NASA Technical Memorandum 102432

Scattered-Light Scanner Measurements of Cryogenic Liquid-Jet Breakup

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Prepared for the
Second International Congress on Optical Particle Sizing
sponsored by Arizona State University
Tempe, Arizona, March 5–9, 1990

(NASA-TM-102432) SCATTERED-LIGHT SCANNER MEASUREMENTS OF CRYOGENIC LIQUID-JET BREAKUP (NASA) 14 p CSCL 14B

N90-22021

Unclas

G3/35 0266122

SCATTERED-LIGHT SCANNER MEASUREMENTS OF CRYOGENIC LIQUID-JET BREAKUP

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ABSTRACT

The effect of highly turbulent Mach 1 gasflow and high thermal-gradients on drop size measurements was investigated with a scattered-light scanner. The instrument, developed at NASA Lewis Research Center, was used to measure characteristic drop diameters of cryogenic-liquid sprays. By correcting for gas-turbulence and thermal-gradient affects, it was possible to obtain good reproducible data with the scattered-light scanner. Tests were conducted primarily in the aerodynamic-stripping regime of liquid-jet atomization and it was found that the loss of small droplets due to vaporization and dispersion had a marked effect on dropsize measurements. The Sauter mean, D_{32}, and volume median, $D_{v.5}$, drop diameters were measured and correlated with nitrogen gas flow rate, W_n, to give the following general expression; $D_c^{-1} = C\,W_n^{1.33}$ where the reciprocal characteristic diameter and gas flow rate are in cm^{-1} and g/sec, respectively. The correlating coefficient, C, was evaluated and gave the following expressions: $D_{32}^{-1} = 210\,W_n^{1.33}$ and $D_{v.5}^{1.33}$, at a downstream distance of $\bar{x} = 1.3$ cm.

The nitrogen-gas flow rate exponent of 1.33 is the same as that predicted by atomization theory for liquid-jet breakup in high velocity gasflow. However, when the sprays were sampled farther downstream of the atomizer, at distances of $\bar{x} = 2.5$ and 4.5 cm, the exponent for W_n decreased to 1.2 and 0.9, respectively. This was attributed to the loss of small droplets due to vaporization when values of $\bar{x}$ exceeded 1.3 cm.

NOMENCLATURE

b	dropsize parameter in Nukiyama-Tanasawa expression, cm
c	drop size parameter in Rosin-Rammler expression, cm
D_c	characteristic drop diameter measured for entire spray, cm
D'_c	characteristic drop diameter for line-of-sight measurements, cm
D_i	diameter of i^{th} drop, cm
$D_{v.5}$	volume median drop diameter, cm
D_{32}	Sauter mean drop diameter, $\sum_i nD_i^3/\sum_i nD_i^2$, cm
D_{31}	volume-linear mean drop diameter, $\left[\sum_i nD_i^3/\sum_i nD_i\right]^{0.5}$, cm
k	correlation coefficient, sec/g-cm
N_n	exponent for Nukiyama-Tanasawa drop size distribution expression
N_r	exponent for Rosin-Rammler drop size distribution expression
n	number of droplets
v	volume fraction of droplets having diameter x

W weight flow of fluid, lb/sec or g/sec

x droplet diameter in drop size distribution expressions, cm

$\bar{x}$ axial downstream spray sampling distance, cm

Subscripts

n nitrogen gas

w water

INTRODUCTION

New drop size measurement techniques are needed to overcome the many difficulties encountered in studies of fuel spray combustion in rocket and gas-turbine combustors and icing cloud formation in wind tunnels. In the task of characterizing liquid sprays, one of the major difficulties encountered with optical instruments is the occurrence of high droplet vaporization rates. Detailed knowledge of fuel spray characteristics is especially needed at the point of initial spray formation close to the atomizer orifice and the effect of vaporization on the spray must be known. From this information, accurate initial conditions can be established for modelling the fuel spray combustion process or the formation of ice on airfoils.

The presence of high velocity and high thermal gradients also contribute to the difficulty of obtaining accurate measurements of characteristic drop diameters, i.e., Sauter mean diameter, D_{32}. For example, a drop size measuring technique using forward light-scattering, i.e., a Malvern instrument, was modified by Dodge and Cerwin,[1] to study evaporating fuel sprays in air at temperatures as high as 700 K. With no spray present, the instrument picked up background noise due to thermally induced density gradients in the gas phase. To correct for this, the distribution of light was obtained by using only the outer 24 channels of a 30 channel detector to measure light scattered mainly from the smaller particles. As a result, it was stated that the light distribution "follows the shape expected for the scattering from a spray" and the usefulness of the instrument was extended to include drop size measurements of evaporating sprays at distances relatively close to the atomizer.

Numerous investigators have obtained experimental drop size data and correlated it with relative velocity, i.e., gas velocity relative to liquid velocity and also with liquid properties, as given in Refs. 2 to 8. Some of the correlations do not agree very well with atomization theory which is generally attributed to the fact that measurement techniques and drop sizing instruments have yet to be developed and standardized to the extent that good agreement might be expected. In the present study, the entire spray cross section was sampled with a 4.4 by 1.9 cm rectangular laser beam at three axial locations downstream of the atomizer. Also, a 0.30 by 1.9 cm narrow laser beam was used to scan across the spray cross section and the characteristic drop size D_{32} was determined at three different atomizing-gas flow rates. Drop size distribution exponents for the Rosin-Rammler and Nukiyama-Tanasawa drop size distribution expressions were also determined with the scattered light scanner.

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APPARATUS AND PROCEDURE

A pneumatic two-fluid atomizer was mounted in the test section as shown in Figs. 1 and 2. The optical path of the scattered-light scanner and a detailed diagram of the atomizer are shown in Figs. 2 and 3, respectively.

FIGURE 1. - APPARATUS AND AUXILLIARY EQUIPMENT.

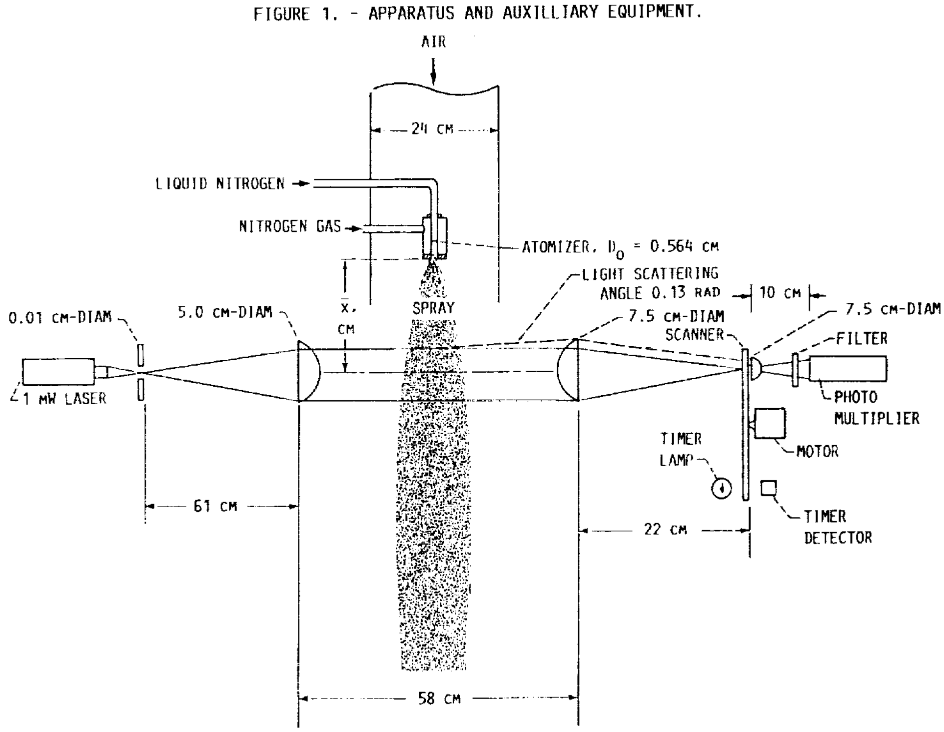


FIGURE 2. - ATMOSPHERIC PRESSURE TEST SECTION AND OPTICAL PATH OF SCATTERED-LIGHT SCANNER.

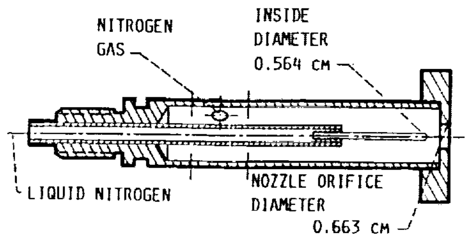


FIGURE 3. - DIAGRAM OF PNEUMATIC TWO-FLUID ATOMIZER.

The Scattered-Light Scanner

The optical system of the scattered-light scanner is shown in Fig. 2. 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 and it is described in detail in Ref. 10.

Data processing consists, as shown in Fig. 4, of locating four points on a plot of scattered-light energy which is normalized to the maximum energy and plotted against scattering angle. The points are used to evaluate Sauter mean, volume median, volume linear and 75-percent volume drop diameters. In Ref. 10, it is demonstarated that the four characteristic drop diameters and the dispersion of drop sizes are substantially independent of particle size distribution function. For a typical measurement, the scan is repeated 60 times per second to average out any temporal variations in the energy curve.

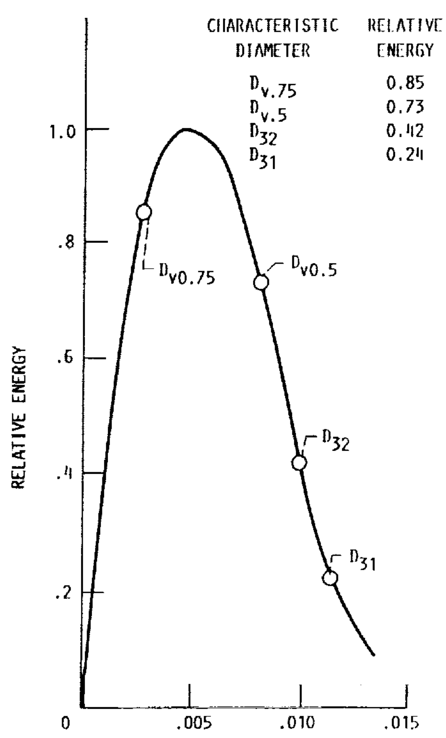
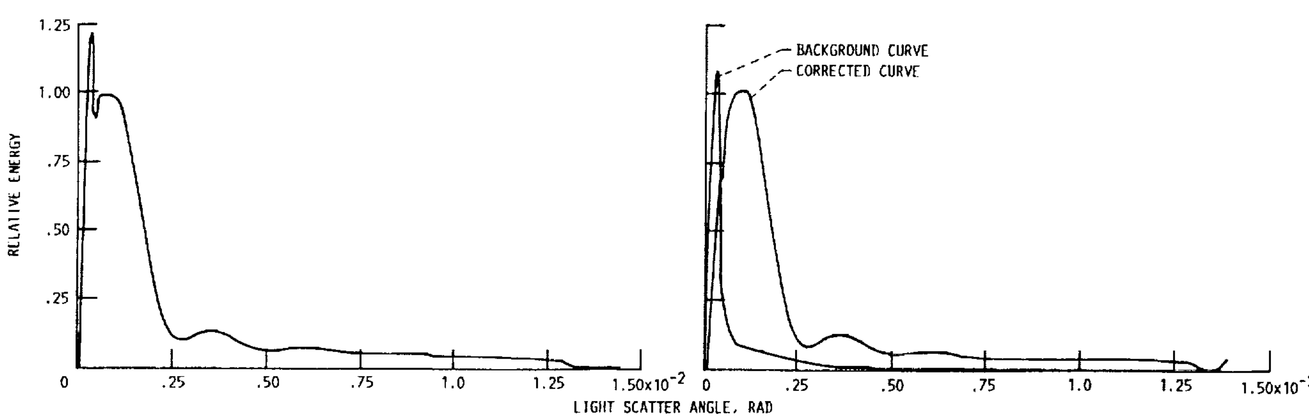


FIGURE 4. - TYPICAL SCATTERED-LIGHT ENERGY CURVE WITH FOUR CHARACTERISTIC DIAMETERS.

Spray pattern affects were minimized by measuring characteristic drop diameters for the entire spray cross section. Reproducibility of characteristic drop size measurements was shown in Ref. 8 to be within ±5 percent. Calibration was accomplished with five sets of nonosized 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 drops. As a result, the light-scattering measurements required correction for multiple scattering as described in Refs. 10 and 11 for the case of high number-density sprays. Drop size measurements were also corrected as described in Ref. 10 to include Mie scattering theory when very small characteristic droplet diameters, i.e., <10 μm, were measured.

In the first part of the present study, the entire spray cross section was sampled with a 4.4 by 1.9-cm rectangular laser beam, Later, the long dimension of the laser beam was reduced from 4.4 to 0.64 cm and the smaller laser beam was used to sample the spray at various traverse positions and at three different atomizing-gas flow rates. When measurements of the characteristic drop size of cryogenic liquid nitrogen sprays were first attempted, it was found that good reproduicible measurements were much more difficult to obtain with cryogenic sprays than with water sprays. This was attributed to excessively high temperature gradients in the gas-film surrounding the droplets caused by a temperature difference of 216 K, i.e., $T_g - T_l = 293 - 77\ K = 216\ K$. Density variations caused by high temperature gradients deflected the laser beam and caused a spike to appear on the light energy curve as shown in Fig. 5(a). To reduce the amplitude of the large spike, the laser beam was moved 0.6 mm from the path of the rotating variable-length slit shown in Fig. 2. This adjustment, described in detail in Ref. 12, causes a distortion of the true scattered light wave shape at a small scatter angle, which is corrected by instrument calibration. The spike was reduced as shown in Fig. 5(b) by computations employing the equations given in Ref. 10. As a result, it was possible to obtain good reproducible drop size data for cryogenic sprays with the scattered-light scanning instrument.



(a) UNCORRECTED CURVE.

(b) BACKGROUND CURVE AND CORRECTED DRIVE.

FIGURE 5. - ENERGY CURVES UNCORRECTED AND CORRECTED FOR BACKGROUND LIGHT-SCATTERING DUE TO HIGH GAS-PHASE TEMPERATURE-GRADIENTS.

Experimental Procedure

The test section, scattered-light scanner and auxiliary equipment are shown in Fig. 1. Air supplied at ambient temperature, 293 K, passed through the 15.24 cm inside diameter test section which exhausted to the atmosphere. The test section was 1 m in length and a 5.08 cm diameter orifice was used to measure airflow rate in the test section. A flow of dry air at a velocity of 5 m/sec was maintained in the test section to aid in transporting small droplets through the laser beam. This prevented ambient humid air from contacting the spray and thereby avoided the formation of ice particles in the laser beam.

The atomizer shown in Fig. 2 was mounted at the center line of the test duct and operated over pressure ranges of 0.2 to 1.0 MPa for both liquid nitrogen and the atomizing nitrogen gas. Liquid nitrogen sprays were injected downstream into the airflow just upstream of the duct exit. The sprays were sampled at distances of 1.3, 2.5 and 4.5 cm downstream of the atomizer orifice with a 4.4 by 1.9 cm rectangular laser beam produced by the aperture shown in Fig. 2. A diagram of the pneumatic two-fluid nozzle used in this study is shown in Fig. 3.

Liquid nitrogen, LN_2, at a temperature of 77 K measured with an I.C. thermocouple, was axially injected into the airstream at a flow of 76.5 g/sec, as indicated by a turbine flow meter. Nitrogen gas was then turned on to atomize the LN_2 jet and weight flow rate was measured with a 0.51 cm diameter sharp-edge orifice. After the air, nitrogen gas and LN_2 flow rates were set, characteristic drop diameters and exponents for drop size distribution expressions were determined from measurements made with the scattered-light scanner.

EXPERIMENTAL RESULTS

A two-fluid atomizer using liquid and gaseious nitrogen was tested to determine the effect of axial sampling distance on characteristic dropsize. Also, exponents for Rosin-Rammler and Nukiyama-Tanasawa dropsize distribution expressions were determined.

Effect of Sampling Distance on Dropsize Measurement

The entire spray cross section was sampled at axial distances of 1.3, 2.5 and 4.5 cm downstream of the atomizer orifice, i.e., $\bar{x}$ = 1.3, 4.5 and 4.5 cm where $\bar{x}$ is the distance from the atomizer orifice to the center line of the laser beam. Liquid nitrogen flow rate was held approximately constant at 76.5 g/sec. Characteristic drop diameters D_{32} and $D_{v.5}$ were measured and plotted against nitrogen gas flow rate, W_n, as shown in Figs. 6(a) and (b). This plot shows the following relationships for the Sauter mean, D_{32} and volume median, $D_{v.5}$, drop diameters:

$$D_{32}^{-1} \text{ and } D_{v.5}^{-1} \sim W_n^{1.33}$$

$$D_{32}^{-1} \text{ and } D_{v.5}^{-1} \sim W_n^{1.2}$$

$$D_{32}^{-1} \text{ and } D_{v.5}^{-1} \sim W_n^{0.9}$$

at downstream distances of $\bar{x}$ = 1.3, 2.5 and 4.5 cm, respectively. The preceding expression, D_{32}^{-1} and $D_{v.5}^{-1} \sim W_n^{1.33}$ as obtained at $\bar{x}$ = 1.3 cm, agrees very well with that given by atomization theory for liquid-jet breakup in the regime of aerodynamic-stripping.[13]

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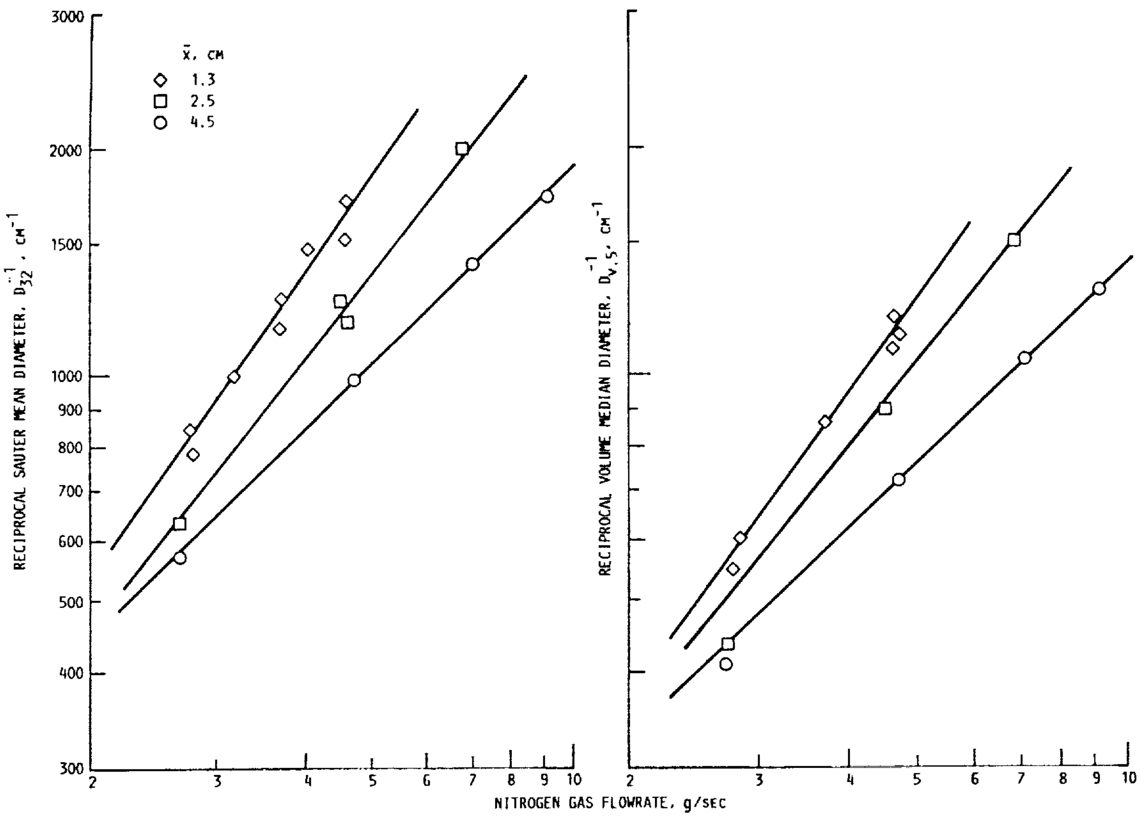


(a) SAUTER MEAN DIAMETER, D_{32}. (b) VOLUME MEDIAN DIAMETER, $D_{v.5}$.

FIGURE 6. - CORRELATION OF CHARACTERISTIC DROP DIAMETERS WITH GAS FLOWRATE, LIQUID NITROGEN FLOWRATE OF 76.5 g/SEC.

Also, it was concluded from these results that measurements obtained at $\bar{x}$ = 1.3 cm, were not appreciably affected by vaporization and dispersion of the very small droplets as compared with measurements made farther downstream from the atomizer orifice. Values of the exponent, n, obtained in other experimental studies are also shown in Table 1 for comparison with atomization theory.[13]

Comparison of Characteristic Dropsize Expressions

Characteristic drop diameters, D_{32} and $D_{v.5}$ were determined for liquid-nitrogen sprays sampled at downstream distances of 1.3, 2.5 and 4.5 cm. In Figs. 7(a), (b) and (c), the reciprocals of the characteristic drop diameters, with units of cm^{-1}, are plotted against nitrogen-gas flow rate raised to the exponent a, which was determined from Fig. 6 as a function of the spray sampling distance $\bar{x}$. From the plots shown in Fig. 7, the values of the correlation coefficient k were determined and the following general expression was derived:

$$D_c^{-1} = k\ W_n^a$$

where D_c is the characteristic drop diameter of a liquid-nitrogen spray. At a sampling distance of 1.3 cm, the following dropsize expressions were obtained:

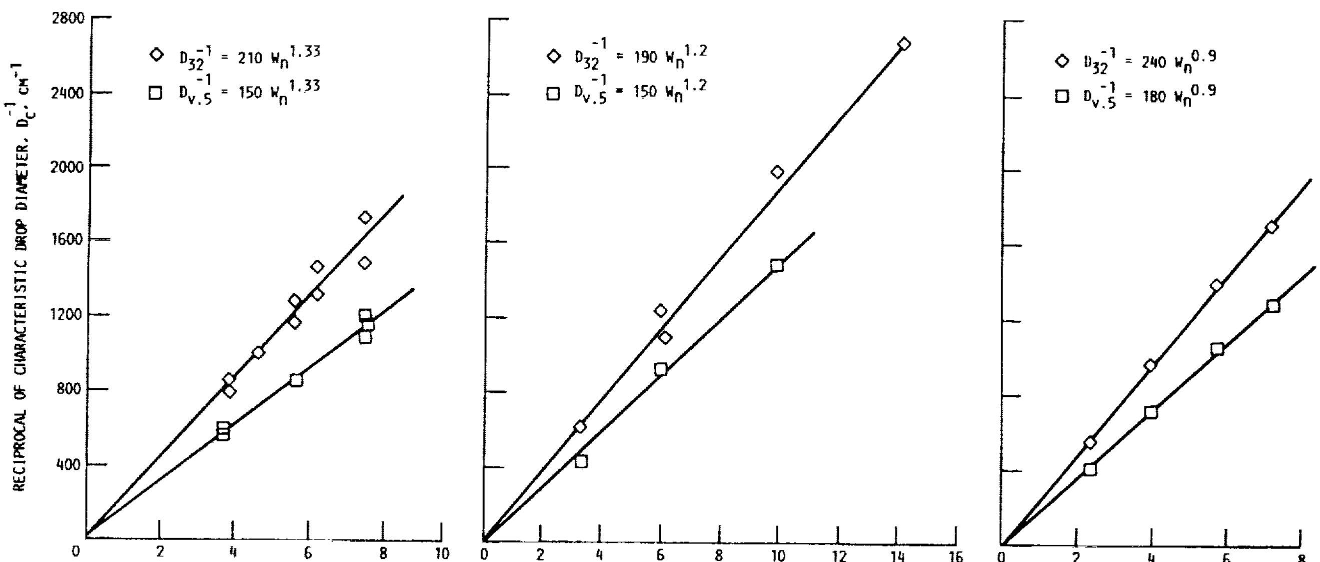
$$D_{32}^{-1} = 210\ W_n^{1.33}$$

$$D_{v.5}^{-1} = 150\ W_n^{1.33}$$

TABLE 1. - VELOCITY EXPONENT, N, FOR LIQUID-NITROGEN JET BREAKUP IN MACH 1 GASFLOW, $D_c \sim V_g^{-n}$.

Source	Exponent
Theory[13]	1.33
Present study, $\bar{x}$ = 1.3 cm	1.33
Weiss and Worsham[3]	[a]1.33
Wolfe and Anderson[4]	1.33
Kim and Marshall[5]	[a]1.14
Nukiyama and Tanasawa[6] $\bar{x}$ = 5 to 25 cm	1.0
Lorenzetto and Lefebvre[7]	1.0

[a]Wax sphere dropsize data.



(a) AT SAMPLING DISTANCE, $\bar{x}$, OF 1.3 CM. (b) AT SAMPLING DISTANCE, $\bar{x}$, OF 2.5 CM. (c) AT SAMPLING DISTANCE, $\bar{x}$, OF 4.5 CM.

FIGURE 7. - COMPARISON OF CHARACTERISTIC DROP DIAMETERS AT LIQUID NITROGEN FLOWRATE OF 76.5 g/SEC.

The correlation coefficient, k, nitrogen gasflow rate exponent, a, are given in Table 2 for comparison. It is interesting to note that at any of the two sampling distances, the value of k varied by only ±10 percent whereas the exponent a changed from 1.33 to 0.9 when $\bar{x}$ was increased from 1.3 to 4.5 cm. This indicated that vaporization of the small droplets had only a minor effect on the correlation coefficient k but a major effect on the exponent a.

Measurement of Characteristic Drop Diameter, D'_{32}

The laser beam height of the scattered-light scanner was reduced from 1.9 to 0.32 cm and line-of-sight measurements of characteristic drop diameter D'_{32} were obtained at several vertical locations in each liquid-nitrogen spray. Values of D'_{32} are plotted against vertical location as shown in Fig. 8. This type of measurement was obtained for the two-fluid atomizer at constant liquid nitrogen flow rate, and for three different atomizing gas flow rates, at an axial downstream sampling distance of $\bar{x}$ = 1.3 cm.

TABLE 2. - COEFFICIENT, k AND EXPONENT, a, FOR CHARACTERISTIC DROP DIAMETER EXPRESSION,

$D_c^{-1} = kW_n^a.$*

Sampling location, $\bar{x}$, cm	1.3	2.5	4.5
Exponent, a	1.33	1.20	.90
Coefficient, k, for characteristic diameter			
D_{32}	210	190	240
$D_{v.5}$	150	150	180

*W_{LN2} = 76.5 g/cm.

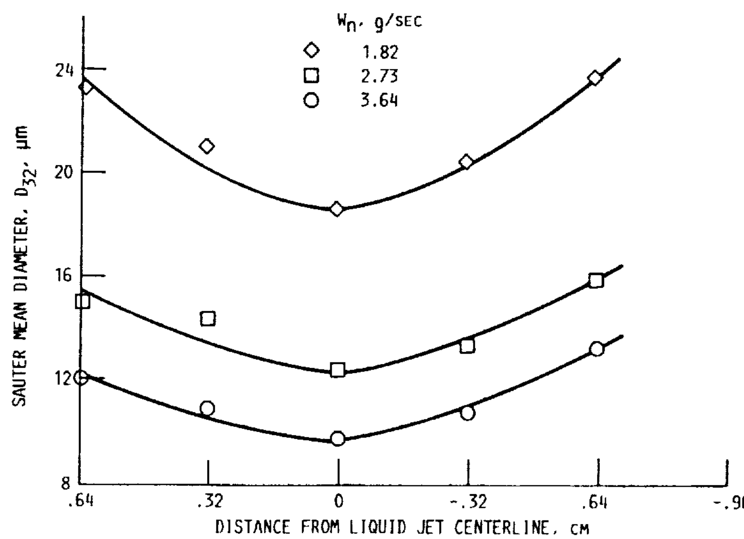


FIGURE 8. - SPRAY PROFILE FOR TWO-FLUID ATOMIZER AT $\bar{x}$ = 1.3 CM.

Minimum values of D_{32}' at the liquid-jet center line were reduced nearly one-third i.e., from approximately 18.5 to 12.3 μm, when nitrogen gas flow rate was increased from 1.82 to 2.72 g/sec. A similar reduction in D_{32}' occurred in the upper and lower fringes of the sprays. The asymetry of the spray shape was attributed to the effect of gravity on the drops and also a possible slight misalignment of the center tube of the atomizer.

Characteristic Exponents for Dropsize Distribution Expressions

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

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

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

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

From a plot of the data obtained with the two-fluid atomizer, as shown in Fig. 9, the following relation was determined:

$$N_r = 2.83 \, N_n^{0.5}$$

which is similar to the expression derived in Ref. 1 for water sprays. Thus, it was found that although the downstream distance, $\bar{x}$, was varied from 1.3 to 4.5 cm, the relation between the exponents was not appreciably affected by vaporization and dispersion of the small droplets.

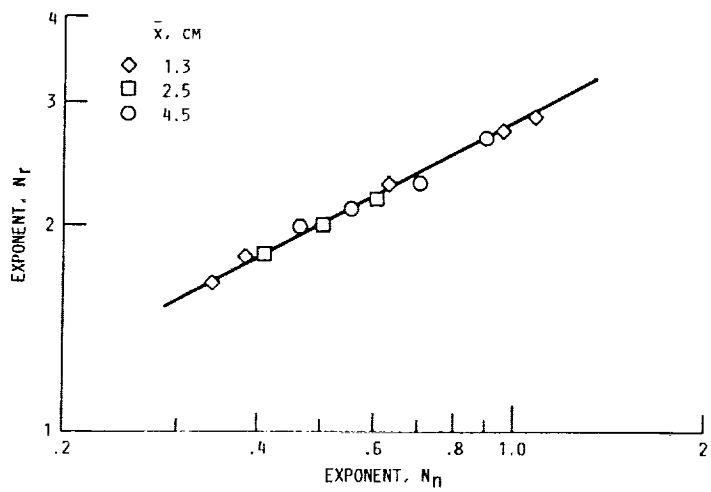


FIGURE 9. - CORRELATION OF EXPONENTS FOR ROSIN-RAMMLER AND NUKIYAMA-TANASAWA EXPRESSIONS.

CONCLUDING REMARKS

Investigating the fluid mechanics of liquid-nitrogen jet breakup in highvelocity gasflow is considerably more difficult than studying the formation of water sprays. This is primarily due to the fact that the surface temperature of liquid-nitrogen jets used in the present study was always near its boiling point which is approximately 77 K. Since the atomizing gas used in this study was at room temperature, approximately 293 K, this created large temperature gradients that deflected the laser beam, i.e., caused beam steering to occur, when characteristic drop diameters were measured with the scattered-light scanner. This problem was minimized in the present investigation by moving the laser beam away from the slit in the scattered-light scanner optical system.

Characteristic drop diameters of cryogenic liquid-nitrogen sprays were measured with a scattered-light scanning instrument at a distance of 1.3 cm downstream of the orifice of a pneumatic two-fluid atomizer. Values of D_{32}^{-1} and $D_{v.5}^{-1}$ were obtained and correlated with nitrogen gas flow rate raised to the 1.33 power. This exponent of 1.33 is the same as that derived theoretically in Ref. 12 for liquid-jet atomization in the aerodynamic-stripping regime of breakup. The fact that experimental results agreed well with atomization theory was attributed to a negligible loss of small droplets due to vaporization and dispersion affects. These affects were not negligible at a distance of 4.5 cm downstream of the atomizer orifice, where the exponent decreased to a value of 0.9. When the laser beam was positioned at a distance of less than 1.3 cm from the atomizer, characteristic dropsize increased very markedly due to incomplete breakup of the liquid jet. With the two-fluid atomizer, at a liquid-nitrogen flowrate of 76.5 g/sec and at a sampling distance of 1.3 cm, the following expressions for characteristic drop diameter of the initial liquid-nitrogen spray were obtained;

$$D_{32}^{-1} = 210\ W_n^{1.33} \text{ and } D_{v.5}^{-1} = 150\ W_n^{1.33}$$

which agree well with atomization theory for liquid-jet breakup in high-velocity gasflow.

Line-of-sight through the sprays were also made with the scattered-light scanner. Such data are useful in comparing the performance of similar atomizers by providing information concerning the spatial pattern of dropsize characteristics within the spray cross-section. Reproducibility of the spray data was within ±5 percent. Also, it was found that experimental values of the exponents N_n and N_r, for the dropsize distribution expressions, were not appreciably affected when the sampling distance, $\bar{x}$, was varied from 1.3 to 4.5 cm downstream of the atomizer orifice.

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National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102432		

4. Title and Subtitle

Scattered-Light Scanner Measurements of Cryogenic Liquid-Jet Breakup

5. Report Date

6. Performing Organization Code

7. Author(s)

Robert D. Ingebo and Donald R. Buchele

8. Performing Organization Report No.

E-5200

10. Work Unit No.

505-62-21

9. Performing Organization Name and Address

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

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

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

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Second International Congress Optical Particle Sizing sponsored by Arizona State University, Tempe, Arizona, March 5-9, 1990.

16. Abstract

The effect of highly turbulent Mach 1 gasflow and high thermal-gradients on drop size measurements was investigated with a scattered-light scanner. The instrument, developed at NASA Lewis Research Center, was used to measure characteristic drop diameters or cryogenic-liquid sprays. By correcting for gas-turbulence and thermal-gradient affects, it was possible to obtain good reproducible data with the scattered-light scanner. Tests were conducted primarily in the aerodynamic-stripping regime of liquid-jet atomization and it was found that the loss of small droplets due to vaporization and dispersion had a marked effect on drop size measurements. The Sauter mean, D_{32}, and volume median, $D_{v.5}$, drop diameters were measured and correlated with nitrogen gas flow rate, W_n, to give the following general expression; $D_c^{-1} = C\ W_n^{1.33}$ where the reciprocal characteristic diameter and gas flowrate are in cm^{-1} and g/sec, respectively. The correlating coefficient, C, was evaluated and gave the following expressions: $D_{32}^{-1} = 210\ W_n^{1.33}$ and $D_{v.5}^{-1} = 150\ W_n^{1.33}$, at a downstream distance of $\bar{x} = 1.3$ cm. The nitrogen-gas flowrate exponent of 1.33 is the same as that predicted by atomization theory for liquid-jet breakup in high velocity gasflow. However, when the sprays were sampled farther downstream of the atomizer, at distances of $\bar{x} = 2.5$ and 4.5 cm, the exponent for W_n decreased 1.2 and 0.9, respectively. This was attributed to the loss of small droplets due to vaporization when values of x exceeded 1.3 cm.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Light scattering; Particle sizing; Liquid-jet breakup; Cryogenic liquids; Multiphase flow; Sprays	Unclassified – Unlimited Subject Category 35

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