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 air streams. 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: $D_o/D_m = 0.013 Re_l^{0.5} + 2 \times 10^{-3} Re_r$. With high velocity air streams, aerodynamic force contributed the most to breakup since $Re_r >> Re_l$. Liquid sheet breakup with splash plate fuel injectors gave the following expression: $D_o/D_m = 2.8 \times 10^{-4} Re_l + 2.4 \times 10^{-3} Re_a$, where $Re_a$ is airstream Reynolds number based on airstream velocity. Hydrodynamic force was much more effective in breakup with splash plates than with impinging jet fuel injectors since $D_o/D_m$ varied with $Re_l$ to the first power. Breakup of swirling water sheets formed with simplex pressure atomizing fuel nozzles gave the following expression: $D_o/D_m = D_{o,h}/D_{m,h} + 2.2 \times 10^{-3} (Re_l - Re_c)$, where $D_{o,h}$ and $D_{m,h}$ 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/sec - 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, $(\ln D_d/\ln D_o)^{0.33}$, cm
- $D_{32}$ Sauter mean diameter, $\ln D_d/\ln D_o^2$, cm
- $Fn$ flow number, $L/hr(N/m^2)^{0.5}$
- $k$ coefficient
- $\Delta P$ liquid differential pressure, $N/m^2$
- $Re_a$ airstream Reynolds number, $D_o V_a/\nu_a$
- $Re_c$ constant
- $Re_l$ liquid jet Reynolds number, $D_o V_l/\nu_l$
- $Re_r$ airstream relative velocity Reynolds number, $D_o V_r/\nu_a$
- $V$ velocity, cm/sec
- $\nu$ absolute viscosity, g/cm-sec
- $\nu_v$ 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 atom-
ization of liquid jets in airstreams. 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 rela-
tively low. However, when the velocity of the air-
stream 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 equals $10^3$.

In the present study of liquid sheet atom-
ization, the effect of hydrodynamic and aerodynamic
forces on mean drop diameter was studied in the
regimes of capillary-wave and acceleration-wave
breakup. Three general conditions of liquid sheet
atomization were investigated, namely, breakup in
quiescent air, in airstream of zero velocity rela-
tive 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 on liquid forces, and
atomization generally occurs in the capillary wave
breakup regime. In the second case, only hydro-
dynamic forces appreciably effect the mean drop dia-
meter since aerodynamic force is negligible. Break-
up 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,
aerodynamic force has the major effect on fine-
ness of atomization and breakup occurs primarily in
the acceleration-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 imping-
ing jet, splash plate and conventional simplex pres-
sure atomizing fuel nozzles. Non-swirling liquid
sheets were injected axially and radially in air-
streams 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 $V_{1}$ was
varied from 1.5 to 25.7 g/cm·sec at 293 K and
atmospheric pressure. Orifice diameters varied from
0.133 to 0.712 cm for the three different types of
fuel injectors. Water flow rates were 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) and determined with an i.c. 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·sec. The bellmouth test section
shown in Fig. 1 has a total length of 15.2 cm, an
inside diameter of a circular duct 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. 2(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 air-
flow 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 air 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 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
0.05- by 0.05-cm slit, a timing light, and a photo-
multiplier 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 tech-
nology 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 pres-
sure atomizing simplex nozzles.

Impinging Jet Fuel Injectors

The effect of airstream relative velocity $V_{r}$ on the reciprocal mean drop diameter
$D_{m}^{-1}$ is shown in Fig. 4 and the following expres-
sion is obtained:

$$D_{m}^{-1} = 0.043 (V_{r} V_{0})^{0.5} + 11 \rho V_{r}$$

where $V_{l}$ and $V_{r}$ are liquid velocity and
airstream velocity relative to the liquid velocity,
respectively. This expression may be rewritten in
terms of the dimensionless ratio of orifice to mean
airstream relative velocity Reynolds number $Re_{r}$
for hydrodynamic breakup as follows:

$$D_{m}^{-1} = 2 \times 10^{-3} Re_{1}^{0.5} + 2.0 \times 10^{-3} Re_{r}$$

since $V_{l} = 10.1 \times 10^{-3}$ cm/sec and $V_{r} = 1.8 \times 10^{-4}$ g/cm·sec. The mean drop diameter $D_{m}$
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, $D_m^{(h)}$, is equal to 110 and 10 for the 0.033 and 0.212 centimeter-diameter orifices, respectively. This occurs when $V_a = V_1$ and therefore $V_r = 0$. Also, Fig. 8 shows that when the data are extrapolated to the condition $V_a = 0$, then $D_m^{(h)}$ 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 $D_{m2}$ as follows:

$$\frac{D_{m2}}{D_{m2}} = 18.6 \times 10^{-3} R e_1^{0.5} + 1.55 \times 10^{-3} Re_a$$

(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 mass velocity, $\rho_a V_a$, range of 7.3 to 25.7 g/cm$^2$-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/cm$^2$-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, $\rho_a V_a$, for the 0.016 and 0.216 centimeter-diameter fuel tubes, respectively. Mean drop diameter data for $D_m$ give the following empirical relation:

$$D_m^{-1} = D_{m0}^{-1} + 13 \rho_a V_a$$

(4)

where $D_{m0}^{-1}$ is the value of $D_m^{-1}$ at $V_r = V_a = 0$. Since breakup data for the condition $V_a = 0$ was not obtained for the splash plate fuel injector, values of $D_{m0}$ were determined by extrapolating the data to $V_a = 0$. These values are then plotted against liquid jet velocity, $V_1$, as shown in Fig. 7 to give the following expression:

$$D_{m0}^{-1} = 0.028 V_1$$

(5)

for the hydrodynamic and aerodynamic breakup of water sheets in quiescent air, i.e. $V_r = 0$. At this condition, $D_{m0}^{-1}$ is directly proportional to the liquid jet velocity and independent of orifice diameter. This result is quite different from that obtained with impinging jets. Thus, the two expressions, Eqs. (4) and (1) cannot be compared directly since the first term on the right hand side of Eq. (1) is derived strictly for hydrodynamic breakup whereas $D_{m0}^{-1}$ 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:

$$D_m^{-1} = 0.028 V_1 + 13 \rho_a V_a$$

(6a)

which may be rewritten as follows:

$$D_m^{-1} = 2.8 \times 10^{-4} Re_l + 2.4 \times 10^{-3} Re_a$$

(6b)

Comparison of equation 6b for splash plate fuel injectors with Eq. (2) for impinging jets shows that hydrodynamic breakup varies with $Re_l$ to the first power in equation 6b and with $Re_a$ to the fifth power in 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. Thus for this study, $D_{m0}^{-1}$ data are plotted against mass velocity, $\rho_a V_a$, as shown in Fig. 8.

At the initial condition, $\rho_a V_a = 0$ and $D_m^{-1} = D_{m0}^{-1}$. 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 $D_{m0}^{-1}$ decreased until it reaches a minimum value of $D_{mh}^{-1}$ since relative velocity, $V_r$, 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/cm$^2$-sec for the small nozzles ($D_0 = 0.09$) there is only a slight increase in $D_{mh}^{-1}$. This intermediate region is primarily a capillary-wave breakup regime which is transformed into an acceleration-wave breakup as mass velocity is increased to the maximum value of 25.7 g/cm$^2$-sec. Thus, the following empirical expressions are derived from the data plotted in Fig. 8:

$$D_m^{-1} = D_{mh}^{-1} + 12(\rho_a V_a - \rho_c V_c)$$

(7a)

which may be rewritten as:
in this study for simplex Monarch nozzles producing water sprays at a cone angle of \(45^\circ\) 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 \(Re_l\) and aerodynamic force in terms of the airstream Reynolds number \(Re_a\) or the airstream relative velocity Reynolds number \(Re_v\) 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, \(D_0/D_m = 0.023 Re_l^{0.5} + 2 \times 10^{-3} Re_v\), and with high velocity airstream, aerodynamic force contributed the most to breakup since \(Re_v > Re_l\).

2. Splash plate fuel injectors gave the empirical relationship, \(D_0/D_m = 2.9 \times 10^{-4} Re_l + 2.4 \times 10^{-3} Re_v\), 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 \(Re_v\) to the first power.

3. Simplex pressure atomizing fuel nozzles gave the empirical relationship, \(D_0/D_m = 0.0182 + 2.4 \times 10^{-3} (Re_l - Re_v)\), \(D_0\) and \(D_m\) are the liquid jet velocity \(V_1\) and orifice diameter respectively. A straight line

\[
\Delta \theta = D_0/100 \times 10^{-3} (Re_l - Re_v) + 2 \times 10^{-3} Re_v
\]

\[
D_0 = k \left( \frac{p_{in}}{m} \right)^{0.30}
\]

where \(k\) is a constant for a given simplex fuel nozzle. By assuming \(D_0/k\) to be a function of the nozzle flow number \(F_n\), the coefficient \(k\) is evaluated to give the following correlating expression for the two simplex fuel nozzles:

\[
D_0 = 0.74 F_n^{0.34} p_{in}^{0.27}
\]

Mean droplet diameters were obtained with a light scattering instrument and keroseen sprays were produced with simplex Delavan nozzles having a cone angle of \(45^\circ\) and flow numbers ranging from 0.0182 to 0.0244. Comparison of Eqs. (9) and (10) shows agreement for the flow number and \(D_0\) agree very well. Also, the coefficients in the two equations are approximately the same. However, the coefficients cannot be compared directly since Eq. (9) was derived

\[
D_0 = 0.74 F_n^{0.34} p_{in}^{0.27}
\]
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, $D_{30} / h$, as follows:

$$\frac{D_{30}}{h \cdot \text{Re}_1} = 0.024 \text{Re}_{1/2}$$

(17)

Since $\text{Re}_1 = \frac{D_{30} \cdot V_{j}}{V_{j}}$ and $V_{j} = 0.0061 \text{cm}^2/\text{sec}$ 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:

$$D_{30} = 0.31 \left( \frac{V_{j}}{V_{r}} \right)^{0.5} + 11 \sigma_{V} V_{r}$$

(13)

where $\sigma_{V}$ 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 $V_{r} = 0$, the following expression is obtained: $D_{30} / h = 11 \sigma_{V}$ since $D_{30} / h$ is evaluated at $V_{r} = 0$. Then as $V_{r}$ increases $V_{r}$ decreases until $V_{r} = 0$ and the value of $D_{30}$ decreased as given by Eq. (11). Further increases in $V_{r}$ increases $V_{r}$ and values of $D_{30}$ increase as given by Eq. (13). The minimum value of $D_{30}$ at $V_{r} = 0$ 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, $\sigma_{V} \text{Re}_{1} > 10$ is recommended when using impinging jet fuel injectors.

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

$$\frac{D_{30}}{D_{30}^{*}} = 0.074 \text{Re}_{1/2}^{0.5} + 2.0 \times 10^{-3} \text{Re}_{1/2}$$

(14)

since $D_{30} = 1.84 \times 10^{-4} \text{gcm}^{-3}$. In terms of the Sauter mean drop diameter $D_{32}$, the expression may be rewritten as follows:

$$\frac{D_{30}}{D_{32}} = 18.6 \times 10^{-3} \text{Re}_{1/2}^{0.5} + 1.55 \times 10^{-3} \text{Re}_{1/2}$$

(15)

since $D_{32} = 1.74 D_{30}$ 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.
Figure 5. - Variation of reciprocal mean drop diameter, $D_m^{-1}$, with airstream mass velocity, $p_a V_a$, for water sheets produced by impinging jet fuel injectors.
Figure 6. - Variation of reciprocal mean drop diameter, $D_m^{-1}$, with airstream mass velocity for water sheets produced by splash plate fuel injector.
Figure 7. Variation of reciprocal mean drop diameter, $D_{m}^{-1}$, with liquid jet velocity in quiescent air ($V_a = 0$) for water sheets produced by splash plate fuel injectors.

Figure 8. Variation of reciprocal mean drop diameter, $D_{m}^{-1}$, 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, $D_{m,0}^{-1}$, with liquid differential pressure, $\Delta P$, for swirled water sheets produced by simplex pressure atomizing nozzles.

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

Figure 12. - Variation of reciprocal mean drop diameter, $D_{30}^{-1}$, with airstream mass velocity, $p_{a}V_{a}$, for n-heptane sheets produced by impinging jet fuel injectors.