Aerodynamic Effect of Combustor Inlet Air Pressure on Fuel Jet Atomization

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Mean drop diameters were measured with a recently developed scanning radiometer in a study of the atomization of liquid jets injected cross stream in high-velocity and high-pressure airflows. At constant inlet air pressure, the reciprocal mean drop diameter D_m^{-1} was correlated with the airflow mass velocity $\rho_a V_a$ to give the relationship $D_m^{-1} \sim (\rho_a V_a)^{1.2}$ for a $\rho_a V_a$ range of 10-177 g/cm$^2\cdot$s at 293 K. Over a combustor inlet air pressure range of 1-21 atm., the ratio of orifice to mean drop diameter D_0/D_m was correlated with the product of the Weber and Reynolds numbers $WeRe$ and with the molecular-scale momentum-transfer ratio of gravitational to inertial forces $gl/\bar{c}^{\,2}$, as follows: $D_0/D_m = 1.4\ (WeRe)^{0.4}(gl/\bar{c}^{\,2})^{0.15}$ for values of $WeRe > 10^6$, where $WeRe = \rho_a D_0^2 V_r^3/\sigma\gamma$; ρ_a and V_r are the airstream density and velocity, respectively; σ and γ the liquid surface tension and kinetic viscosity, respectively; g the acceleration due to gravity, 980 cm/s^2; l the mean free molecular path, 6.11×10^{-6} cm for air at atmospheric pressure; and $\bar{c}$ the root mean square molecular velocity, 4.85×10^4 cm/s for air at 273 K.

Nomenclature

$\bar{c}$	= root mean square molecular velocity, cm/s
$b_{g,w}$	= molecular mass diffusivity, g/cm·s
D	= diameter, cm
D_{32}	= Sauter mean diameter, $\Sigma nD^3/\Sigma nD^2$, cm
g	= acceleration due to gravity, 980 cm/s^2
h	= heat-transfer coefficient, g·cal/cm^2·s·°C
k	= thermal conductivity, g·cal/cm·s·°C
l	= mean free molecular path, cm
M	= molecular weight, g·mole
Nu	= Nusselt number for heat transfer, hD/k
n	= number of molecules per unit volume, cm^{-3}
P	= static pressure, atm
R	= universal gas constant, 8.31×10^7 erg/K·mole
Re	= Reynolds number based on orifice diameter, $D_0 V_r/\gamma_l$
Sc	= Schmidt number based on mass diffusivity, $\mu/b_{g,w}$
V	= velocity, cm/s
We	= Weber number based on orifice diameter, $D_0\rho_a V_r^2/\sigma$
γ	= kinematic viscosity, cm^2/s
σ	= surface tension, dyne/cm
ρ	= density, g/cm^3
μ	= absolute viscosity, g/cm·s

Subscripts

a	= airstream
g	= gas molecule
l	= liquid
m	= mean
o	= orifice
r	= relative
v	= vapor

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Introduction

AN experimental investigation was conducted to determine the effect of combustor inlet airflow static pressure on mean drop diameters obtained by the atomization of water jets injected cross stream from simple orifices into axial flow airstreams. An improved scanning radiometer was developed at the NASA Lewis Research Center and was used to obtain the mean drop diameter data of the sprays. Such data are needed to supplement previous theoretical and experimental studies of liquid atomization in order to extend our knowledge to the aerodynamic breakup of fuels in both high-pressure and high-velocity airflows.

Previous studies have shown that the force or mass velocity of an airstream is a very important factor in determining the atomization fineness of the fuel in the primary zone of a combustor. As a result, the effect of the airstream mass velocity on the fuel atomization is receiving considerable attention in advanced combustor research investigations.[1] Also, earlier studies have shown that high combustion efficiencies can be attained and exhaust emissions reduced by controlling the aerodynamic force of the airstream in the breakup of liquid fuel jets, instead of relying on the hydrodynamic pressure drop of the fuel to do the work as is the case in pressure-atomizing fuel nozzles.[2] The high combustion efficiency and reduction in pollutants was attributed to improved fuel atomization. This conclusion was substantiated in a later study[3] in which it was found that nitrogen oxide emissions in the exhaust gases of the swirl can combustor modules varied directly with the square of the mean drop diameter in the fuel spray.

The present trend of advanced combustor research toward higher primary-zone inlet air pressures and temperatures has stimulated the need to know the effect of the airstream pressure on fuel atomization and combustion. Although there are very little data available that show this effect, expressions have been derived that relate the Weber and Reynolds numbers to the mean drop diameter of fuel sprays and predict the effect of the airstream pressure on the mean drop size. Different expressions have been derived that depending on whether atomization occurs in the capillary or acceleration wave regimes. In Ref. 4 it was found that, when the transition from capillary to acceleration or aerodynamic wave breakup occurs, the effect of the product of the Weber and Reynolds numbers on the mean drop size increases considerably. As a result, a marked change in the effect of the airstream pressure on the mean drop size is also predicted. Such a correlation is quite useful in the design of fuel injectors for combustor applications since fuel nozzles can be calibrated with water and the mean drop diameters can then be calculated for the desired fuel, such as Jet-A, with the aid of such correlations.

In the present investigation, relationships involving the product of the Weber and Reynolds numbers were investigated for the condition $WeRe > 10^6$. This acceleration or aerodynamic wave breakup regime was chosen for investigation since high-velocity airstreams are required in simulating fuel atomization in turbojet combustors at idle, takeoff, and cruise operating conditions. Thus, water jets were injected from an airfoil type of spray bar cross stream or normal to the airflow and the mean drop diameters of the sprays were measured with an improved scanning radiometer recently developed at NASA Lewis Research Center. Combustor inlet air static pressure was varied at 1-21 atm over a range of airflow rates per unit area of 10-177 g/cm^2· s at 293 K. The spray bar orifice diameters were 0.033-0.132 cm and the liquid flow-rates 27-68 liter/h. Mean drop diameter data were then correlated with the product of the Weber and Reynolds numbers and the pressure-sensitive molecular scale dimensionless group $gl/_c^{-2}$. The resulting empirical relationships for the liquid-jet breakup were compared with those obtained from a previous experimental study of the cross-stream injection of radical jets in high-velocity airflows.[4]

Apparatus and Procedure

The test section is shown in Fig. 1 with two 5.1 cm diam windows passing a laser light beam through the spray of droplets produced in the high-velocity, high-pressure airflow. The closed-duct high-pressure test facility in which the test section was mounted is shown in Fig. 2. The airflow was drawn from the laboratory supply system at ambient temperature (293 K) and exhausted into the altitude exhaust system to obtain drop size data at low airstream pressure and into the atmosphere for high-pressure airflow test conditions. The airflow control valve was opened until the desired airflow rate per unit area was obtained. The bellmouth test section shown in Fig. 3 has a total length of 0.152 m and inside diameter of 0.076 m and is mounted inside of a duct that is 2.1 m in length with an inside diameter of 0.152 m.

Multiple jets of water were injected at the duct centerline and directed cross stream with the fuel spray bar shown in Fig. 3. The water flow rate was controlled by gradually opening and regulating the value over a range of 27-68 liter/h. One of the fuel spray bars is shown in detail in Fig. 4. Three different spray bars were investigated to obtain drop size data over an orifice diameter range of 0.033-0.130 cm. The first spray bar had 12 orifices, the second had 4 and the final configuration had 3, 0.033, 0.102, and 0.130 cm in diameter, respectively. Thus, at a liquid flow rate of 22.7 liter/h, liquid/jet velocities were 614, 194.4, and 158.4 cm/s (20.1, 6.4, and 5.2 ft/s), respectively, for the three spray bars.

After the water and airflow rates were set, the mean drop diameter data were obtained with the scanning radiometer mounted 25.4 cm downstream of the fuel tube supporting the spray bar. The scanning radiometer optical system shown in Fig. 5 consisted of a 1 mW helium-neon laser, a 0.003 cm diam

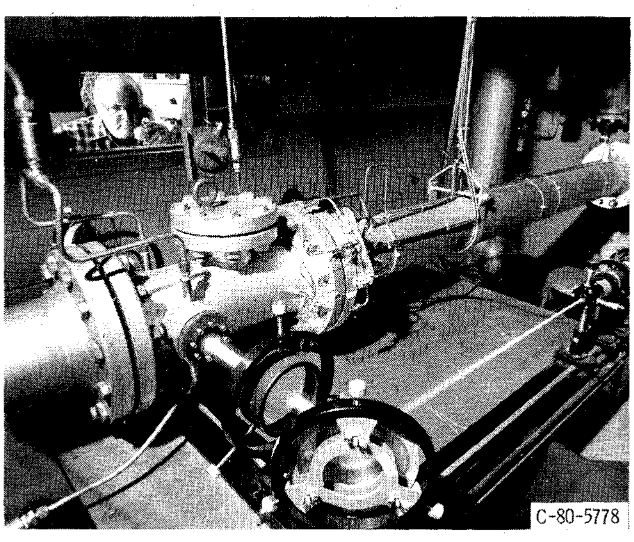


Fig. 1 Apparatus and auxiliary equipment.

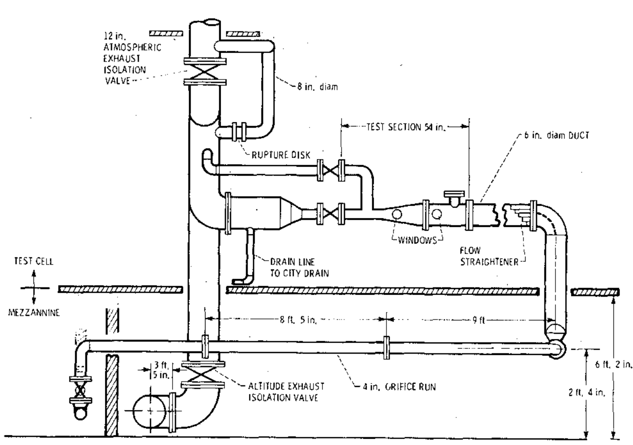


Fig. 2 Test facility and auxiliary equipment.

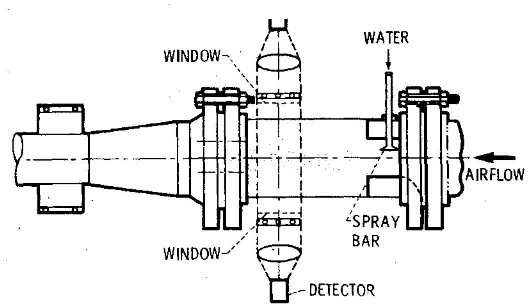


Fig. 3 High-pressure test section.

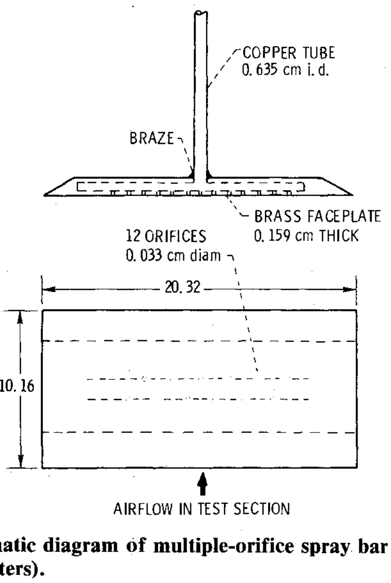


Fig. 4 Schematic diagram of multiple-orifice spray bar (dimensions are in centimeters).

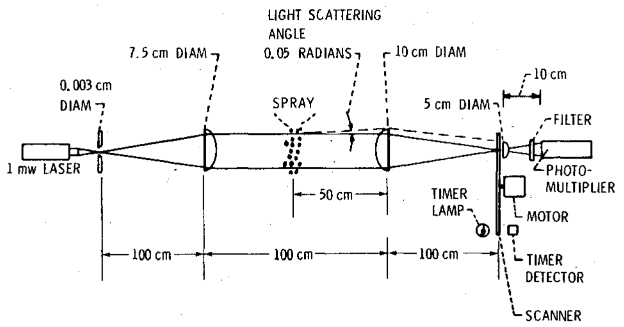


Fig. 5 Scanning radiometer optical path.

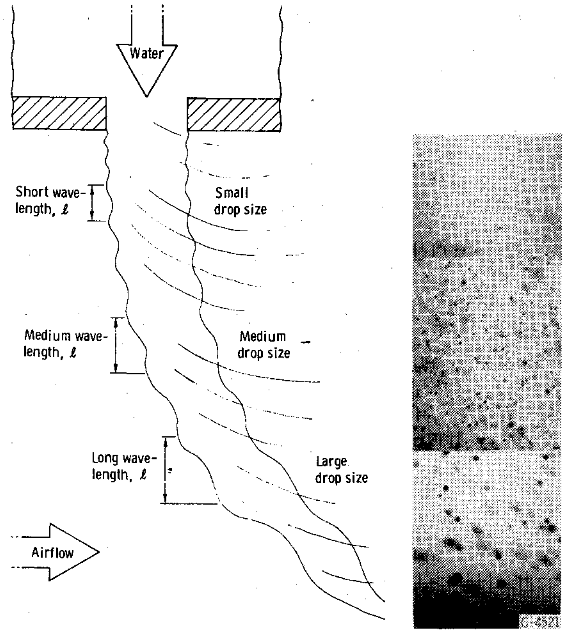
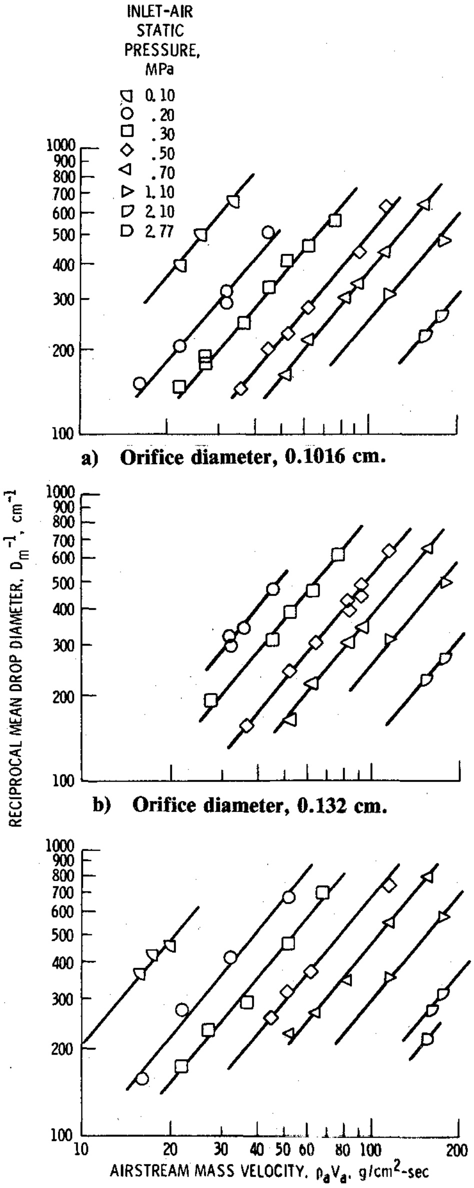


Fig. 6 Schematic of a liquid jet breaking up into ligaments and drops.



a) **Orifice diameter, 0.1016 cm.**

b) **Orifice diameter, 0.132 cm.**

c) **Orifice diameter, 0.033 cm.**

Fig. 7 Variation of reciprocal mean drop diameter D_m^{-1} with airstream mass velocity $\rho_a V_a$.

aperture, a 7.5 cm diam collimating lens, a 10 cm diam converging lens, a 5 cm diam collecting lens, a scanning disk with a 0.5×2.5 cm slot, a timing light, and a photomultiplier detector. A more complete description of the improved scanning radiometer, the mean drop diameter range of 10-500 μm, and the method of determining the mean particle size are discussed in Refs. 5 and 6.

The spatial resolution of the scanning radiometer is 2.86 cm, which is also the laser beam diameter in the test section where a sufficient volume of spray was sampled to minimize the spray pattern effects on the mean drop size. Also, the effect of the drop size distribution function on the scanning radiometer measurements is disscussed in detail in Ref. 7, where it was found that the irradiance distribution is only weakly related to the particle diameter distribution function. Thus, irradiance distribution was used in determining the Sauter mean diameter and changes in the drop size distribution function were assumed to have a negligible effect on the mean drop size measurements. Reproducibility tests showed that experimental measurements of the mean drop diameter agreed within $\pm 5\%$. Three sets of monosized polystyrene spheres having diameters of 25, 50, and 100 μm, respectively, were used to calibrate the scanning radiometer.

Experimental Results

To obtain a better understanding of the liquid jet atomization theory and thereby advance fuel injection technology for jet engine applications, the aerodynamic wave breakup of liquid jets in high-pressure, high-velocity airflow was investigated in a simulated gas turbine combustor primary zone. Mean drop diameter data were obtained for water jets atomized under simulated high-pressure combustor inlet airflow conditions. The atomization of a liquid jet in an axial flow airstream is depicted in Fig. 6 as a process of forming ligaments from the crests of waves formed on the surface of a liquid jet. The ligaments are then atomized into drops. Short-wavelength disturbances near the tip of the injector produced relatively small droplets, whereas long-wavelength disturbances farther out in the airstream produced relatively large drops.

Airstream Mass Velocity Effect on Mean Drop Size

The spray was well dispersed in 25.4 cm and the mean drop diameter data were determined for the breakup of water jets injected cross stream in axial airflows. As a measure of the fineness of the atomization or spray specific surface area, the reciprocal of the mean drop diameter D_m^{-1} was determined with the scanning radiometer and plotted against mass velocity $\rho_a V_a$, as shown in Fig. 7. D_m^{-1} was used since it is useful in characterizing a spray in terms of the surface area per unit volume of the spray and can be related to Sauter mean

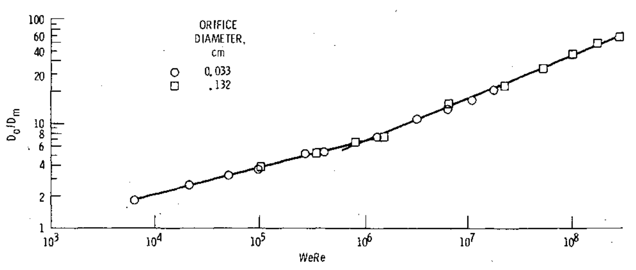
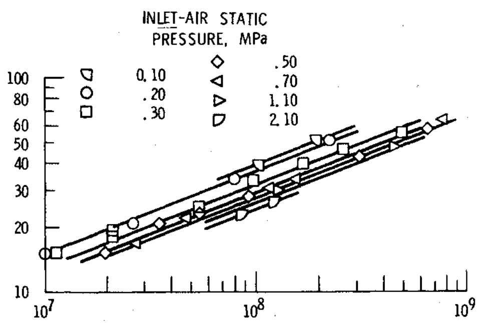
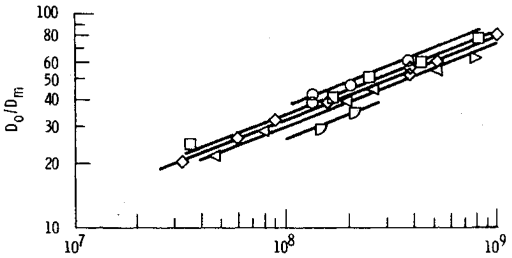


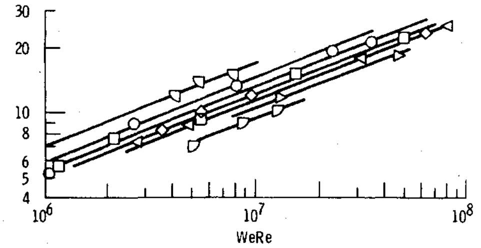
Fig. 8 Relation between orifice-to-mean-diameter ratio and product of Weber and Reynolds numbers.



a) Orifice diameter, 0.1016 cm.



b) Orifice diameter, 0.132 cm.



c) Orifice diameter, 0.033 cm.

Fig. 9 Variation of mean drop diameter D_m with product of Weber and Reynolds numbers.

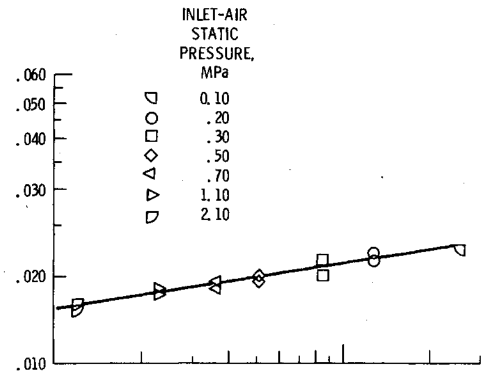
diameter D_{32} as

$$D_m \sim D_{32} = \Sigma nD^3/\Sigma nD^2 \qquad (1)$$

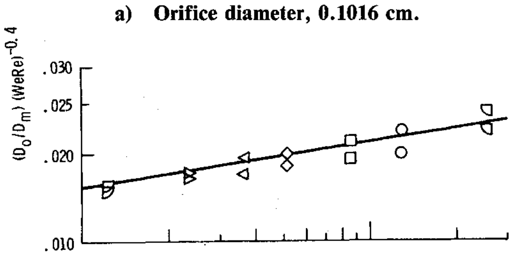
since it was found in Ref. 7 that the irradiance of forward-scattered light is a function of the Sauter mean diameter D_{32}.

Figure 7 shows the effect of airstream momentum, or mass velocity, on D_m^{-1} at seven different inlet air pressures over a range of 1-21 atm. The slope of each of the seven plots indicates that the expression $D_m^{-1} \sim (\rho_a V_a)^{1.2}$, which was obtained in Ref. 4, is valid over the entire inlet air pressure range used in this study.

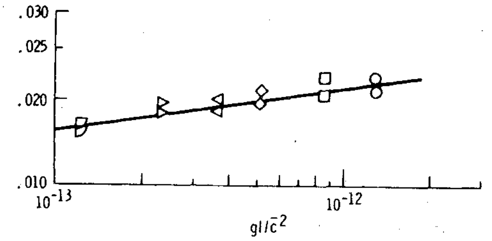
From the plot in Fig. 7 it is evident that, at a high combustor inlet air pressure of 21 atm., a very high airflow mass velocity of 200 g/cm^2·s is required to produce a spray having a value of $D_m^{-1} = 300$ cm^{-1}. On the other hand, a mass velocity of only 30 g/cm^2·s was required to produce the same mean drop size at an inlet air pressure of only 2 atm.



a) Orifice diameter, 0.1016 cm.



b) Orifice diameter, 0.033 cm.



c) Orifice diameter, 0.132 cm.

Fig. 10 Correlation of mean drop diameter D_m with dimensionless group $gl/\bar{c}^2$.

WeRe Effect on Mean Drop Size

In a previous study described in Ref. 8, it was found that the mean drop size of sprays produced by cross stream injection of a number of different liquids into airstreams could be correlated with the product of the Weber and Reynolds numbers, *WeRe* as

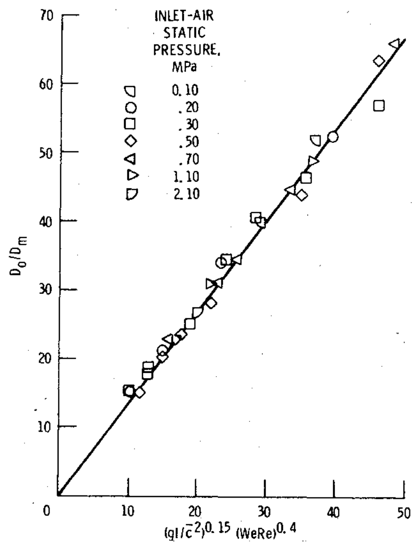
$$D_0/D_{32} = 0.20(WeRe)^{0.25} \text{ for } WeRe < 10^6 \qquad (2)$$

for the case of capillary wave breakup of liquid jets. However, more recently it was shown in Ref. 4 that, at high values of airstream mass velocity, aerodynamic wave breakup occurs and the expression becomes

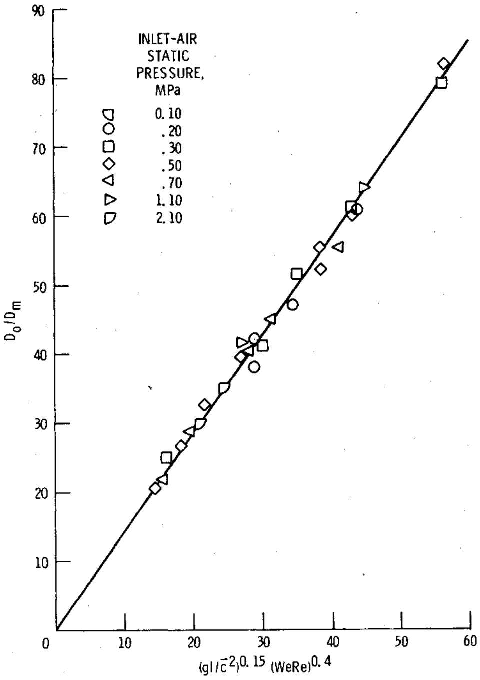
$$D_0/D_m = 0.027(WeRe)^{0.4} \text{ for } WeRe > 10^6 \qquad (3)$$

and the transition from capillary wave to aerodynamic wave breakup occurs at $WeRe = 10^6$, as shown in Fig. 8 (which is taken from Ref. 4).

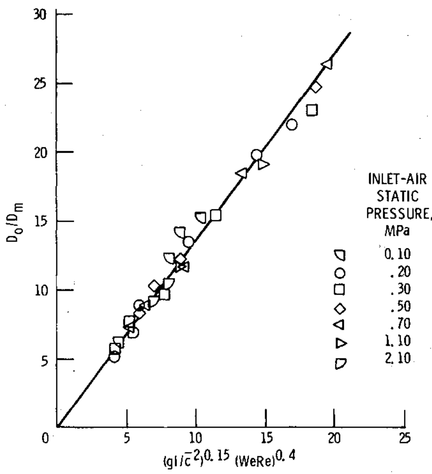
Aerodynamic wave breakup is the regime of primary concern in this study, that is, $WeRe > 10^6$ as given in Eq. (3). This is demonstrated in Fig. 9 where experimental values of D_0/D_m are plotted against calculated values of *WeRe*. The slope of each plot shows good agreement with the exponent 0.4 as given in Eq. (3) for the aerodynamic wave breakup of liquid jets.



a) **Orifice diameter, 0.1016 cm.**



b) **Orifice diameter, 0.132 cm.**



c) **Orifice diameter, 0.033 cm.**

Fig. 11 Correlation of mean drop diameter D_m with dimensionless group $gl/_c^{-2}$ and *WeRe*.

Airstream Pressure Effect on Mean Drop Size

In a previous study described in Ref. 9, it was found that the heat-transfer coefficients for vaporizing drops and the Nusselt number *Nu* could be correlated with the product of the Reynolds and Schmidt numbers *ReSc*. It was also found that a new pressure-sensitive dimensionless group gl/c^{-2} was needed in the correlation to make it valid over an airstream static pressure range of 0.59-1.97 atm. Thus, the following semiempirical expression was derived:

$$Nu = 2 + 2.6 \times 10^6 (ReSc\, gl/c^{-2})^{0.6} (k_g/k_v)^{0.5} \qquad (4)$$

where $Nu = hD/k$, $Re = DV/\gamma_l$, and $Sc = \mu/b_{g,w}$. In the formation of a spray of drops, it could also be assumed that the reciprocal mean drop diameter might be a function of the molecular scale momentum-transfer ratio of gravitational to inertial forces, gl/c^{-2}, as follows:

$$D_0/D_m = f(WeRe, g/c^{-2}) \qquad (5)$$

To test the validity of this asumption, $D_0/D_m\,(WeRe)^{-0.4}$ is plotted against the dimensionless group gl/c^{-2} in Fig. 10. From the slope of this plot, it is evident that $D_0/D_m \sim gl/c^{-2}$. Thus, by plotting D_0/D_m against $(WeRe)^{0.4}$ $(gl/c^{-2})^{0.15}$ as shown in Fig. 11, the following expression is obtained:

$$D_0/D_m = 1.4(WeRe)^{0.4}(gl/c^{-2})^{0.15} \qquad (6)$$

for the aerodynamic breakup of liquid jets injected cross stream in high-pressure, high-velocity airflow. This expression shows that the effect of the combustor inlet air pressure P_a on the reciprocal mean drop diameter D_m can be written as, $D_m^{-1} \sim P_a^{0.25}$, since $(gl/c^{-2})^{0.15} \sim P_a^{0.15}$ and $(WeRe)^{0.4} \sim P_a^{0.4}$. This agrees well with Ref. 10, which gives $D_{32} \sim P_a^{-0.3}$. Equation (6) also indicates that $D_m^{-1} \sim \rho_a^{0.4}$, whereas acceleration wave breakup theory predicts $D_m^{-1} \sim \rho_a^{0.66}$. Thus, the effect of the combustor inlet-air temperature on the mean drop size needs to be investigated at high airstream temperatures in order to actually determine the effect of the combustor inlet air density on the mean drop diameter of fuel sprays. Such a study would entail the difficulty of determining the drop size of rapidly evaporating sprays.

Summary of Results

Empirical correlations of reciprocal mean drop diameter with airstream mass velocity were derived for the aerodynamic wave breakup of liquid jets injected cross stream into the airflow with combustor inlet air pressures of 1-21 atm. A newly developed scanning radiometer was used to obtain atomization data over an airstream mass velocity range of 10-177 $g/cm^2 \cdot s$ at 293 K. The results of this investigation are as follows:

1) At constant combustor inlet air pressure, the reciprocal mean drop diameter D_m^{-1} was correlated with airflow mass velocity $\rho_a V_a$ to give the relationship

$$D_m^{-1} \sim (\rho_a V_a)^{1.2}$$

2) With values of $WeRe > 10^6$ and over a combustor inlet air pressure range of 1-21 atm, the ratio of orifice to mean drop diameter D_0/D_m was correlated with the product of the Weber and Reynolds numbers *WeRe* and with the pressure-sensitive dimensionless group gl/c^{-2} as follows:

$$D_0/D_m = 1.4(WeRe)^{0.4}(gl/c^{-2})^{0.15}$$

$gl/c^2 = 2.55 \times 10^{-12}$ for airstreams at atmospheric pressure.

Appendix: Calculation of Molecular-Scale Momentum-Transfer Group, gl/c^{-2}

The mean free molecular path l may be expressed as

$$l = 1/\sqrt{2}\, nD_g^{\,2} = 6.11 \times 10^{-6} \text{ cm}$$

since the number of molecules per unit volume n is 2.7×10^{19} at a temperature of 0°C and a pressure of 1 atm. and the diameter of an air molecule D_g is 3.7×10^{-8} cm.

The root mean square molecular velocity c may be expressed as $c = (3RT/M)^{0.5}$, which yields

$$c^{-2} = \frac{(3)(8.31 \times 10^7)(273)}{(29)} = 2.35 \times 10^9 \text{ (cm/s)}^2$$

Since g is 980 cm/sec^2

$$gl/c^{-2} = \frac{(980)(6.11 \times 10^{-6})}{(2.35 \times 10^9)} = 2.55 \times 10^{-12}$$

References

[1]Ingebo, R. D., "Aerodynamic-Wave Break-Up of Liquid Sheets in Swirling Airflows and Combustor Modules," NASA TM-83353, 1983.

[2]Ingebo, R. D., Doskocil, A. J., and Norgren, C. T., "High Pressure Performance of Combustor Segments Utilizing Pressure-Atomizing Fuel Nozzles and Airswirlers for Primary-Zone Mixing," NASA TN D-6491, 1971.

[3]Ingebo, R. D., "Atomizing Characteristics of Swirl Can Combustor Modules with Swirl Blast Fuel Injectors in Terms of NOX Emission Rate," NASA TM-79297, 1980.

[4]Ingebo, R. D., "Capillary and Acceleration Wave Breakup of Liquid Jets in Axial-Flow Airstreams," NASA TP-1791, 1981.

[5]Buchele, D. R., "Scanning Radiometer for Measurement of Forward-Scattered Light to Determine Mean Diameter of Spray Particles," NASA TM X-3454, 1976.

[6]Buchele, D. R., "Particle Sizing by Measurement of Forward-Scattered Light at Two Angles," NASA TP-2156, 1983.

[7]Dobbins, R. A., Crocco, L., and Glassman, I., "Measurement of Mean Particle Sizes of Sprays from Diffractively Scattered Light," *AIAA Journal,* Vol. 1, Aug. 1963, pp. 1882-1886.

[8]Ingebo, R. D., and Foster, H. H., "Drop-Size Distribution for Cross-Current Breakup of Liquid Jets in Airstreams," NACA TN-4087, 1957.

[9]Ingebo, R. D., "Study of Pressure Effects on Vaporization Rate of Drops in Gas Streams," NACA TN-2850, 1953.

[10]Lorenzetto, G. E., and Lefebvre, A. H., "Measurements of Drop Size on a Plain Jet Airblast Atomizer," *AIAA Journal,* Vol. 15, July 1977, pp. 1006-1010.