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Experimental Study of the Spray Characteristics of a Research Airblast Atomizer

Waldo A. Acosta
Propulsion Laboratory
AVSCOM Research and Technology Laboratories
Lewis Research Center
Cleveland, Ohio

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Waldo A. Acosta
Propulsion Laboratory
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Lewis Research Center
Cleveland, Ohio

ABSTRACT
An experimental study of airblast atomization was conducted using an especially designed atomizer in which the liquid first impacts on a splash plate, then is directed radially outward and is atomized by the air passing through two concentric, vaned swirlers that swirl the air in opposite directions. The effect of flow conditions, air mass velocity (mass flow rate per unit area, \( \rho \dot{A}U \)) and liquid to air ratio on the mean drop size was studied. Seven different ethanol solutions were used to simulate changes in fuel physical properties. The range of atomizing air velocities was from 30 to 80 m/s. The mean drop diameter was measured at ambient temperature (295 K) and atmospheric pressure.

NOMENCLATURE
- \( D_p \): prefilmer diameter, m
- \( \text{PE} \): peak of the weight distribution
- \( R_0 \): Reynolds number, \( \rho \dot{A}U/\mu \)
- \( \text{SMD} \): Sauter mean diameter, m
- \( \dot{U} \): velocity, m/s
- \( \dot{W} \): mass flow rate, kg/s
- \( \dot{W}' \): width of the weight distribution
- \( \text{Me} \): Weber number, \( \dot{W} \sqrt{\rho} \)
- \( \rho \): density, kg/m³
- \( \gamma \): gamma function
- \( \sigma \): surface tension, kg/s²
- \( \nu \): dynamic viscosity, kg/ms
- \( q \): efficiency factor

Subscripts:
- A: air
- L: liquid

INTRODUCTION
The fuel spray characteristics have a great influence on the performance of gas turbine combustors. A change in the flow conditions or in the physical properties of the fuel produces a change in the spray characteristics of the fuel injector. The latter will have a greater influence in the future when the supply of high-quality fuels cannot be satisfied and fuels with different physical properties must be used. During the past few decades many researchers have studied the effect of liquid properties and flow conditions on atomization and found empirical equations for the type of fuel injector investigated.

The work of Radcliffe (1) showed that for a swirl atomizer the degree of atomization depends on the viscosity, surface tension, mass flow rate and pressure drop of the fuel. He found the exponents 0.6, 0.2, 0.25, and -0.4 for the surface tension, viscosity, mass flow rate, and pressure drop, respectively.

Usajua (2) worked on fuels having surface tensions ranging in viscosity from 1.0x10⁻⁴ to 93.0x10⁻⁴ m²/s finding a different power for the viscosity, 0.16. He observed the same power for the surface tension, 0.6, but the variation was only 20 percent and was accompanied by a large variation in viscosity.

Simmons and Harding (3) studied the atomizing performance of six simplex pressure-atomizers using water and kerosene, liquids with almost the same viscosity, a 30 percent difference in density and a water surface tension three times higher. They concluded that any difference in Sauter Mean Diameter (SMD) was due to the difference in surface tension rather than density. It was found that the power for the surface tension is 0.16 for a constant liquid pressure and 0.19 if the mass flow rate was held constant.

Merrington and Richardson (4) found that the SMD for a plain-orifice atomizer was proportional to the
viscosity of the fuel raised to the 0.2 power and inversely proportional to the fuel velocity. For liquid jet axis-flow airstreams, Ingebo (5) found that the mean drop diameter was proportional to the product of the Weber and Reynolds numbers (We/Re) raised to the 0.28 power for We/Re > 100 and proportional to the 0.4 power for We/Re < 100.

Fraser, Bonkowski and Routley (8) studied the rotary atomizer. Their studies showed that the SMD is a combination of a constant plus a term including the effects of surface tension, kinetic viscosity, mass flow rates and the relative velocity of the air and the fuel. The powers 0.5 and 0.21 were found for surface tension and kinetic viscosity, respectively. Using a range of disc types, Friedman, Gluckert and Marshall (7) correlated their results for SMD in terms of the operating and liquid variables in dimensionless groups. These groups present the viscosity raised to the 0.6 power, the surface tension raised to the 0.2 power and the surface tension and kinematic viscosity, respectively. The effect of mass velocity (mass flow rate/unit area, \( \frac{\text{mass}}{\text{area}} \)) on SMD for the fuel injector modules investigated is clearly shown in Figs. 4 and 5. The Malvern instrument is a nonintrusive optical system based on the Fraunhofer diffraction of a parallel monochromatic light beam scattered by moving droplets. The transmissive portion of the Malvern instrument houses the 2-mW helium-neon laser and beam expander, which emits an approximately 9-mm-diameter beam. The receiver consists of a focusing lens (Fourier transform lens), a multielement photoelectric detector, beam alignment knobs, lamps, and an indicator. A computer with an 8 K memory receives, stores, and processes data inputs from the detector. A teleprinter with a hard copy printer is used for data output. The output is discussed in the appendix. Two data points were taken at each condition and stored in the computer memory. Measurements were made at the center line of the spray at a distance of 7.62 cm downstream of the fuel injector module.

RESULTS AND DISCUSSION

Mass Velocity

The effect of mass velocity (mass flow rate per unit area, \( \frac{\text{mass}}{\text{area}} \)) on SMD for the fuel injector modules investigated is clearly shown in Figs. 4 and 5. These figures show in general that the SMD decreases with an increase in the mass velocity. The same effect was observed for both modules. Changes in mass velocity were obtained by changing the total air flow rate through the injector modules while keeping the available flow area (including both swirlers) constant. The range of mass velocities was from 37 to 113 kg/sec and the calculated flow area was 6.47 \( \times 10^{-4} \) m² for injector module 1 and 4.51 \( \times 10^{-4} \) m² for injector module 2. The area was calculated at the upstream side of the injector modules.

Liquid to Air Ratio

Tests were conducted to study the effect of liquid to air ratio on SMD. These tests covered a range of liquid to air ratios from 0.0147 to 0.0462 for module 1 and from 0.0220 to 0.0636 for module 2. Figures 6 and 7 show no effect of the liquid flow rate on SMD when
the air velocity rate is kept constant at different concentrations of ethanol.

**Liquid Properties**

Many tests were made to determine the atomizing performance of two especially designed fuel injector modules operating with liquids of different physical properties. A number of aqueous solutions of ethanol were prepared representing the following range of liquid properties:

- **Surface tension**: 0.0290 to 0.0555 kg/s²
- **Dynamic viscosity**: 0.001226 to 0.002684 kg/ms
- **Density**: 890.7 to 988.0 kg/m³

Samples of the solutions were analyzed using standard laboratory techniques to measure surface tension, viscosity and density. Table 1 presents the results of these measurements.

The effect of ethanol concentration on SMD for the fuel modules studied is shown in Fig. 8. Both figures show a decrease in the SMD with an increase in the ethanol concentration, i.e., decrease in surface tension.

Figure 8 shows a comparison between data from Ref. 12 for an airblast atomizer and data from this investigation. Both fuel injector modules produced smaller droplets than the airblast atomizer for the same air velocity, 60 m/s. The only difference is the liquid flow rate, but Figs. 6 and 7 showed the SMD is not affected by changes in the liquid to air ratio. This figure shows the benefits created by the high shearing action between the flows exiting the counter rotating air swirlers compared with the airblast atomizer of Ref. 12. Note that the liquid surface tension was used as a parameter because the liquid used in Ref. 12, aqueous solutions of Butan-2-ol, have almost the same physical properties.

**Linear Scale**

Two identically designed fuel injector modules were used in this investigation. The only difference was the size and the number of swirler vanes (Fig. 3). Module 2 is approximately 20 percent smaller in diameter than module 1, having a prefilmer diameter, Dp, of 1.2 and 1.3 cm, respectively. The influence of atomizer scale on SMD is illustrated in Fig. 9. This figure shows module 2 producing smaller droplets than module 1 under the same operating conditions.

**Data Analysis**

The experimental data gathered in this investigation were correlated using the basic equation derived by Lefebvre (8) with the experimental constants of Ref. 13:

\[
\text{SMD} = \left( \frac{q}{pA} \right)^{0.6} \left( \frac{U}{U_A} \right)^{0.1} \left( \frac{p}{p_A} \right)^{0.4} + 0.015 \frac{2D}{U_A D_L} \left( 1 + \frac{U_L}{U_A} \right)
\]

As stated in Ref. 13, the experimental constants 0.073 and 0.015 may have to be modified by an efficiency factor, \( \phi \), whose values will depend on the atomizer design, and will take into account the presence of extraneous devices, such as air swirlers, and the different methods of drop size measurement. Figures 10 and 11 compare the SMD measured in the present investigation with values predicted by Eq. (1). Good agreement is shown in Fig. 11 for a value of \( \phi \) of 0.59.

Figure 10 shows good agreement in the high velocity region for the same value of \( \phi \), but does not describe the experimental data very well in the intermediate to low velocity region i.e., less than 60 m/s, corresponding to drop sizes greater than 60 \( \mu \).

**SUMMARY AND CONCLUSIONS**

An experiment was conducted at atmospheric pressure to determine the effect of liquid physical properties and flow conditions on the Sauter Mean Diameter, SMD, using two geometrically-similar research airblast atomizers designed for high pressure and temperature combustors.

After studying the effects of the different variables involved in this investigation it is found that:

1. The SMD of the spray decreases with increases in ethanol concentration due to changes in the physical properties as shown in Table 1.

2. Increasing the air velocity decreases the SMD which varied inversely with air velocity, of all the variables, air velocity has the most dominant effect on the atomization process of the fuel injector modules investigated.

3. An increase in atomizer scale increases the mean drop diameter.

4. The air to liquid ratio has no measurable effect on the SMD of sprays produced by any of the two fuel injector modules.

5. The SMD performance of the airblast atomizers, when spraying in stagnant air at atmospheric pressure, is predicted with a reasonable degree of accuracy by the correlation:

\[
\text{SMD} = \left( \frac{q}{pA} \right)^{0.6} \left( \frac{U}{U_A} \right)^{0.1} \left( \frac{p}{p_A} \right)^{0.4} + 0.025 \frac{2D}{U_A D_L} \left( 1 + \frac{U_L}{U_A} \right)
\]

for the following range of test conditions

- **Surface tension**: 0.0290 to 0.0555 kg/s²
- **Dynamic viscosity**: 0.001226 to 0.002684 kg/ms
- **Density**: 890.7 to 988.0 kg/m³
- **Air velocity**: 30 to 80 m/s
- **Liquid to air ratio**: 0.0147 to 0.0776

Air density was not varied appreciably.

**REFERENCES**


APPENDIX - OUTPUT FROM THE MALVERN S.T. 1000 PARTICLE AND DROPLET SIZE DISTRIBUTION ANALYZER

The Malvern instrument is a noninvasive optical system based on the laser diffraction principle. This instrument uses the Rosin-Rammler weight distribution model. The Rosin-Rammler distribution is defined as follows

$$P(x) = \frac{W' x W' - 1}{PE} \exp \left\{ - \frac{(x/PE)^W'}{PE} \right\}$$

where $P(x)$ is the weight or volume fraction of particles in the range $x$ to $x + dx$ where $x$ is in microns. The parameters $PE$ and $W'$ characterize the peak of the weight distribution and its width. $PE$ is in microns and $W'$ is a dimensionless number usually in the range from one for very wide weight distributions to 10 for very narrow weight distributions. The values of the two parameters, $PE$ and $W'$, which give the minimum error, define the size distribution. Using the values of $PE$, $W'$ and the gamma function the Sauter Mean Diameter (SMD) can be calculated. The following formula is used

$$SMD = PE \frac{W'}{\Gamma(1 - \frac{1}{W'})}$$

where SMD is in microns and $\Gamma$ is the tabulated gamma function.

Figure 13 shows an example of the output. The first line of output is the peak PE, width $W'$, and error E of the distribution. The first column gives the droplet size ranges in microns. The next three columns are the spray distributions as percent weight fraction, cumulative percent by weight, and normalized percent by number density. The last two columns are the calculated and actually measured energy distributions.
### TABLE I. LIQUID PROPERTIES

<table>
<thead>
<tr>
<th>Level tested</th>
<th>Solution percent ethanol</th>
<th>$\mu$, kg/ms</th>
<th>$\alpha$, kg/s$^2$</th>
<th>$\rho$, kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0.001226</td>
<td>0.0555</td>
<td>988.0</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>0.001264</td>
<td>0.0530</td>
<td>985.3</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.001438</td>
<td>0.0485</td>
<td>980.8</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>0.001973</td>
<td>0.0395</td>
<td>969.4</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>0.002468</td>
<td>0.0340</td>
<td>952.4</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>0.002684</td>
<td>0.0325</td>
<td>936.0</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>0.002424</td>
<td>0.0290</td>
<td>890.7</td>
</tr>
</tbody>
</table>
Figure 2. - Test facility.
Figure 3 - Schematic of fuel modules.

<table>
<thead>
<tr>
<th>MODULE</th>
<th>Dimension cm</th>
<th>Dp</th>
<th>D0</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODULE 1</td>
<td>1.5</td>
<td>0.084</td>
<td>2.2</td>
<td>3.6</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>MODULE 2</td>
<td>1.2</td>
<td>0.084</td>
<td>1.8</td>
<td>2.9</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>

- **Fuel**
- **Airflow through fuel-module air**
- **Number of vanes**

The diagram shows two modules, Module 1 and Module 2, with labeled dimensions and features.
Figure 4. - Relationship between SMD and mass velocity for different concentrations of ethanol for Module 1.

Figure 5. - Relationship between SMD and mass velocity at different concentrations of ethanol for Module 2.
Figure 6. - Variation of SMD with liquid to air ratio at a constant atomizing air velocity for Module 1. $U_A = 60$ m/s.

Figure 7. - Variation of SMD with liquid to air ratio at a constant atomizing air velocity for Module 2. $U_A = 60$ m/s.
Figure 8. - Comparison between an airblast atomizer and the fuel injector modules. \( U_A = 60 \text{ m/s} \).
Figure 9. - Effect of linear scale on SMD. $U_A = 60$ m/s.
Figure 10. - Comparison of measured and predicted values of SMD from equation (2), Module 1.

Figure 11. - Comparison of measured and predicted values of SMD from equation (2), Module 2.
Figure 12. - Example of output from Malvern particle and droplet size distribution analyzer.

> PE = +102.0  W = +2.4  E = 00313752

D = +562.86 > +261.71  P = +0.01%  R = +99.99%  N = +0.00%  C = 0698  A = 0756
D = +261.71 > +160.29  P = +5.18%  R = +94.91%  N = +0.05%  C = 1005  A = 1157
D = +160.29 > +112.86  P = +22.76%  R = +72.05%  N = +0.54%  C = 1380  A = 1424
D = +112.86 > +84.29  P = +25.17%  R = +46.88%  N = +1.60%  C = 1707  A = 1646
D = +84.29 > +64.57  P = +18.50%  R = +28.38%  N = +2.73%  C = 1970  A = 1780
D = +64.57 > +50.29  P = +11.64%  R = +16.74%  N = +3.74%  C = 2044  A = 2002
D = +50.29 > +38.86  P = +7.34%  R = +9.39%  N = +5.05%  C = 1980  A = 2047
D = +38.86 > +30.29  P = +4.11%  R = +5.28%  N = +6.06%  C = 1783  A = 2002
D = +30.29 > +23.71  P = +2.31%  R = +2.97%  N = +7.14%  C = 1542  A = 1869
D = +23.71 > +18.57  P = +1.31%  R = +1.66%  N = +8.42%  C = 1303  A = 1557
D = +18.57 > +14.57  P = +0.73%  R = +0.93%  N = +9.77%  C = 1067  A = 1112
D = +14.57 > +11.43  P = +0.41%  R = +0.52%  N = +11.39%  C = 0867  A = 0623
D = +11.43 > +9.14  P = +0.22%  R = +0.31%  N = +12.08%  C = 0691  A = 0356
D = +9.14 > +7.14  P = +0.14%  R = +0.17%  N = +15.39%  C = 0541  A = 0222
D = +7.14 > +5.71  P = +0.07%  R = +0.10%  N = +16.06%  C = 0419  A = 0178