Hydrodynamic and Aerodynamic Breakup of Liquid Sheets

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ABSTRACT

Hydrodynamic and aerodynamic breakup of water sheets into sprays formed by impinging jet, splash plate and conventional simplex fuel nozzles were investigated in quiescent air and high velocity airstreams. Mean drop diameter $D_m$ for each spray was determined with a scanning radiometer previously developed at NASA Lewis Research Center. With impinging jet fuel injectors, the ratio of orifice diameter $D_o$ to mean drop diameter $D_m$ was correlated with hydrodynamic force in terms of the liquid jet Reynolds number $Re_l$ and aerodynamic force in terms of the airstream relative velocity Reynolds number $Re_r$ as follows: $D_o/D_m = 0.013 Re_l^{0.5} + 2 \times 10^{-9} Re_r$. With high velocity airstreams, aerodynamic force contributed the most to breakup since $Re_r >> Re_l$. Liquid sheet breakup with splash plate fuel injectors gave the following expression: $D_o/D_m = 2.8 \times 10^{-4} Re_a + 2.4 \times 10^{-3} Re_a$ where $Re_a$ is airstream Reynolds number based on airstream velocity. Hydrodynamic force was considered more effective in breakup with splash plates than with impinging jet fuel injectors since $D_o/D_m$ varied with $Re_a$ to the first power. Breakup of swirling water sheets formed with simplex pressure atomizing fuel nozzles gave the following expression: $D_o/D_m = D_o/D_m^* + 2.2 \times 10^{-3} (Re_l - Re_c)$ where $D_o/D_m^*$ and $Re_c$ are constants defined as the hydrodynamic mean drop diameter and the critical Reynolds number for aerodynamic breakup, respectively. Hydrodynamic force was considerably more effective in breakup with swirling sheets than with splash plate fuel injectors. However, aerodynamic force tended to decrease the cone angle and increase mean drop size with airstream Reynolds numbers below the critical Reynolds number $Re_c$. Experimental conditions included water flow rates of 27 to 68 liter per hour and airflow mass velocities of 1.7 to 25.7 g/cm$^2$ - sec at 293 K and atmospheric pressure.

NOMENCLATURE

- $D$ diameter, cm
- $D_m$ experimental mean drop diameter, cm
- $D_{30}$ volume-number mean drop diameter, $(\ln D_d/\ln 3)^{0.33}$, cm
- $D_{32}$ Sauter mean diameter, $\ln D_d/\ln 2$, cm
- $Fn$ flow number, $L/hr(N/m^2)^{0.5}$
- $k$ coefficient
- $AP$ liquid differential pressure, N/m$^2$
- $Re_a$ airstream Reynolds number, $D_o V_a/v_a$
- $Re_c$ constant
- $Re_l$ liquid jet Reynolds number, $D_o V_l/v_l$
- $Re_r$ airstream relative velocity Reynolds number, $D_o V_r/v_a$
- $v$ velocity, cm/sec
- $u$ absolute viscosity, g/cm-sec
- $v$ kinematic viscosity, cm$^2$/sec
- $\rho$ density, g/cm$^3$

Subscripts:

- $a$ airstream
- $c$ critical
- $d$ droplet
- $l$ liquid
- $m$ mean
- $o$ orifice
- $r$ relative

INTRODUCTION

An investigation was conducted to study the interaction and determine the effect of hydrodynamic, aerodynamic and liquid surface forces on the mean drop diameter of water sprays that are produced by the breakup of nonswirling and swirling water sheets in quiescent air and in airflows similar to those encountered in gas turbine combustors. The mean drop diameter is used to characterize fuel sprays and it is a very important factor in determining the performance and exhaust emissions of gas turbine combustors. This is demonstrated in Ref. 1 where nitrogen oxide emissions in the exhaust gases...
were found to vary directly with the square of the mean drop diameter of the fuel spray.

Several investigators have studied the atomization of liquid jets in airstream. In Ref. 2, Mayer identifies capillary-wave breakup as occurring when relatively large liquid jets are injected in quiescent or very low-velocity airstreams. In this case, hydrodynamic and aerodynamic forces are relatively low. However, when the velocity of the airstream relative to the liquid jet velocity is large and the aerodynamic force is sufficiently high, then according to Adelberg in Ref. 3 another type of breakup occurs which he defines as acceleration-wave breakup. In Ref. 4 it was found that the mean drop diameter of liquid jet breakup could be correlated with the product of the Weber and Reynolds number, and transition from capillary to acceleration wave breakup occurred when the value of the product of the Weber and Reynolds number equaled 10^6.

In the present study of liquid sheet atomization, the effect of hydrodynamic and aerodynamic force on mean drop diameter was studied in the regimes of capillary-wave and acceleration-wave breakup. Two general conditions of liquid sheet atomization were investigated, namely, breakup in quiescent air, in airstream of zero velocity relative to liquid jet velocity, and in high-velocity airstreams. In the first case, i.e., liquid sheet breakup in quiescent air, both hydrodynamic and aerodynamic forces are liquid force, and atomization generally occurs in the capillary wave breakup regime. In the second case, only hydrodynamic forces appreciably effect the mean drop diameter since aerodynamic force is negligible. Breakup is primarily in the capillary-wave regime and as a result mean drop diameters are larger than those obtained with quiescent air. In the final case of liquid sheet breakup in high velocity airstreams, the aerodynamic force has the major effect on fineness of atomization and breakup occurs primarily in the capillary-wave regime. This condition is most applicable to gas turbine combustors operating at idle, take-off and cruise conditions.

Non-swirling and swirling liquid sheets were injected in airstreams and mean drop diameter data were obtained from water sprays produced by impinging-jet, splash plate and conventional simplex pressure atomizing fuel nozzles. Non-swirling liquid sheets were injected axially and radially in airstreams and swirling hollow-cone sheets were injected at a cone-angle of 45° in quiescent and non-swirling airstreams in a 7.6 cm inside diameter duct. The airstream mass velocity, \( \rho AV_\text{F} \), was varied from 1.5 to 25.7 g/cm\( ^2 \)-sec at 293 K and atmospheric pressure. Orifice diameters varied from 0.033 to 0.072 cm for the three different types of fuel injectors. Water flow rates varied from 27 to 68 liter per hour. Mean drop diameter data were then correlated with hydrodynamic forces based on liquid velocity and orifice diameter and with aerodynamic forces based on airstream mass velocity.

**APPARATUS AND PROCEDURE**

Fuel injectors were mounted in the open-duct facility as shown in Fig. 1. Airflow was drawn from the laboratory supply system, at ambient temperature (293 K) as determined with an E-type thermocouple, and exhausted into the atmosphere. Airflow rate was determined with an orifice as the airflow control valve was opened until the desired airflow rate per unit area was obtained over a mass velocity range of 1.7 to 25.7 g/cm\( ^2 \)-sec. The bellmouth test section shown in Fig. 1 has a total length of 15.2 cm, an inside diameter of 7.6 cm and it is mounted inside of a duct that is 5 m in length with an inside diameter of 15.2 cm.

Water sheets were produced at the duct center line and directed axially downstream with the fuel injectors shown in Figs. (a) to (c). The impinging jets produced a relatively flat sheet flowing in the same direction as the airflow. The splash plate produced a liquid sheet injected radially or normal to the airflow, and the conventional Monarch simplex nozzle produced a swirling hollow-cone sheet with a cone-angle of 45° in quiescent air, i.e., no airflow in the duct. The water sheets, at 293 K as determined with an I.C. thermocouple, were formed by gradually opening a water flow control valve until the desired water flow rate over a range of 27 to 68 liters/hour was obtained as measured with a turbine flow meter.

When the airflow and water flow rates were set, mean drop diameter data were obtained with the scanning radiometer mounted 11.4 cm downstream of the open-duct exit. The scanning radiometer optical system shown in Fig. 3 consisted of a 1-milliwatt helium-neon laser, a 0.003-cm-diam collimating lens, a 10-cm-diam converging lens, a 5-cm-diam collecting lens, a scanning disk with a 0.05- by 0.05-cm slit, a timing light, and a photomultiplier detector. A more complete description of the scanning radiometer, the mean drop diameter range, and the method of determining mean particle size are discussed in Refs. 5 and 6.

**EXPERIMENTAL RESULTS**

To obtain a better understanding of liquid sheet atomization and thereby advance fuel injector technology for gas turbine combustor and augmentor applications, mean drop diameters were determined for the breakup of water sheets in high-velocity airstreams. Axially and radially injected sheets were produced with impinging jet and splash plate fuel injectors, respectively. Swirling hollow-cone sheets were injected axially downstream with pressure atomizing simplex nozzles.

**Impinging Jet Fuel Injectors**

The effect of airstream relative mass velocity \( \rho AV_\text{F} \) on the reciprocal mean drop diameter \( Dm^{-1} \) is shown in Fig. 4 and the following expression is obtained:

\[
Dm^{-1} = 0.23 (V_\text{D}D_\text{m})^{0.5} + 11 \rho AV_\text{F}
\]

where \( V_\text{D} \) and \( V_\text{F} \) are liquid velocity and airstream velocity relative to the liquid injection velocity, respectively. This expression may be rewritten in terms of the dimensionless ratio of orifice to mean drop diameter \( D_\text{m}/D_\text{m} \), the liquid jet Reynolds number \( Re_\text{L} \) for hydrodynamic breakup, and the airstream relative velocity Reynolds number \( Re_\text{F} \) for aerodynamic breakup as follows:

\[
\frac{D_\text{m}}{D_\text{m}} = 23 \times 10^{-3} Re_\text{L}^{0.5} + 2.0 \times 10^{-3} Re_\text{F}
\]

since \( V_\text{F} = 10.1 \times 10^{-3} \text{ cm/sec} \) and \( V_\text{D} = 1.8 \times 10^{-4} \text{ g/cm/sec} \). The mean drop diameter \( D_\text{m} \)
measured with the scanning radiometer is assumed to be approximately equal to the Sauter mean diameter, SMD or \( D_{m} \).

The effect of mass velocity \( \rho_{a}V_{a} \) on \( D_{m} \) is shown in Fig. 5. This plot gives a better overall picture of liquid sheet breakup and shows that the reciprocal mean drop diameter for hydrodynamic breakup, \( D_{m}^{-1} \), is equal to 110 and 10 for the 0.033 and 0.212 centimeter-diameter orifices, respectively. This occurs when \( V_{s} = V_{l} \) and therefore \( \rho_{s}V_{a} = 0 \). Also, in Fig. 8 shows that when the data are extrapolated to the condition \( V_{s} = 0 \), then \( D_{m}^{-1} \) is equal to 210 and 20 for the 0.033 and 0.212 centimeter-diameter orifices, respectively. Similar relationships for the breakup on n-heptane sheets produced with impinging jet fuel injectors for rocket combustors are derived in the Appendix. The derivation is based on mean drop size data given in Ref. 7, which were obtained with a photographic technique. As a result, the following expression is derived in terms of the Sauter mean drop diameter \( D_{m} \) as follows:

\[
0 \frac{0}{D_{m}} = 18.6 \times 10^{-3} \rho_{s}^{0.5} + 1.55 \times 10^{-3} \rho_{a} \tag{3}
\]

Comparison of Eq. (3) with Eq. (2) shows that the hydrodynamic breakup coefficient of 23.0 \( \times \) 10^{-3} for water sprays is somewhat higher than that of 18.6 \( \times \) 10^{-3} for n-heptane sprays. Also, the aerodynamic breakup coefficient of 2 \( \times \) 10^{-3} for water sprays is somewhat larger than that for n-heptane sprays. This may be attributed to the fact that Eq. (2) is obtained for very high momentum airstreams with a mass velocity, \( \rho_{a} \), range of 7.3 to 25.7 g/cm²-sec which is primarily in the acceleration-wave breakup regime. Equation (3), as derived from Ref. 7, only covers a mass velocity range of 2.4 to 11 g/cm²-sec which is primarily in the capillary-wave breakup regime for low momentum airstreams.

### Splash Plate Fuel Injectors

Breakup in airstreams of radially injected water sheets produced by the splash plate fuel injector shown in Fig. 3 was investigated. As shown in Figs. 6(a) and (b), values of \( D_{m} \) are plotted against mass velocity, \( \rho_{a} \), for the 0.016 and 0.216 centimeter-diameter fuel tubes, respectively. Mean drop diameter data for \( D_{m}^{-1} \) give the following empirical relation:

\[
D_{m}^{-1} = D_{m,0}^{-1} + 13 \rho_{a} \tag{4}
\]

where \( D_{m,0}^{-1} \) is the value of \( D_{m}^{-1} \) at \( \rho_{a} = 0 \). Since breakup data for the condition \( V_{s} = 0 \) was not obtained, for the splash plate fuel injector, values of \( D_{m,0}^{-1} \) were determined by extrapolating the data to \( \rho_{a} = 0 \). These values are then plotted against liquid jet velocity, \( V_{l} \), as shown in Fig. 7 to give the following expression:

\[
D_{m,0}^{-1} = 0.028 V_{l} \tag{5}
\]

for the hydrodynamic and aerodynamic breakup of water sheets in quiescent air. i.e. \( V_{s} = 0 \). At this condition, \( D_{m}^{-1} \) is directly proportional to the liquid jet velocity and \( \rho_{a} \)-dependent or orifice diameter. This result is quite different from that obtained with impinging jets. Thus, the two expressions, Eq. (7) and Eq. (1), cannot be compared directly since the first term on the right hand side of Eq. (1) is derived strictly for hydrodynamic breakup whereas \( D_{m,0}^{-1} \) includes both hydrodynamic and aerodynamic breakup.

By substituting Eq. (5) into Eq. (4), the following expression for splash plate fuel injector breakup of water sheets in high velocity airstreams is obtained:

\[
D_{m}^{-1} = 0.028 V_{l} + 13 \rho_{a} \tag{6a}
\]

which may be rewritten as:

\[
D_{m}^{-1} = 2.8 \times 10^{-4} Re + 2.4 \times 10^{-3} Re_{a} \tag{6b}
\]

Comparison of equation 6b for splash plate fuel injectors with Eq. (2) for impinging jets shows that hydrodynamic breakup varies with \( Re_{a} \) to the first power in Eq. (6b) and with \( Re_{a}^{0.5} \) in Eq. (2). However, the coefficient for \( Re_{a} \) is considerably higher in Eq. (2) than in Eq. (6b). Data from Fig. 5 for impinging jets are plotted in Fig. 6(b) for comparison and show that values of \( D_{m}^{-1} \) were somewhat lower for impinging jets of approximately the same orifice diameter of 0.216 centimeters.

### Pressure Atomizing Simplex Nozzles

Breakup of swirling hollow-cone water sheets injected axially downstream in high momentum airflows was investigated. This is a much more complicated type of liquid sheet breakup to analyze due to the difficulty of establishing the velocity of the swirling liquid relative to the airstream, i.e. \( V_{s} \). Also, the effect of airstream mass velocity on varying and reducing the cone angle obtained with various sizes of simplex nozzles adds to the difficulties of determining \( V_{s} \). Thus, for this study, \( D_{m}^{-1} \) data are plotted against mass velocity, \( \rho_{a} \), as shown in Fig. 8.

At the initial condition, \( \rho_{a}V_{a} = 0 \) and \( D_{m}^{-1} = D_{m,0}^{-1} \). Both hydrodynamic and aerodynamic forces are affecting the liquid sheet breakup process. However, as mass velocity, \( \rho_{a}V_{a} \), is increased the value of \( D_{m}^{-1} \) decreased until it reaches a minimum value of \( D_{m,0}^{-1} \) since relative velocity, \( V_{s} \), approaches zero and the breakup process is primarily controlled by the hydrodynamic pressure drop of the liquid. As mass velocity is increased from 4 to 14.5 g/cm²-sec for the small nozzles (\( D_{m} = 0.09 \)) there is only a slight increase in \( D_{m}^{-1} \). This intermediate region is primarily a capillary-wave breakup regime which is transformed into acceleration-wave breakup as mass velocity is increased to the maximum value of 25.7 g/cm²-sec. Thus, the following empirical expressions are derived from the data plotted in Fig. 8:

\[
D_{m}^{-1} = D_{m,0}^{-1} + 12 (\rho_{a}V_{a} - \rho_{c}V_{c}) \tag{7a}
\]

which may be rewritten as:
in this study for simplex Monarch nozzles producing water sprays at a cone angle of 45° in quiescent air.

SUMMARY OF RESULTS

Empirical correlations of the ratio of orifice diameter \(D_0\) to mean drop diameter \(D_m\) with hydrodynamic force in terms of the liquid jet Reynolds number \(R_{Re}\) and aerodynamic force in terms of the airstream Reynolds number \(R_{Re}\) or the airstream relative velocity Reynolds number \(R_{Re}\) were derived in this investigation of liquid sheet breakup in non-swirling airflow. They are listed as follows:

1. Impinging jet fuel injectors gave the empirical relationship, \(D_0/D_m = 0.023 \times 10^{-3} \times R_{Re}^{-1.5} + 2.10 \times 10^{-3} \times R_{Re}^{-1}\) and with high velocity airstream, aerodynamic force contributed the most to breakup since \(R_{Re} \gg R_{Re}\).

2. Splash plate fuel injectors gave the empirical relationship, \(D_0/D_m = 2.99 \times 10^{-4} \times R_{Re}^{-1.5} + 2.4 \times 10^{-3} \times R_{Re}\) and hydrodynamic force was much more effective in breakup with splash plates than with impinging jet fuel injectors since \(D_0/D_m\) varied with \(R_{Re}\) to the first power.

3. Simplex pressure atomizing fuel nozzles gave the empirical relationship, \(D_0/D_m = 0.0005 \times 10^{-3} \times R_{Re}^{-1.5} + 2.2 \times 10^{-3} \times R_{Re}\) where \(D_0\) and \(D_m\) are constants defined as the hydrodynamic mean drop diameter and the critical Reynolds number for aerodynamic breakup, respectively. Hydrodynamic force was considerably more effective in breakup with swirling sheets than with splash plate fuel injectors. However, aerodynamic force tended to decrease the cone angle and increase mean drop size when airstream Reynolds numbers were below the critical Reynolds number \(R_{Re}\).

APPENDIX

Liquid Sheet Atomization with Impinging Jet Fuel Injectors

In a previous experimental investigation described in Ref. 8, the breakup of n-heptane sheets axially injected in airstreams was studied. Mean drop diameter, \(D_{32}\), data were obtained with a photographic technique for sprays produced by air-atomizing impinging-jet fuel injectors for rocket combustors. The effect of liquid pressure drop or hydrodynamic forces on the spray mean drop size was determined first. Then, the interacting or additive effect of hydrodynamic and aerodynamic forces on mean drop size was investigated.

Hydrodynamic Breakup

In Ref. 8, the following expression for the reciprocal mean drop diameter for hydrodynamic breakup, \(1/D_{32}\), was obtained from a study of the breakup of pairs of impinging jets in airstreams with relative velocity \(V_r = 0\) and \(V_0 = V_1\):

\[
1/D_{32} = 0.31 \left( \frac{V_1}{V_0} \right)^{0.5}
\]

where \(V_1\) and \(V_0\) are the liquid jet velocity and orifice diameter respectively. A straight line
plot of Eq. (11) and the data for Ref. 8 are shown in Fig. 10. Equation 11 may be rewritten in terms of the dimensionless ratio of orifice diameter to hydrodynamic mean drop diameter, \( \frac{D_{30}}{d_0} \), as follows:

\[
\frac{D_{30}}{d_0} = 0.024 \text{ Re}_1 0.5
\]

(17)

since \( \text{Re}_1 = D_{30} \text{V}_1 / d_0 \) and \( \text{V}_1 = 0.0061 \) cm/Sec for n-heptane.

**Aerodynamic Breakup**

Data from Ref. 8 for aerodynamic breakup with hydrodynamic force held constant are plotted in Fig. 11 and give the following expression for mean drop size:

\[
D_{30}^{-1} = 0.31 \left( \frac{\text{V}_1}{\text{V}_r} \right) 0.5 + 11 \sigma_0 \text{V}_r
\]

(13)

where \( \sigma_0 \text{V}_r \) is the relative mass velocity which produces the aerodynamic breakup of the liquid sheet. The usefulness of Eq. (13) is illustrated in Fig. 12 which shows, that initially when \( \text{V}_r = 0 \), the following expression is obtained:

\[
D_{30}^{-1} = 11 \sigma_0 \text{V}_r
\]

since \( \text{V}_r = 0 \), then as \( \text{V}_r \) increases \( \text{V}_r \) decreases until \( \text{V}_r = 0 \) and the value of \( D_{30} \) decreased until \( D_{30} = D_{30}^{0} \), as given by Eq. (11).

Further increases in \( \text{V}_r \) increases \( \text{V}_r \) and values of \( D_{30} \) increase as given by Eq. (13). The minimum value of \( D_{30} \) at \( \text{V}_r = 0 \) is due to the negligible effect of aerodynamic force on breakup and illustrates the need of having mass velocities sufficiently high to more than compensate for the fuel velocity and obtain good fuel atomization in a combustor. Thus, \( \sigma_0 \text{V}_r > 10 \) is recommended when using impinging-jet fuel injectors.

Equation (13) may be rewritten in terms of the dimensionless ratio \( \frac{D_{30}}{d_0} \) as follows:

\[
\frac{D_{30}}{d_0} = 0.074 \text{ Re}_1^{0.5} + 2.0 \times 10^{-3} \text{ Re}_1
\]

(14)

since \( \sigma_0 = 1.81 \times 10^{-4} \) g/cm³. In terms of the Sauter mean drop diameter \( D_{32} \), the expression may be rewritten as follows:

\[
\frac{D_{32}}{d_0} = 18.6 \times 10^{-3} \text{ Re}_1^{0.5} + 1.55 \times 10^{-3} \text{ Re}_1
\]

(15)

since \( D_{32} = 1.79 \frac{D_{30}}{d_0} \) as given in Ref. 9.

**REFERENCES**


Figure 1. - Test facility and auxiliary equipment. (Dimensions are in meters.)
(a) Impinging jets with axially injected flat spray.
(b) Splash plate with radially injected flat spray.
(c) Simplex pressure atomizing nozzle with axially injected swirling hollow-cone spray.

Figure 2. - Liquid sheet fuel injectors.
**Figure 3.** Scanning radiometer optical path.

**Figure 4.** Variation of reciprocal mean drop diameter, $D_m^{-1}$, with airstream relative mean velocity, $\rho_a V_r$, for water sheets produced by impinging jet injectors.

**Table:**

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<th>Orifice Diameter, $D_0$</th>
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<td>7372</td>
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<tr>
<td>0.212 cm</td>
<td>576</td>
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$$D_m^{-1} = 0.23 (V_r / D_0)^{0.5} + 11 \rho_a V_r$$
Figure 5. - Variation of reciprocal mean drop diameter, $D_m^{-1}$, with airstream mass velocity, $\rho_a V_a$, for water sheets produced by impinging jet fuel injectors.
LIQUID FLOW RATE, $l$/hr

LIQUID VELOCITY, $V_1$, cm/sec

<table>
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<th>$V_1$</th>
<th>$Q$</th>
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<td>2313</td>
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<td>1542</td>
<td>46</td>
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</table>

IMPINGING JET, $D_0 = 0.212$ cm, FROM FIG. 5

$$D_m^{-1} = D_{m,0}^{-1} + \rho_a V_a$$

Figure 6. - Variation of reciprocal mean drop diameter, $D_m^{-1}$, with airstream mass velocity for water sheets produced by splash plate fuel injector.

(a) Q = 1.016 cm-inside-diameter fuel tube.

(b) Q = 2.16 cm-inside-diameter fuel tube.
Figure 7. - Variation of reciprocal mean drop diameter, $D_{\text{M,0}}^{-1}$, with liquid jet velocity in quiescent air ($V_a = 0$) for water sheets produced by splash plate fuel nozzles.

Figure 8. - Variation of reciprocal mean drop diameter, $D_{\text{M,1}}^{-1}$, with airstream mass velocity, $p_a V_a$, for swirling water sheets produced by simplex pressure atomizing nozzles.
Figure 9. - Variation of reciprocal mean drop diameter, $D_m^{-1}$, with liquid differential pressure, $\Delta P$, for swirling water sheets produced by simplex pressure atomizing nozzles.

Figure 10. - Variation of hydrodynamic reciprocal mean drop diameter, $D_h^{-1}$, with square root ratio of liquid jet velocity to orifice diameter for $n$-heptane sheets produced by impinging jet fuel injectors, with $V_f = 0$ and $D_0 = 0.74$ cm.
Figure 11. Variation of reciprocal mean drop diameter, $D_{30}$, with airstream relative mass velocity, $\rho_a V_r$, n-heptane sheets produced by impinging jet fuel injectors.

Figure 12. Variation of reciprocal mean drop diameter, $D_{30}$, with airstream mass velocity, $\rho_a V_a$, for n-heptane sheets produced by impinging jet fuel injectors.