Liquid Fuel Spray Processes in High-Pressure Gas Flow

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Atomization of single liquid jets injected down-stream in high-pressure and high-velocity airflow was investigated to determine the effect of airstream pressure on mean drop size as measured with a scanning radiometer developed at NASA Lewis Research Center. For aerodynamic-wave breakup of liquid jets, it was found that mean drop diameter $D_{32}$ varied with airstream pressure $P_a$ as follows: $D_{32} \propto P_a^{-0.25}$. This result was compared with the effect of airstream pressure on drag and heat-transfer coefficients of accelerating and vaporizing drops.

INTRODUCTION

The fluid mechanics of producing sprays and the aerothermodynamics of droplet acceleration and vaporization have been receiving considerable attention in spray process research studies. Spray drying for food processing, spray painting of manufactured items, pesticide sprays for agricultural use, icing sprays in wind tunnels, and fuel sprays in gas turbine combustors are some of the major fields of application of spray process studies. In the field of combustion, Ingebo (1) determined that the fuel spray vaporization rate is very important in determining burning characteristics such as ignition delay, flame stability, and completeness of burning. Fuel droplets formed by atomization simultaneously accelerate and evaporate in airstreams and thereby produce a combustible fuel-air mixture. Chemical reaction between fuel and air, or oxidant vapor, produces a combustion gas stream of relatively high velocity, temperature, and pressure, which accelerates the drops as the chemical reaction continues to accelerate the combustion gas flow in the combustor. Thus, a clear understanding of liquid fuel spray combustion requires knowledge of how aerothermodynamics and fluid mechanics may control the processes of atomization, vaporization, and acceleration, and how these processes are related to chemical reaction in determining combustor performance and exhaust emissions. More specifically, initial drop size and velocity as well as combustion gas conditions must be known to calculate heat-transfer and drag coefficients and thereby determine the lifetime histories of burning fuel drops. New data of this type are especially needed to

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determine rates of drop vaporization and combustion under high-pressure gas flow conditions.

Empirical expressions are quite useful in the design of fuel injectors for combustor applications since fuel nozzles can be calibrated with water, and mean drop diameters can then be calculated for the desired fuel, such as Jet-A, with the aid of such correlations. The product of the Weber and Reynolds numbers \( \text{WeRe} \) has been correlated with atomization data, and, for the condition \( \text{WeRe} > 10^5 \), atomization occurs in the regime of aerodynamic breakup. This condition was chosen for this investigation since the airstream velocity in turbojet combustors at idle, takeoff, and cruise operating conditions is usually quite high; i.e., combustor reference velocities are generally of the order of 20 to 30 m/s.

Since previous studies on atomization were limited to atmospheric pressure conditions, the present investigation was made to determine the effect of airstream pressure on mean drop size. Water jets injected downstream were atomized in the airflow, and mean drop diameters were measured with an improved scanning radiometer recently developed at NASA Lewis Research Center. Combustor inlet-air static pressure was varied from 0.10 to 2.10 MPa over a range of airflow rates per unit area of 10 to 177 g/(cm\(^2\))\(\cdot\)s at 293 K. Two injector tubes with orifice diameters of 0.1016 and 0.216 cm, respectively, were used with liquid flow rates of 27 to 68 liters/hr. Mean drop diameter data were correlated with the Weber-Reynolds number \( \text{WeRe} \) and a pressure sensitive molecular scale dimensionless group \( g_l/G \). The resulting empirical relations for liquid jet breakup were compared with expressions obtained in previous experimental investigations. Also, the effect of airstream pressure on atomization is compared with airstream pressure effects on droplet acceleration and vaporization rates as reported in previous spray studies in order to bring together high-pressure airflow data for spray processes reported in the literature.

APPARATUS AND PROCEDURE

The high-pressure airflow apparatus and auxiliary equipment are shown in figure 1. The test section, water spray, and scanning radiometer optical path are shown in figure 2. Two 5.1-cm-diameter windows pass the laser beam through the spray 25.4 cm downstream of the fuel injector. Single jets of water were injected downstream at the duct centerline with the fuel tube shown in figure 2. Two different 0.635-cm-outside-diameter tubes were used to obtain drop size data with two orifice diameters of 0.1016 and 0.216 cm, respectively.

At 273 K, single water jets were injected downstream at flow rates of 27 and 68 liters/hr, respectively, as measured with a turbine flowmeter. After setting water and airflow rates, mean drop diameter data were obtained with the scanning radiometer shown in figure 2. The optical system consisted 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 disk with a 0.05-cm-diameter hole, a
timing light, and a photomultiplier detector.

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 spray pattern
effects on mean drop diameter. Also, the effect of drop size
distribution function on the scanning radiometer measurements is
discussed in detail by Dobbins, et al. (2), who found that the
irradiance distribution is only weakly related to the particle
diameter distribution function. Thus, irradiance distribution
was used in determining Sauter mean diameter, and changes in the
drop size distribution function were assumed to have negligible
effect on mean drop size correlations. Reproducibility tests
showed that experimental measurements of mean drop diameter agreed
within ±5 percent. Three sets of monosized polystyrene spheres
having diameters of 25, 50, and 100 μm, respectively, were used
to calibrate the scanning radiometer. A more complete description
of it and the method of determining mean particle size are
discussed by Buchele (3,4).

EXPERIMENTAL RESULTS

To determine the effect of airstream pressure on liquid jet atomi-
ization, an improved model of the scanning radiometer was developed
at NASA Lewis Research Center. It was used to measure the mean
diameter of droplets in sprays produced by liquid jets breaking up
in high-pressure and high-velocity airflow.

Liquid jet atomization

In a previous study conducted with atmospheric pressure air-
streams, drop size distribution data for the breakup of liquid
jets were obtained with the high-speed droplet tracking camera
shown in figure 3 and described by Ingebo and Foster (5). Photo-
micrographs of the droplets and a schematic of the liquid jet
breakup process are shown in figure 4. Short wavelength distur-
bances near the injector orifice produce relatively small droplets
and grow into longer wavelengths as the jet penetrates farther
into the airstream and produces relatively large drops. Mean
drop size measurements obtained with this imaging technique gave
the data shown in figure 5 for five different liquids. The fol-
lowing correlation of the ratio of mean diameter to orifice diam-
eter $D_{30}/D_o$ with the Weber-Reynolds number $WeRe$ was derived
for values of $WeRe < 10^6$:

$$D_{30}/D_o = 3.9(WeRe)^{-0.25}$$  (1)

In deriving this relationship in reference (5), the spatial size
distribution data obtained with the high-speed camera were mass
weighted using the liquid-concentration profile data obtained
with a sampling probe. The temporal size distribution produced
is more useful in combustion studies.

In a later study, an early model of the scanning radiometer as
described by Ingebo (6) was used to study liquid jet breakup.
Here it was found that equation (1) was valid only in the regime
of capillary-wave breakup which occurs for values of \( \text{WeRe} \leq 10^6 \). At values of \( \text{WeRe} > 10^6 \), it was found in reference (6) that

\[
\frac{D_0}{D_{32}} = 0.027(\text{WeRe})^{0.4}
\]  \hspace{1cm} (2)

for liquid jet atomization in the regime of acceleration-wave breakup. Data from reference (6) for both capillary and acceleration-wave breakup are plotted in figure 6.

In this investigation an attempt was made to extend the application of equation (2) to the atomization of liquid jets in high-pressure airflow. Single jets of water were injected axially downstream in airstreams having static pressures from 0.1 to 2.7 MPa. Atomization data obtained with the two different fuel injector tubes are shown in figure 7 where the reciprocal mean drop diameter \( D_m^{-1} \) is plotted against airstream mass velocity \( \rho_a V_t \). As shown, the effect of \( \rho_a V_t \) on \( D_m^{-1} \) decreases markedly as airstream pressure is increased from 0.1 to 2.7 MPa. To extend equation (2) and make it applicable to high airstream pressures, \( \left( \frac{D_0}{D_m} \right)(\text{WeRe})^{0.4} \) is plotted against the pressure sensitive group \( gl/c^2 \) (fig. 8). In this dimensionless group \( g \) is the acceleration due to gravity, \( l \) the mean free molecular path, and \( c^2 \) the root-mean-square velocity of the air molecules.

The evaluation of this dimensionless group is as follows. The mean free molecular path \( l \) may be expressed as

\[
l = l/\sqrt{2nD_g^2} = 6.11 \times 10^{-6} \text{ cm}
\]

since the number of molecules per cubic centimeter \( n \) is \( 2.7 \times 10^{19} \) at a temperature of 0 °C and a pressure of 1 atm and the diameter of an air molecule \( D_g \) is \( 3.7 \times 10^{-8} \) cm.

The root-mean-square molecular velocity \( \bar{c} \) may be expressed as

\[
\bar{c} = (3RT/M)^{0.5},
\]

which yields

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

Since \( g \) is 980 cm/s/s,

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

From the data plotted in figure 8, it is evident that \( D_m^{-1} \propto (gl/c^2)^{0.15} \). Thus, the following expression is obtained from the data plotted in figure 9:

\[
\frac{D_0}{D_{32}} = 1.2(\text{WeRe})^{0.4}(gl/c^2)^{0.15}
\]  \hspace{1cm} (3)

which agrees with the expression obtained by Ingebo (7) for the cross stream injection of liquid jets - i.e.,

\[
\frac{D_0}{D_{32}} = 1.4(\text{WeRe})^{0.4}(gl/c^2)^{0.15}
\]
for acceleration-wave breakup of liquid jets with values of \( \text{WeRe} \sim 10^6 \). Since the molecular-scale momentum-transfer group \( g_1/c^2 \) is inversely proportional to airstream pressure, it is evident that \( g_1/c^2 \sim \text{Pa}^{-1} \). It was just shown that, at 273 K and 1 atm pressure, \( g_1/c^2 = 2.55 \times 10^{-12} \). Also, since \( \text{WeRe} \sim \text{Pa} \), equation (3) shows that \( D_{32} \sim \text{Pa}^{-0.25} \). Thus, the effect of airstream pressure on \( D_{32} \) is somewhat less than that which would be obtained by extrapolating an atmospheric pressure expression up to high airstream pressures. For example, equation (2) would indicate that \( D_{32} \sim \text{Pa}^{-0.4} \).

A comparison of the results obtained by several investigators of airstream effects on atomization is given in table I. Best agreement was obtained with Lorenzetto and Lefebvre (8) where it was found that \( D_{32} \sim \text{Pa}^{-0.3} \). This is in good agreement with equation (3) since it is assumed that \( D_m = D_{32} \) for the measurements of \( D_m \) made with the improved scanning radiometer in the present study. Kim and Marshall (11) and Wolfe and Andersen (12) give values more in agreement with the theoretically predicted relationship \( D_{32} \sim \text{Pa}^{-0.67} \) given by Adelberg (13). The atomization data presented in this study and in reference (8) were obtained over a much broader airstream pressure range than that used in references (11) and (12). This indicates a need to improve the theory proposed in reference (13), which does not account for molecular-scale forces such as those given in the group \( g_1/c^2 \).

**Droplet drag coefficients for accelerating sprays**

The high-speed droplet tracking camera used to obtain drop size data also gave drop velocity data. Thus, it was possible to determine drag coefficients of drops accelerating in gas streams. In the study described by Ingebo (14), it was found that the drag coefficient \( C_d \) could be correlated with Reynolds \( \text{Re} \) based on drop diameter as follows:

\[
C_d = 27\text{Re}^{-0.84}
\]

at atmospheric pressure.

Studies of propellant atomization and droplet acceleration in the high-pressure rocket combustor shown in figure 10 were made with the droplet tracking camera as described by Ingebo (15). It was found that the drag coefficient based on the mean drop diameter \( D_{20} \) could be correlated with the Reynolds number \( \text{Re} \) and the dimensionless group \( g_1/c^2 \) as follows:

\[
C_d = 0.13\text{Re}^{-0.84}(g_1/c^2)^{-0.2}
\]

where \( \text{Re} \) is based on the area number mean drop diameter \( D_{20} \). A plot of the data used to derive this expression is shown in figure 11. From equation 4, the effect of airstream pressure on drag coefficient appears to be \( C_d \sim \text{Pa}^{-0.64} \). As in the study of atomization, the effect of airstream pressure is somewhat less than that predicted from atmospheric pressure studies.
Heat-transfer coefficients for vaporizing drops

In the study of vaporization rates of single drops in atmospheric pressure airstreams, Ingebo (16) found that the Nusselt number $\text{Nu}$ could be correlated with the product of the Reynolds and Schmidt numbers $\text{ReSc}$ as follows: $\text{Nu} = 2 + 0.30(\text{ReSc})^{0.6}$, where $\text{Nu} = hD/k_g$, $h$ is the heat-transfer coefficient, $D$ the drop diameter, $\text{Sc} = \mu/b_{gw}$, $k_g$ and $\mu$ the gas thermal conductivity and viscosity, respectively, and $b_{gw}$ the vapor diffusivity.

In a later study by Ingebo (17), at an airstream static pressure range of 0.6 to 2 atm, data for the Nusselt number were obtained as shown in figure 12 and the following expression was derived:

$$\text{Nu} = 2 + 2.6 \times 10^6 [(\text{ReSc})(\text{g} l/\text{c}^2)]^{0.6} (k_g/k_v)^{0.5}$$

where $k_v$ is the thermal conductivity of the vapor. Thus, $\text{Nu} \propto P_a^0$. However, airstream pressure still influenced vaporization rate by its effect on temperature difference across the air-vapor film surrounding the drop.

CONCLUSIONS

As a result of this study and previous spray studies in high-pressure airstreams, graphical or numerical integration methods of calculating spray vaporization rates will not be very useful until more atomization, drag coefficient, and heat-transfer coefficient data are available for very high-pressure airstreams. The effects of airstream pressure on mean drop diameter $D_{32}$, drag coefficient $C_d$, and Nusselt number $\text{Nu}$ are shown in table II for comparison. Probably the most critical need at present is for high-pressure airstream data on drop size distribution and on mean drop size for spray processes in high-temperature and highly turbulent gas streams. Also, a more fundamental picture of simultaneous heat, momentum, and mass transport properties is needed for a more comprehensive treatment of fuel spray processes and the overall combustion process.

NOMENCLATURE

$b_{gw}$ = molecular mass diffusivity (g/(cm)(s))

$C_d$ = drag coefficient

$c$ = root-mean-square molecular velocity (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)/(sec)(cm$^2$)(°C)

$k$ = thermal conductivity (g-cal)/(sec)(cm$^2$)(°C/cm)

$l$ = mean free molecular path (cm)
$M$ = molecular weight
$Nu$ = Nusselt number for heat transfer, $hD/k$
$n$ = number of molecules per unit volume
$P$ = static pressure (atm)
$R$ = universal gas constant ($8.31 \cdot 10^7$ ergs/(K)(mole))
$Re$ = Reynolds number based on orifice diameter, $D_0V_r/\gamma_l$
$Sc$ = Schmidt number based on mass diffusivity, $\mu/b_g, w$
$V$ = velocity (cm/s)
$We$ = Weber number based on orifice diameter, $D_0\rho_\alpha V_r^2/\sigma$
$T$ = kinematic viscosity (cm$^2$/s)
$\sigma$ = surface tension (dynes/cm)
$\rho$ = density (g/cm$^3$)
$\mu$ = absolute viscosity (g/(cm)(s))

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

REFERENCES


9 Nukiyama S, and Tanasawa Y, Japan Society of Mechanical Engineers, Transactions, 5 (1939) 63.


13 Adelberg M, AIAA J., 6 (1968) 1143.


TABLE I. - EXPERIMENTALLY DETERMINED EXONENTS OF PROPERTIES PROPORTIONAL TO RECIPROCAL MEAN DROP DIAMETER $D_m^{-1}$ FOR AERODYNAMIC-WAVE BREAKUP OF LIQUID SHEETS AND JETS

<table>
<thead>
<tr>
<th>Sources for exponents</th>
<th>Airstream velocity, $V_a$, cm/s</th>
<th>Orifice diameter, $D_o$, cm</th>
<th>Airstream pressure, $P_a$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental (eq. (3))</td>
<td>1.2</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>Nukiyama and Tanasawa (9)</td>
<td>1.0</td>
<td>.00</td>
<td>0</td>
</tr>
<tr>
<td>Weiss and Worsham (10)</td>
<td>1.14</td>
<td>-.16</td>
<td>(a)</td>
</tr>
<tr>
<td>Kim and Marshall (11)</td>
<td>1.33</td>
<td>.00</td>
<td>.57</td>
</tr>
<tr>
<td>Wolfe and Andersen (12)</td>
<td>1.33</td>
<td>-.17</td>
<td>.67</td>
</tr>
<tr>
<td>Lorenzetto and Lefebvre (8)</td>
<td>1.0</td>
<td>0</td>
<td>.30</td>
</tr>
</tbody>
</table>

aUsed variable $1 + \rho_a/\rho_l$.
bExponent for initial drop diameter instead of orifice diameter.

TABLE II. - COMPARISON OF EFFECT OF AIRSTREAM PRESSURE $P_a$ ON SPRAY PROCESS PARAMETERS $D_m$ and $C_d$ AND NUSSELT NUMBER $Nu$

<table>
<thead>
<tr>
<th>Process</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomization</td>
<td>$D_o/D_m = 1.2(WeRe)^{0.4}(gl/c^2)^{0.15} D_m \sim P_a^{-0.25}$</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$C_d = 0.13Re^{-0.84}(gl/c^2)^{-0.2} C_d \sim P_a^{-0.64}$</td>
</tr>
<tr>
<td>Vaporization</td>
<td>$Nu = 2 + 2.6 \times 10^6[(ReSc)(gl/c^2)]^{0.6} h \sim P_a^0$</td>
</tr>
</tbody>
</table>
Figure 1. - Apparatus and auxiliary equipment.
Figure 2. - High-pressure test section and scanning radiometer optical path.
Figure 3. - Diagram of test section equipment and camera unit.
Figure 4. - Schematic of a liquid jet breaking up into ligaments and drops with cross-stream injection.
Figure 5. - Relation between mean to orifice diameter ratio and Weber-Reynolds number ratio.

Figure 6. - Relation between orifice to mean diameter ratio and Weber-Reynolds number.
Figure 7. Variation of reciprocal mean drop diameter with airstream mass velocity.
Figure 8. - Correlation of mean drop diameter $D_m$ with airstream pressure sensitive group $gl/c^2$. 

- (a) Orifice diameter, $D_o$, 0.216 cm.
- (b) Orifice diameter, $D_o$, 0.1016 cm.
Figure 9. - Correlation of mean drop diameter $D_m$ with dimensionless groups $gl/c^2$ and $WeRe$. 

**ORIFICE DIAMETER, $D_0$ cm**

- 0.1016
- 0.216
Figure 10. - Diagram of experimental apparatus.
FUEL SPRAY EVALUATION TEMPERATURE AT

<table>
<thead>
<tr>
<th>FINE</th>
<th>COARSE</th>
<th>EXPERIMENTAL NUSSELT NUMBER, Nu20</th>
<th>EXPERIMENTAL REYNOLDS NUMBER, Re20</th>
<th>TOTAL HEAT REQUIREMENT PER UNIT OF MASS, H, g-cal/g</th>
</tr>
</thead>
</table>

\[
T_f = \frac{T_s + T_g}{2}, \quad T'_f = \frac{T'_s + T'_g}{2}, \quad T'_f
\]

\[
(C_D)_{20} = 0.13 \, Re_20^{0.84} (g/l/c)^{-0.25}
\]

Figure 11. - Correlation of drag coefficient with Reynolds number and g/l/c group.
Figure 12 - Correlation of Nusselt number with momentum-transfer groups and thermal-conductivity ratio.