Gas-Phase Flowrate Effect on Disintegrating Cryogenic Liquid-Jets

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Abstract

Two-phase liquid and gaseous nitrogen flow in a pneumatic two-fluid atomizer was investigated. Characteristic dropsizes for cryogenic sprays were measured with a scattered-light scanning instrument developed at NASA Lewis Research Center. Tests were conducted primarily in the aerodynamic-stripping regime of liquid-jet atomization. At a sampling distance of $\bar{x} = 1.3$ cm, the Sauter mean, D_{32}, and volume median, $D_{v.5}$, drop diameters were measured and correlated with nitrogen gas flowrate, W_n, to give the following expressions: $D_{32}^{-1} = 210 \, W_n^{1.33}$ and $D_{v.5}^{-1} = 150 \, W_n^{1.33}$, where reciprocal diameters and gas flowrate are in cm^{-1} and g/sec, respectively.

The exponent 1.33 for nitrogen gas flowrate, W_n, is the same as that predicted by atomization theory for liquid-jet breakup in high velocity gasflow. When the spray was sampled at axial distances of $\bar{x} = 2.5$ and 4.5 cm downstream of the atomizer, the exponent decreased to 1.2 and 0.9, respectively. This was attributed to the loss of small droplets due to their rapid vaporization.

1-INTRODUCTION

When cryogenic liquid propellants are injected into rocket combustors, they are rapidly atomized into clouds of vaporizing droplets that quickly ignite and burn. To accurately describe this fuel-spray combustion process in a rocket or gas turbine combustor, detailed knowledge of fuel spray formation is required and characteristic dropsize measurements are needed at the point of initial spray formation near the atomizer orifice. Also, to better understand how liquid propellants and fuels are atomized, mathematical expressions are needed that accurately describe processes such as two-fluid atomization in which various cryogenic liquid and atomizing gas combinations may be used to produce cryogenic liquid sprays. To do this, the effects of liquid and gas properties on spray dropsize must be determined. The investigators listed in references [1] to [6] have correlated experimental dropsize data with relative velocity, i.e., gas velocity relative to liquid-surface velocity and various gas and liquid properties. Some of their correlations agree whereas others differ considerably from atomization theory. This could be attributed to the fact that measurement techniques and instrumentation have not yet been sufficiently developed or standardized to the extent that good agreement might be expected.

Prior to this study, an investigation of water sprays was made with two-fluid atomizers and good agreement of experimental results with atomization

theory was obtained as discussed in Ingebo [1]. It was found that the Sauter mean drop diameter, D_{32}, could be correlated with nitrogen gas flowrate, W_n, raised to the -1.33 power, which agrees very well with atomization theory for liquid-jet breakup in high-velocity gasflow. As a continuation of that study, the present investigation was initiated to extend experimental conditions to include the breakup of cryogenic liquid-jets in high-velocity gasflow. The flowrate of liquid nitrogen was 76.5 g/sec and the atomizing nitrogen-gas flow rate was varied from 2 to 9 g/sec.

2-APPARATUS AND PROCEDURE

The test section and scattered-light scanner are shown in Figure 1. Air was supplied at ambient temperature, 293 K. It passed through the 24 cm inside diameter test section and then exhausted to the atmosphere. An airstream velocity of 5 m/sec was maintained in the test section to aid in transporting small droplets through the laser beam. To study disintegrating liquid-nitrogen jets, the two-fluid atomizer shown in Figure 1 was mounted at the center line of 24 cm diameter duct. Pressure ranges of 0.2 to 1.0 MPa were used 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. A sufficient volume of each spray was sampled to minimize spray pattern effects when measuring characteristic drop diameters for the entire spray cross section. Reproducibility tests gave experimental measurements of dropsize that agreed within ±5 percent. Five sets of
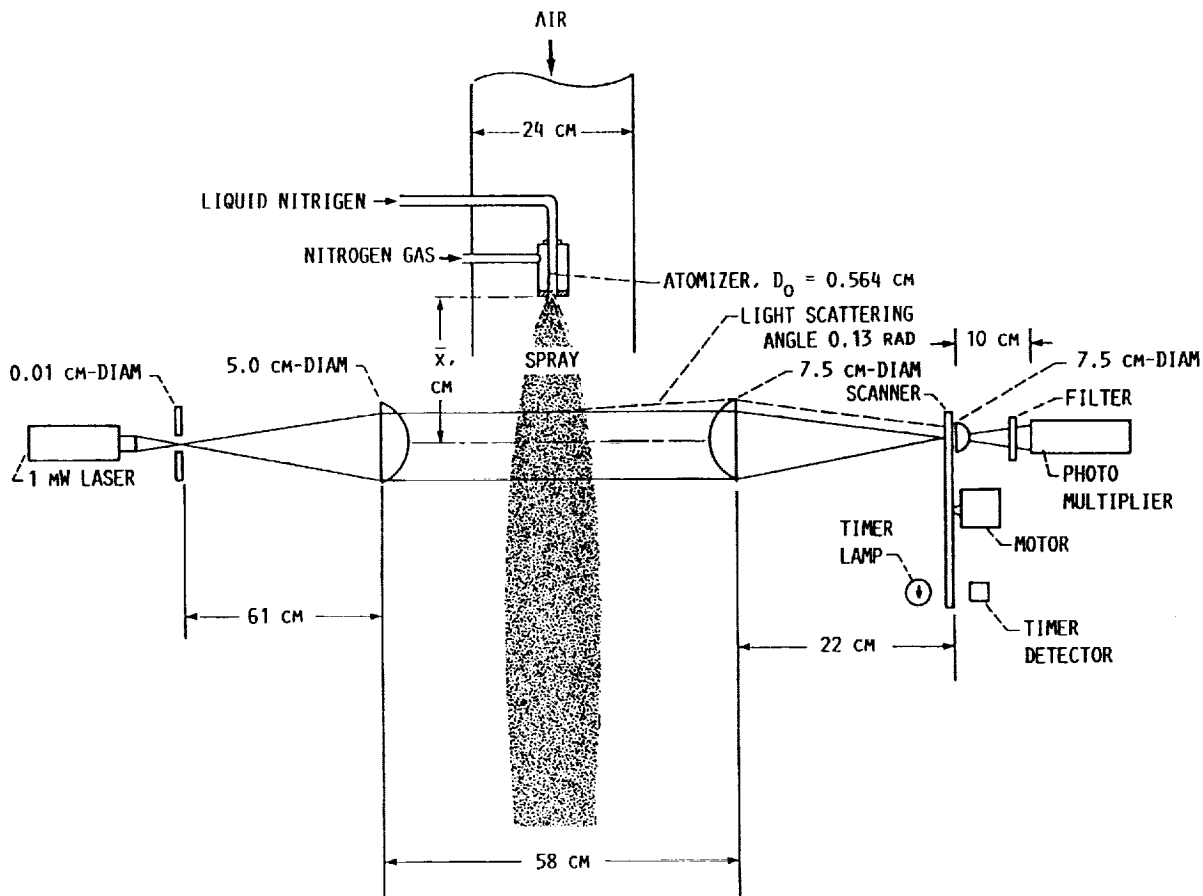

FIGURE 1. - ATMOSPHERIC PRESSURE TEST SECTION AND OPTICAL PATH OF SCATTERED-LIGHT SCANNER.

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monosized polystyrene spheres having diameters of 8, 12, 25, 50 and 100 μm were used to calibrate the scattered-light scanner. A more complete description of the instrument and methods of determining mean or median particle diameter can be found in Buchele [7] and Ingebo & Buchele [8].

3-EXPERIMENTAL RESULTS

A two-fluid atomizer was initially tested to determine the effect of axial sampling distance on characteristic dropsize expressions. 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, 2.5 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 nearly constant at 76.5 g/sec. Characteristic drop diameters D_{32} and $D_{v.5}$ were measured and related to nitrogen gas flowrate, W_n, as follows:

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

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

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

at downstream distances of $\bar{x}$ = 1.3, 2.5 and 4.5 cm, respectively. In the preceeding expression, D_{32}^{-1} and $D_{v.5}^{-1} \sim W_n^{1.33}$, obtained at $\bar{x}$ 1.3 cm, the exponent 1.33 agrees very well with that given by atomization theory for liquid-jet breakup in the regime of aerodynamic-stripping, i.e., high velocity airflow. Also, it was concluded from these results that measurements obtained at $\bar{x}$ = 1.3 cm, were not appreciably affected by vaporization of the very small drops 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 I for comparison with atomization theory given in Adelberg [9].

TABLE I. - VELOCITY EXPONENT, n, FOR

LIQUID-NITROGEN JET BREAKUP

IN MACH 1 GASFLOW,

$$D_c \sim V_g^{-n}$$

Source	Exponent
Theory (Adelberg [9])	
Present study, $\bar{x}$ = 1.3 cm	1.33
Weiss and Worsham [2]	1.33
Wolfe and Anderson [3]	[a]1.33
Kim and Marshall [4]	1.33
Nukiyama and Tanasawa [5]	1.14
$\bar{x}$ = 5 to 25 cm	1.0
Lorenzetto and Lefebvre [6]	1.0

[a]Wax sphere dropsize data.

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In Figure 2, the reciprocals of the characteristic drop diameters, with units of cm^{-1}, are plotted against nitrogen-gas flowrate raised to the appropriate exponent a. From the plots shown in Figure 2, 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:

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

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

The correlation coefficient, k, and nitrogen gas flowrate exponent, a, are given in Table II 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.
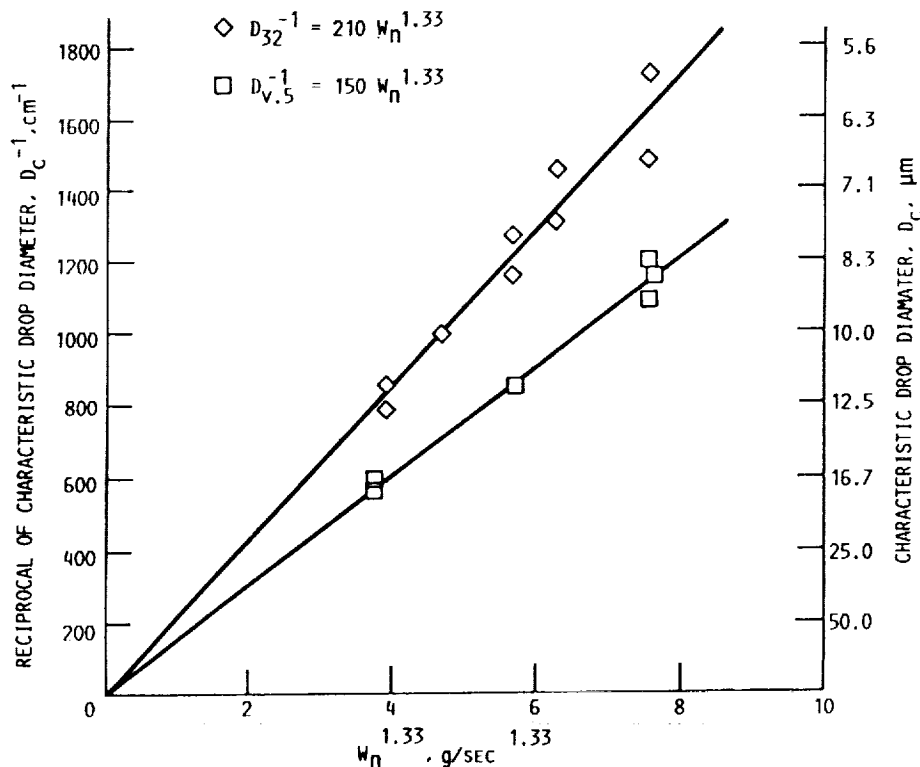

FIGURE 2. - COMPARISON OF CHARACTERISTIC DROP DIAMETERS AT LIQUID NITROGEN FLOWRATE OF 76.5 g/SEC. AND $\bar{x}$ = 1.3 CM.

TABLE II. - COEFFICIENT, k AND EXPONENT, a, FOR

CHARACTERISTIC DROP DIAMETER EXPRESSION,

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

$$[W_{LN2} = 76.5 \text{ g/cm.}]$$

Sampling location, $\bar{x}$, cm	1.3	2.5	4.5
Exponent, a	1.33	1.20	0.90
Coefficient, k, for characteristic diameter:			
D_{32}	210	190	240
$D_{v.5}$	150	150	180

4-CONCLUDING REMARKS

Investigating the fluid mechanics of liquid-nitrogen jet breakup in high-velocity gasflow was found to be 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 the boiling point of approximately 77 K. Since the atomizing gas used in this study was at room temperature, approximately 293 K, this created high gas-phase temperature-gradients which caused severe background noise to arise when drop-sizes were measured with the scattered-light scanner. This problem was minimized in the present investigation by adjusting the alignment of the scattered-light scanner optical system.

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