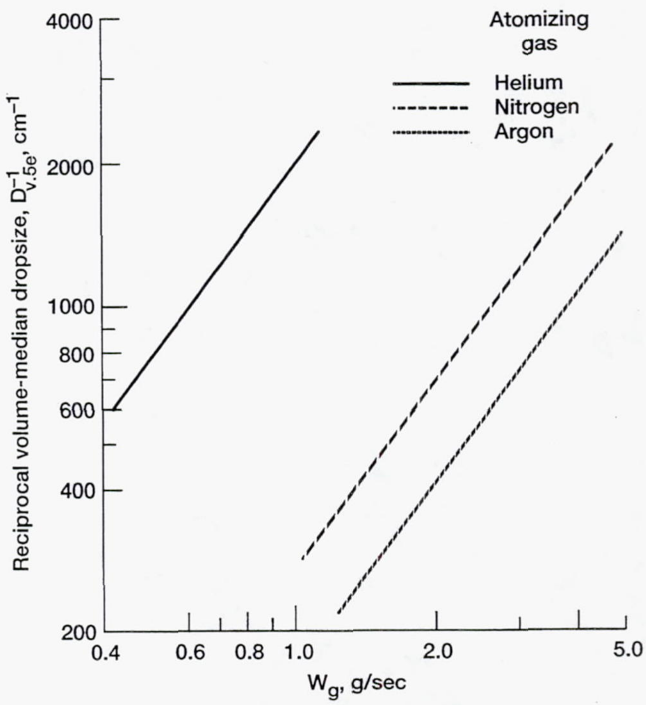

Figure 7.—Effect of W_g on initially unvaporized $D_{v.5e}$, at fuel-nozzle orifice, x = 0.

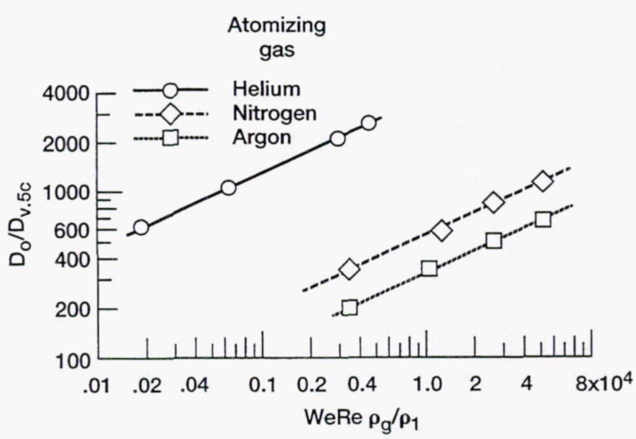

Figure 8.—Correlation of $D_o/D_{v.5c}$ with dimensionless groups.

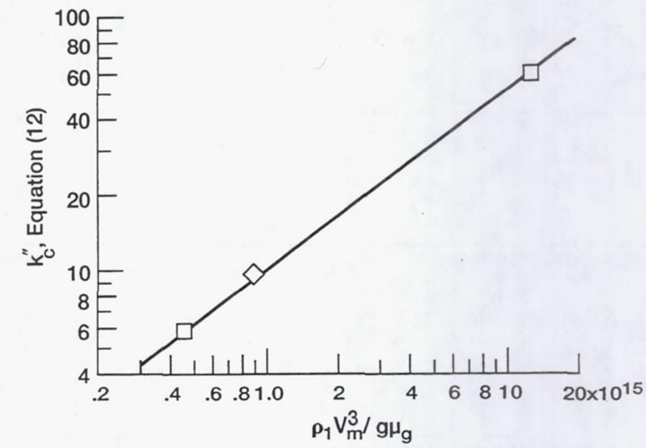

Figure 9.—Correlation of coefficient k^1 with dimensionless group, $\rho_1 V_m^3 / g\mu_g$.

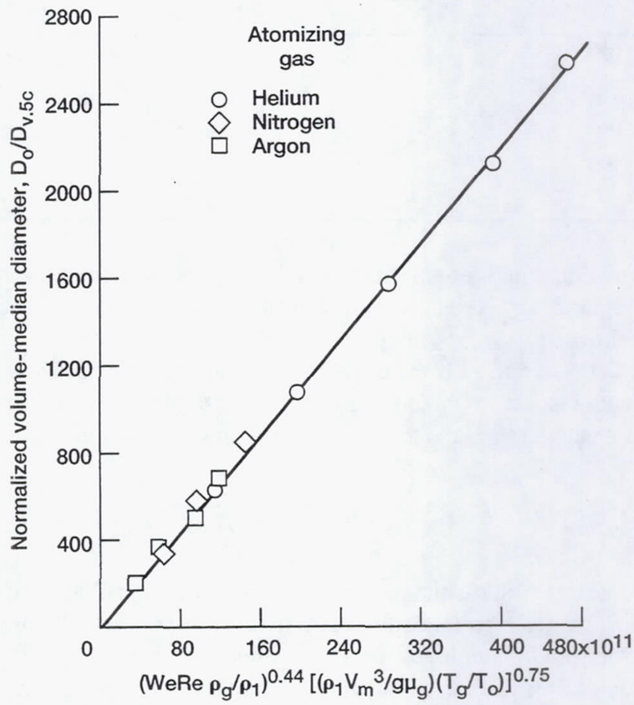

Figure 10.—Correlation of volume-median diameter, $D_{v.5c}$, with dimensionless groups.

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Robert D. Ingebo

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Lewis Research Center
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13. ABSTRACT ***(Maximum 200 words)***

Effects of gas properties on cryogenic liquid-jet atomization in high-velocity helium, nitrogen and argon gasflows were investigated. Volume median diameter, $D_{v.5e}$, data were obtained with a scattered-light scanning instrument. By calculating the change in spray dropsize, $-\Delta D_{v.5}^2$, due to droplet vaporization, it was possible to calculate $D_{v.5c}$ from the expression, $-\Delta D_{v.5}^2 = D_{v.5}^2 - D_{v.5c}^2$. $D_{v.5c}$ is the unvaporized characteristic dropsize formed at the fuel-nozzle orifice. $D_{v.5c}$ was normalized with respect to liquid-jet diameter, D_o, to give the dimensionless ratio $D_o/D_{v.5c}$. It was then correlated with several dimensionless groups to give the following expression:

$$D_o / D_{v.5c} = k_c (\mathrm{We\,Re}\ \rho_g / \rho_\ell)^{0.44} [(\rho_\ell V_m{}^3 / g\mu_g)(T_g / T_o)]^{0.75}$$

where k_c is a proportionality constant, WeRe is the product of Weber and Reynolds number, ρ_g/ρ_ℓ is the fluid density ratio, and $\rho_\ell V_m^3 / g\mu_g$ is a molecular-scale group derived in this study to correlate the original characteristic dropsize, $D_{v.5c}$, with atomizing forces produced by the three atomizing gases. This expression, for the volume median diameter of cryogenic LN_2 sprays, correlates dropsize $D_{v.5c}$ with aerodynamic and liquid-surface forces so that it can be readily determined in the design of multiphase-flow propellant injectors for rocket combustors.

14. SUBJECT TERMS
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