Fluid Spray Simulation With Two-Fluid Nozzles

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Abstract

Two-phase interacting flow inside a two-fluid fuel atomizer was investigated and a correlation of aerodynamic and liquid-surface forces with characteristic drop diameter was obtained for liquid-jet breakup in Mach 1 gasflow. Nitrogen gas mass-flux was varied from 6 to 50 g/cm² sec by using four differently sized two-fluid atomizers with nozzle diameters varying from 0.32 to 0.56 cm. The correlation was derived by using acoustic gas velocity, V_C, as a basic parameter in defining and evaluating the dimensionless product of the Weber and Reynolds numbers as follows:

\[ \text{Do/Dr} = 8 \left( \frac{\rho_g}{\rho_l} \right) \left( \frac{V_g}{\sigma} \right)^{0.44} \]

From this expression, it is evident that

\[ D_{\text{r}} \approx V_C^{1.33} \] which agrees very well with atomization theory for the case of acceleration-wave breakup of liquid jets.

Nomenclature

- b: dropsize parameter in Nukiyama-Tanasawa expression, cm
- c: dropsize parameter in Rosin-Rammler expression, cm
- Do: characteristic drop diameter measured for entire spray, cm
- bi: diameter of ith drop, cm
- D50: volume median drop diameter, cm
- D32: Sauter mean drop diameter, cm
- Nn: exponent for Nukiyama-Tanasawa dropsize distribution expression
- Nf: exponent for Rosin-Rammler dropsize distribution expression
- n: number of droplets
- Re: Reynolds number, D_o V / \mu

Introduction

An experimental investigation of interacting aerodynamic and liquid-surface forces was conducted to determine the effect of two dimensionless force ratios, i.e., Weber and Reynolds numbers, on the characteristic dropsize of sprays produced by atomizing liquid jets in high-velocity gasflow. Such information is needed to better understand the breakup of liquid fuel jets in rocket and jet engines. The present study was conducted primarily in the aerodynamic-stripping regime at Mach 1 gasflow.

When liquid fuels are injected into gas turbine or rocket combustors they are rapidly atomized into clouds of vaporizing droplets that quickly ignite and burn. To accurately describe the fuel-spray combustion process, 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 fuels are atomized, mathematical expressions are needed that adequately describe processes such as two-fluid atomization in which various liquid and gas combinations may be used to produce the sprays. To do this, the effects of liquid and gas properties on spray dropsize must be determined. Numerous investigators have reported experimental results that correlate spray characteristic dropsize with...
relative velocity, i.e., gas velocity relative to liquid-surface velocity, and also with liquid properties as given in Refs. 1 to 5. Some of the correlations agree very well with atomization theory whereas others differ considerably. This could be attributed to the fact that measurement techniques and instrumentation have not yet been sufficiently developed or standardized to such an extent that good agreement might be expected. Experimental studies are needed that will produce correlations of characteristic drop size measurements with dimensionless force ratios such as the Reynolds and Weber numbers. Such correlations are very useful in calibrating fuel nozzles for jet engines. This can be accomplished by first making drop size measurements of water sprays produced with the fuel nozzle and then using the correlation to correct for the effects of liquid density, viscosity, and surface tension on the drop size that would be produced with the nozzle using a fuel such as a Jet-A.

Prior to the present study, an investigation was conducted with two-fluid atomizers and good agreement of experimental results with atomization theory was obtained, as discussed in Ref. 6. 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 agree well with atomization theory for liquid jet breakup in high-velocity gasf low. As a continuation of that study, the present investigation was initiated to extend experimental conditions to include a variation in the nozzle orifice diameter. By using four differently sized atomizers, it was possible to investigate the effects of nitrogen gas mass-flux, $pgV_g$, on the characteristic drop size, $D_c$, of the sprays and values of $w_n$, the Sauter mean diameter, and also with liquid properties as given in Refs. 1 to 5. The spatial resolution of the scattered-light scanner is 2.86 cm and corresponds to the laser beam diameter. A sufficient volume of each spray was sampled to capture the entire spray. From a study reported in Ref. 6, it was found that the effect of droplet vaporization on spray samples could be minimized by taking the sample at a distance of 2.2 cm downstream of the atomizer orifice. This was done to give the best agreement between theoretical and experimental effects of nitrogen gas flowrate on Sauter mean, $D_{32}$, volume-linear mean, $D_{31}$, and volume median, $D_w$, drop sizes. Therefore in the present study, characteristic drop diameters were measured at a sampling distance of 2.2 cm downstream of the nozzle orifice with a 7.5 cm diameter collecting lens and a photomultiplier detector. The effect of nitrogen gas weight flow per unit area, $W_n$/$A_0$, and values of $A_0$ for the different nozzle orifices varied from 0.0804 to 0.246 cm². By further analysis of the data, it was possible to describe the atomization process in terms of the effect of dimensionless force ratios, i.e., Weber and Reynolds numbers, on characteristic drop size, $D_c$, at Mach 1 gasflow conditions.

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To study liquid-jet break-up, four pneumatic two-fluid atomizers with orifice diameters ranging from 0.32 to 0.56 cm were used to produce clouds of small droplets. The atomizer, illustrated in Fig. 3 as mounted at the center line of 24 cm diameter duct and operated over pressure ranges of 0.2 to 1.0 MPa for both water and nitrogen gas. Water sprays were injected downstream into the airflow just upstream of the duct exit. The sprays were sampled at a distance of 2.2 cm downstream of the atomizer orifice with a 7.5 cm diameter laser beam.

Water at a temperature of 293 K, measured with an I.C. thermocouple, was axially injected into the airstream by gradually opening a control valve until the desired flow rate was obtained as indicated by a turbine flowmeter. Nitrogen gas was then turned on to atomize the water jet and weight flowrate was measured with a 0.51 cm diameter sharp-edge orifice. After air, nitrogen, and water flowrates were set, the Sauter mean, volume median, and volume-linear drop diameters were measured with the scattered-light scanner to characterize the sprays. Exponents for both the Rosin-Rammler and Nukiyama-Tanasawa dropsize distribution expressions were also determined using the scattered-light scanner. The optical components are shown in Fig. 4 and consist of a 1 mW helium-neon laser, a 0.003-cm-diameter aperture, a 7.5-cm-diameter collimating lens, a 10-cm-diameter converging lens, a 5-cm-diameter collecting lens, a scanning disc with a 0.05-cm-slit, a timing light, and a photomultiplier detector.

The spatial resolution of the scattered-light scanner is 2.86 cm and corresponds to the laser beam diameter. A sufficient volume of each spray was sampled to capture the entire spray. The effect of drop size distribution functions on scattered-light scanner measurements is discussed in detail in Ref. 7. Very briefly, it was found in Ref. 7 that the irradiance distribution is only weakly related to the particle diameter distribution function; therefore, the irradiance distribution was used to determine characteristic drop diameters and changes in the drop size distribution function were assumed to have a negligible effect on drop size measurements made with the scattered-light scanner. Reproducibility tests gave experimental measurements of drop size that agreed within ±5 percent. Five sets of 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 scattered-light scanner can be found in Refs. 7 and 8.

**Experimental Results**

Atomization of liquid jets in high-velocity gasflow was studied to determine the effect of Weber and Reynolds numbers on characteristic drop size. Measurements of three different characteristic drop diameters were made 2.2 cm downstream of the atomizer and correlated with nitrogen gas flowrate, $W_n$. The effect of atomizer orifice-area on

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characteristic drop size was then determined from drop size data obtained from the four atomizers. Reynolds and Weber numbers for the sprays were related to the following characteristic drop sizes: Sauter mean, O32, volume median, Dv,5, and volume-linear mean, D31, drop diameters.

**Effect of Gas Flowrate, \( W_g \), on Characteristic Dropsize**

In Fig. 4, the reciprocal of the Sauter mean drop diameter \( D_{32} \) is plotted versus nitrogen gas flowrate, \( W_g \), and the following relationship is obtained for the four atomizers:

\[
D_{32}^{-1} = W_{g}^{1.33} \tag{1}
\]

at a water flowrate of 3.15 g/sec and at a distance of 2.2 cm downstream of the atomizer orifice. The entire spray was sampled using the scattered-light scanner. It is evident from the plot that at a given nitrogen gas flowrate the surface area/unit volume of spray, or \( O_{32} \), was lower for atomizers having larger orifice diameters. This was expected since mass flux also varies inversely with orifice diameter or orifice area.

Measurements of the volume median \( D_{v,5} \) and volume-linear \( D_{31} \) drop diameters were also obtained and from plots similar to Fig. 4, the following relationships were obtained:

\[
D_{v,5}^{-1} = W_{g}^{1.33} \tag{2}
\]

\[
D_{31}^{-1} = W_{g}^{1.33} \tag{3}
\]

These results are in good agreement with atomization theory which predicts that the reciprocal characteristic drop size, \( D_c \), is directly proportional to the gas flowrate raised to the 1.33 power, for liquid jet breakup in the regime of aerodynamic-stripping, i.e., high velocity gasflow.

**Effect of Nitrogen Gas Mass Velocity on Characteristic Dropsize**

Values of the Sauter-mean, volume-median and volume-linear mean drop sizes were obtained at a gas flowrate of 4 g/sec and plotted against atomizer orifice area as shown in Fig. 5. The three plots have the same slope indicate that \( D_{32}^{-1} = A_0^{-1.33} \).

Since \( D_{32} \) is also proportional to \( W_g^{1.33} \), as shown by Eqs. (1) to (3), it is evident that

\[
D_{32}^{-1} = (W/A_0)^{1.33} \tag{4}
\]

which may be rewritten in terms of mass flux as follows:

\[
D_{32}^{-1} = (\rho g V_g)^{1.33} \tag{5}
\]

Here it should be noted that the open area of the nozzle orifice as encountered by the gas phase is reduced due to blockage by the liquid droplets formed inside the atomizer and accelerating through the nozzle orifice.

In Fig. 6(a), values of \( D_{32}^{-1} \) are plotted against nitrogen mass flux and the following expression is obtained for the Sauter-mean diameter:

\[
D_{32}^{-1} = 11.7(W/A_0)^{1.33} \tag{6}
\]

In Fig. 6(b), a similar expression is obtained for the volume-median diameter:

\[
D_{v,5}^{-1} = 8.9(W/A_0)^{1.33} \tag{7}
\]

**Acoustic Mass-Flux Effect on Dropsize**

It is very difficult to measure gas and liquid velocities inside a two-fluid atomizer. Such data are needed in order to determine the gas velocity relative to liquid surface velocity, \( V_r \), in the dimensionless force ratio defined as follows:

\[
W_{Re} = (\rho g V_c)/\mu_l \tag{8}
\]

If the product of the Weber and Reynolds numbers, \( W_{Re} \), is multiplied by the density ratio, \( \rho_l/\rho_g \), and it is assumed that the acoustic gas-flux, \( V_c \), may be substituted for the relative velocity, \( V_r \), since the liquid velocity is negligible compared with \( V_c \), Eq. (8) may be rewritten as:

\[
D_{32}^{-1} = (\rho g V_c/\mu_l)^{1.33} \tag{9}
\]

Acoustic mass-flux is assumed equal to \( W_g/A_0 \), which is the quantity measured in the present study.

In Fig. 7, values of the dimensionless ratio, \( D_0/D_{32} \), are plotted against the product of fluid density ratio, \( \rho_l/\rho_g \), and dimensionless force ratio \( W_{Re} \). The slope of this plot gives the exponent 0.44 and the following expression is obtained:

\[
D_0/D_{32} = \left(\rho_l/\rho_g\right)^{0.44} \tag{10}
\]

From this expression, it is evident that:

\[
D_{32} = V_c^{-1.33} \tag{11}
\]

This relationship between Sauter-mean diameter and acoustic gas-flux agrees very well with atomization theory.\(^9\) For liquid jet breakup in the aerodynamic-stripping regime, i.e., at Mach 1 gasflow, as shown in Table 1. Also shown in Table 1 are the results of other investigators who have also evaluated the exponent \( n \) in the following expression for characteristic dropsize: \( D_c = V_c^n \).

The relationship given in Eq. (10) is plotted in Fig. 8 and the following expression is derived for liquid jet breakup at Mach 1 gasflow in pneumatic two-fluid atomizers:

\[
D_0/D_{32} = 8.0\left(\rho_l/\rho_g\right)^{0.44} \tag{11}
\]

which also agrees well with atomization theory for liquid-jet atomization in high velocity gas streams. A similar expression for the volume-median drop diameter, \( D_{v,5} \), was obtained as follows:

\[\text{ORIGINAl PAGe NO. OF POOR QUALITY}\]
Characteristic Exponents for Drop-Size Distribution Expressions

With the scattered-light scanner, experimental data were obtained for the exponent $N_r$, which appears in the Rosin-Rammler drop-size distribution expression as follows:

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

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

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

From a plot of the data obtained with the four atomizers, as shown in Fig. 9, the following relation was determined:

$$
N_r = 2.8 N_n^{0.45}
$$

which is the same as that derived in Ref. 6. Thus, it was found that experimental values of exponents $N_n$ and $N_r$ for the two drop-size distribution expressions were not appreciably affected when atomizer orifice area was varied from 0.0804 to 0.2463 cm$^2$.

Concluding Remarks

Characteristic drop-size produced with four differently sized pneumatic two-fluid atomizers were measured with a scattered-light scanning instrument at a distance of 2.2 cm downstream of the nozzle orifice. As a result, a correlation of characteristic drop-size with dimensionless force ratios, i.e., Weber and Reynolds numbers, was obtained for liquid jet breakup in Mach 1 gasflow. The expression obtained for the Sauter mean, $D_{32}$, and volume median, $D_{5.0}$, drop diameters are as follows:

$$
\frac{D_{o}/D_{32}}{D_{o}/D_{V,5}} = 8 \left[\frac{\rho_g}{\rho_l} \frac{W_e}{Re}\right]^{0.44} \text{ and } D_{o}/D_{V,5} = 6.1 \left[\frac{\rho_g}{\rho_l} \frac{W_e}{Re}\right]^{0.44}
$$

where the dimensionless groups in the brackets may be defined as follows:

$$
\rho_g W_e = D_2^2 \left(\frac{\rho_g}{\rho_c}\right) \frac{V_c}{\rho_c}
$$

$D_2$ is the acoustic mass-velocity of the gas phase and is equal to the weight flow of nitrogen gas per unit area, $W_e/\rho_c$. Thus from the preceding expression, it is evident that: $D_{32} = (\rho_g W_e)^{-1.33}$.

The exponent, -1.33 is in good agreement with atomization theory for liquid jet breakup in the aerodynamic-stripping regime at Mach 1 gasflow.

The experimental values of the exponents $N_n$ and $N_r$ for the Nukiyama-Tanasawa and Rosin-Rammler drop-size distribution expressions, respectively, were not appreciably affected as atomizer orifice diameter was varied from 0.32 to 0.56 cm.

References


Table 1. - Velocity Exponent, $n$, for Acceleration-Force Breakup of Liquid JETS: $D_{o} = \frac{1}{v^{n}}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Exponent n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>1.33</td>
</tr>
<tr>
<td>Present study, $\hat{x} = 2.2$ cm</td>
<td>1.33</td>
</tr>
<tr>
<td>Weiss and Worsham</td>
<td>1.33</td>
</tr>
<tr>
<td>Wolf and Andersen</td>
<td>1.14</td>
</tr>
<tr>
<td>Kim and Marshall</td>
<td>1.14</td>
</tr>
<tr>
<td>Nukiyama and Tanasawa, $\hat{x} = 5$ to 25 cm</td>
<td>1.0</td>
</tr>
<tr>
<td>Lorenzetto and Lefebvre</td>
<td>1.0</td>
</tr>
</tbody>
</table>

* Drop-size data for wax spheres.
* Ref. 9.
* Ref. 4.
* Ref. 5.
* Ref. 1.
* Ref. 3.
* Ref. 2.
FIGURE 1. - APPARATUS AND AUXILIARY EQUIPMENT.
FIGURE 2. - ATMOSPHERIC PRESSURE TEST SECTION AND OPTICAL PATH OF SCATTERED-LIGHT SCANNER.

FIGURE 3. - DIAGRAM OF PNEUMATIC TWO-FLUID ATOMIZER.
FIGURE 4. VARIATION OF SAUTER MEAN DIAMETER, $D_{32}$, WITH NITROGEN GAS FLOWRATE, $W_g$, AT $x = 2.2$ cm AND $W_1 = 3.15$ g/sec.
FIGURE 5. - VARIATION OF CHARACTERISTIC DROP DIAMETER, $D_c$, WITH ATOMIZER ORIFICE AREA, $A_0$, AT $W_g = 4$ g/sec.
FIGURE 6. - EFFECT OF GAS MASS-FUX ON SAUTER-MEAN AND VOLUME-MEDIAN DROPSIZES.
FIGURE 7. - VARIATION OF $D_0/D_{32}$ WITH PRODUCT OF
DIMENSIONLESS GROUPS $(\rho_g/\rho_f)\text{Re}$. 

ATOMIZER
ORIFICE
AREA,
$A_0$,
$\text{cm}^2$

- $0.0804$
- $0.1257$
- $0.1781$
- $0.2463$
FIGURE 8. - CORRELATION OF SAUTER MEAN DIAMETER WITH REYNOLDS NUMBER, WEBER NUMBER, AND FLUID-DENSITY RATIO.
FIGURE 9. - CORRELATION OF ROSIN-RAMMLER AND NUKIYAMA-TANASAWA Exponents $n_r$ AND $n_R$, RESPECTIVELY.
Two-phase interacting flow inside a two-fluid fuel atomizer was investigated and a correlation of aerodynamic and liquid-surface forces with characteristic drop diameter was obtained for liquid-jet breakup in Mach 1 gasflow. Nitrogen gas mass-flux was varied from 6 to 50 g/cm² sec by using four differently sized two-fluid atomizers with nozzle diameters varying from 0.32 to 0.56 cm. The correlation was derived by using acoustic gas velocity, $V_c$, as a basic parameter in defining and evaluating the dimensionless product of the Weber and Reynolds numbers as follows:

$$\text{We} \times \text{Re}^2 = \frac{\rho_g D_o^2 V_c^3}{\mu_l \sigma}$$

where $\rho_g$ is gas density, $D_o$ is liquid-flow orifice diameter, $V_c$ is the acoustic velocity of the gas, $\mu_l$ is the liquid viscosity and $\sigma$ is the liquid surface tension. By using the definition of We Re given above, it was found that the ratio of orifice diameter to Sauter mean drop diameter, $D_o/D_{32}$, could be correlated with the dimensionless ratio We Re and the gas to liquid density ratio, $\rho_g/\rho_l$, as follows:

$$D_o/D_{32} = 8 \left[ (\rho_g/\rho_l) \right]^{0.44} \text{We} \times \text{Re}^2$$

From this expression, it is evident that $D_{32} \sim V_c^{-1.33}$ which agrees very well with atomization theory for the case of acceleration-wave breakup of liquid jets.