ABSTRACT

Experimental studies were performed to investigate the size distribution of liquid droplets produced in highly energetic atomization processes. Two atomization processes were studied: 1 – break-up of high-velocity jets discharged into stagnant air, and 2 - airblast sprays operated under high ambient air velocity conditions. In the jet atomization experiments, small amounts of explosive compound were used to eject test liquids at velocities up to almost 500 m/s through a 9.5 mm diameter discharge opening. Droplet size distributions obtained were found to be consistent within the range of test conditions and relatively narrow, described well with the log-normal frequency distribution function and having a geometric standard deviation of approximately 1.8. A number of correlations available in the literature for calculating the mean drop diameters were evaluated.

The airblast spray tests were performed in Battelle’s Ambient Breeze Tunnel (ABT), a 20x20x150 ft³ flow structure capable of maintaining airflow of up to 4.5 mph and also equipped with a high-velocity airflow module for simulating such processes as aerial application of agricultural chemicals. The high air velocity module generated winds up to 190 mph around the nozzle. Drop size distributions were measured using Phase Doppler Anemometry. For the high ambient-velocity airblast atomization process, the Nukiyama-Tanasawa distribution function was found to agree well with the test results.

Keywords: Liquid Atomization, High Velocity Jet, Airblast Spray, Droplet Size Distribution

1. INTRODUCTION

Atomization of liquids using spray nozzles is a complex process in which droplets are formed as a combined effect of several different mechanisms. While some of these mechanisms are more systematic and can be described based on the deterministic laws of physics, some other mechanisms are rather random in nature and require stochastic methods of analysis for predicting their effects. It is of a fundamental interest to better understand the disintegration behavior of high velocity jets, especially those close to the speed of sound in the air.

As a result of the complexity of most liquid atomization processes, droplet size distributions are usually assessed using empirical and semi-empirical correlations obtained in certain experimental studies. Because of the empirical nature of such correlations, their validity is not readily extendable beyond the conditions used in the experiments.

The main purpose of this paper is to present experimental data on liquid atomization obtained for highly energetic processes involving relatively large, high-velocity liquid jets and assess currently available droplet size distribution correlations with regard to aerodynamic disintegration of such jets.

2. LIQUID JET ATOMIZATION

2.1 Experimental Apparatus and Study Approach

This study was performed to investigate the aerodynamic breakup of a high velocity liquid jet discharged through a relatively large-diameter opening. To achieve this objective, a test device was constructed in which a known amount of liquid is ejected in a short time interval with a piston driven by highly pressurized gas. Figure 1 shows a schematic drawing of the test device used in this work.

Figure 1. Schematic of the Jet Atomization Test Device

In principle, the device consisted of two 2.54 cm (1 inch) diameter compartments separated by a plastic piston; one of the compartments contained the test liquid and the other compartment was used to generate high pressure gas needed for driving the piston. A small amount of explosive was used to achieve instantaneously the pressure required in the gas compartment. Volume of the liquid compartment was approximately 27 cm³; volume of the gas compartment was approximately 80 cm³. The test liquid was sealed in the first chamber with a piece of thin Mylar film, attached at
the inner surface of a 2.54 cm thick plate. The plate contained a 9.525 mm (0.375 in) diameter liquid discharge opening. A Reynolds RP-80 Exploding Bridgewire Detonator (EBW) was utilized to initiate small amounts of Ensign Bickford 2 gm/in² Primasheet explosive. The liquid ejection apparatus was set up in an aerosol containment chamber built to facilitate undisturbed gravitational deposition of small liquid drops on the floor, which was used for direct and accurate measurements of the overall size distribution of spray droplets. The chamber was 24-foot long, 10-foot wide, and 8-foot high. Two fans were installed in the chamber to achieve even distribution of fine aerosol particles in the air, which were operated after the large droplets had settled on the floor.

The floor of the chamber was covered with a large pre-weighted polyethylene sheet for collecting the drops. Twenty-five 37-mm diameter glass slides were strategically positioned on the drop collection sheet, analysis of which was used to determine the size distribution functions for the liquid sprays.

An Aerodynamic Particle Sizer (Model APS-33) manufactured by TSI, Inc., was set up in the chamber to monitor fine airborne droplets with aerodynamic diameters down to 0.5 μm. Aerosol samples were also collected using four 47-mm filters (Millipore 0.5 μm, type FH), which were positioned in the corners of the test chamber for determining the average particle mass concentration and assessing if the aerosol was evenly mixed throughout the chamber. It was found, however, that contribution of persistent aerosol particles was minimal to the overall size distribution of the jet spray.

The tests were conducted using a liquid composition based on diethyl phthalate (DEP), which had the following physical properties: density $\rho = 1208$ kg/m³, dynamic viscosity $\mu = 0.088$ kg/ms, surface tension $\sigma = 35$ dyne/cm.

In this work, the effects of jet exit velocity and ejection pressure on the distribution of droplet diameters were addressed. Accordingly, two liquid discharge parameters were measured – pressure history in the gas compartment of the test device and jet initial velocity. The pressure was recorded with a Kistler 211B2 ballistic piezoelectric pressure transducer, having 0.1 μsec time resolution. It was set to transmit data to the oscilloscope for pressures of up to approximately 48 MPa (7,000 psi).

It should be noted that the test apparatus was not designed to strictly maintain constant pressure in the gas compartment, which would require using more sophisticated design. Therefore, since most of the liquid was assumed to eject at the initial stage of the process, when maximum pressure value was measured in the gas compartment, the peak pressure was used in subsequent analyses.

Hewlett Packard 150kV flash radiograph instrumentation was used to accurately measure the initial velocity of the jet. This equipment was set up to generate two consecutive X-ray images of the jet, separated by a precisely controlled time interval. The images were taken at 500 μsec and 650 μsec after detonation, resulting in a 150 μsec time interval between them. Then, measuring the distance the tip of the jet has traveled during this time interval, initial jet velocity can be determined. In this work, jet velocities were found using this approach to range from approximately 140 m/sec to as high as 470 m/sec. Figure 2 shows a single video frame of the jet (left picture, taken at 30 frames/second), during which the entire amount of liquid was discharged, and a representative X-ray radiograph obtained in this work (right picture), which corresponded to a 314 m/sec jet exit velocity. It should also be noted that the X-ray images visualize the densest structures of the jet, not showing the fine aerosol cloud seen in the video frame.

Droplet size distributions were obtained for each test using image analysis software PC_Image® Version 2.2. Each of the twenty-five drop deposition glass slides collected in a test was first inspected under a Zeiss Ultrafot III microscope manufactured by Oberkochen/Wuertt, Germany, after which their representative view fields were photographed under 10X magnification. Figure 3 shows a representative photomicrograph of the droplets deposited on one of the slides as well as droplets’ digital representations.
For each droplet on a photograph, an equivalent diameter of its image, $d_{\text{image}}$, was calculated from the corresponding footprint area assuming that the image has circular shape. After that, the mass of the droplet was evaluated using an empirical correlation (Eq. 1), obtained from a series of simple experiments that related liquid drop masses to the equivalent diameters of their images:

$$m = 3 \cdot 10^{-4} \cdot d_{\text{image}}^{3.0149} \quad (1)$$

where:
- $d_{\text{image}}$ is the footprint diameter of a drop deposited on a slide (mm),
- $m$ is the droplet mass (g).

From the mass of the droplet, and using liquid density, droplet diameter ($d$) was calculated assuming its spherical shape. Droplet diameters were thus determined for all the images and then imported into the SigmaPlot® software and combined with the other slides to generate the overall droplet size distribution histogram for a test. The slides were combined using their weights to weigh their contributions to the overall size distribution density. Mass balance calculations were performed using these data, which resulted in an average balance closure of 95.1%. An example histogram depicted in Figure 4 shows a typical drop size distribution frequency obtained from these measurements.

### 2.2 Mean Drop Diameter of Jet Spray

A total of 16 tests were performed in this work; jet exit velocities were obtained in 14 of the tests conducted. Table 1 summarizes the test conditions and the spray droplet test results.

Based on these measurements, no systematic correlation was observed between $m_{\text{md}}$ and $V_{\text{jet}}$ in the high-velocity range of jet conditions; in fact, the data were found to scatter about an average $m_{\text{md}}$ of approximately 126 $\mu$m, with a standard deviation ($\sigma_{m_{\text{md}}}$) of 24 $\mu$m.
Table 1. Jet Atomization Test Conditions and Measurement Results

<table>
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<tr>
<th>Test #</th>
<th>% mass recovered</th>
<th>V&lt;sub&gt;jet&lt;/sub&gt; m/sec</th>
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<th>mmd µm</th>
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A total of 11 correlations available in the literature were evaluated with regard to their ability to predict the size distributions of spray droplets measured in this work [1-11]. All correlations in which jet velocity appeared as an independent variable predicted significantly larger average droplet sizes for the test conditions used.

One correlation, suggested by Merrington and Richardson [1] (see Eq. 2), was found to give reasonable estimates of the mmd for jets approaching and exceeding the speed of sound in the air; it should be pointed out, however, that this correlation was proposed for estimating the mode of the distribution, which corresponds to a smaller droplet diameter than mmd:

\[
d_{\text{mode}} = \frac{500 \left( \frac{\mu}{\rho} \right)^{0.2}}{V_{\text{jet}}} \tag{2}
\]

Equation 2 is an empirical correlation obtained using the CGS system, where:
- \(d_{\text{mode}}\) is the modal diameter, cm,
- \(\mu\) is the dynamic viscosity of liquid, g/(cm sec)
- \(\rho\) is the density of liquid, g/cm\(^2\), and
- \(V_{\text{ave}}\) is the jet exit velocity, cm/sec.

From the review of available correlations performed in this work, the best fit to the experimental data was obtained using the following correlation (developed by Elkotb [3] for plain-orifice atomizers):

\[
smd = 3.08 \left( \frac{\mu}{\rho} \right)^{0.385} \left( \sigma \rho \right)^{0.737} \left( \sigma \rho \right)^{0.06} \left( \frac{\Delta P}{\rho_{\text{air}}} \right)^{0.54} \tag{3}
\]

Note that Eq. 3 is also an empirical correlation, but obtained using the SI system, where:
- \(smd\) is the Sauter mean diameter, m,
- \(\sigma\) is liquid surface tension, N/m,
- \(\rho_{\text{air}}\) is air density, kg/m\(^3\), and
- \(\Delta P\) is pressure differential across the nozzle, N/m\(^2\).

Droplet diameters predicted using Eq. 3 for the test conditions are shown in Figure 5 using the solid line. It should be noted again that although the Elkotb correlation appears to predict the mmd of the jet sprays reasonably well, considering also the scatter of the test data, this correlation was actually developed for calculating the Sauter mean diameter, which is different from and smaller than the mmd plotted in Figure 5.

2.3 Droplet Size Distribution of Jet Spray

An analysis was also performed of the distribution of droplet diameters around their average values. A representative histogram of the droplet size distribution frequencies obtained in the experiments is shown as a bar chart on Figure 6.

Two analytical functions were evaluated in this analysis: the log-normal distribution function (Eq. 4) and the Nukiyama-Tanasawa type distribution function (Eq. 5).

\[
dV = \frac{1}{\sqrt{2\pi} \cdot d \cdot \ln(\sigma_d)} \cdot \exp \left[ \frac{-0.5 \ln^2 \left( \frac{d}{mmd} \right)}{\ln^2(\sigma_d)} \right] \tag{4}
\]

where \(dV\) is the volume fraction of droplets having diameters in the range \(d(d)\).

In this work, considering the log-normal distribution function, an average value of the geometric standard deviation (\(\sigma_d\)) was found to be 1.805 (\(\sigma_d\) varied around this average value of 1.805 with a standard deviation of 0.232).
no clear trend, or correlation was identified for $\sigma_g$ with respect to the test variables used. As a representative example, Figure 6 shows a plot of the log-normal distribution frequency, using the blue solid line, which was obtained using the experimentally determined $mmld$ and $\sigma_g = 1.8$. Qualitatively, this plot suggests that the log-normal distribution function describes our experimental results reasonably well.

The Nukiyama-Tanasawa type distribution function examined was based on the work of Li and Tankin [12]. According to their work, for a completely random formation of spray droplets around some representative size, a droplet size distribution will develop that maximizes the so-called information entropy, which results in the following equation:

$$
\frac{dV}{d(d)} = \frac{3d^5}{(\Gamma_{5/3} \cdot smd)^3} \exp\left(-\frac{d}{\Gamma_{5/3} \cdot smd}\right)
$$

where: $\Gamma_{5/3}$ is the gamma function of 5/3, which gives a value of approximately 0.9027.

Results of calculations performed using Eq. 5 are also plotted in Figure 6. These calculations were performed for this particular test using both the experimentally determined $smd$ of approximately 75 $\mu$m (dash-dotted curve), as well as an $smd$ predicted by Eq. 3, i.e., 120 $\mu$m (dashed curve). As shown in Figure 6, the Nukiyama-Tanasawa type distribution function results in a more narrow distribution of droplet diameters, which would more likely correspond to an ideal atomization process in which the droplets are generated about $smd$ through a purely stochastic process. Many nozzles will produce distributions that are broader than the one described by Eq. 5, in part due to the presence of some “order” in the atomization mechanism (e.g., existence of the core and boundary regions of the jet flow), which therefore results in a spray process that is not perfectly random.

3. HIGH-WIND AIRBLAST ATOMIZATION

The second phase of the study involved using a typical prefilming airblast atomizer under conditions simulating an aerial application of agricultural chemicals. In this work, a series of experiments was performed to assess the effect of high external airflow on the size distribution of droplets generated by the atomizer.

The tests were conducted in Battelle’s Ambient Breeze Tunnel (ABT, shown in Figure 7), equipped with a High Velocity Duct (HVD) for performing large-scale spray research under high ambient flow conditions. ABT is approximately 150 ft long, 20 ft wide at the base, and 20 ft high at the top point. It is equipped with an air handling system supplying up to 70.8 m$^3$/sec of air (150,000 cfm), which is filtered before being exhausted from the facility. The HVD system provides a localized high-velocity air stream capable of reaching velocities of ~85 m/s (190 mph).

The airblast atomizer was tested using water, under both still-air and high velocity ambient conditions. Droplet size distribution measurements were performed using a Dantec Particle Dynamics Analyzer (PDA).

First, a series of airblast atomization tests was performed under still-air conditions, during which a non-dimensional ratio of water spray rate to the rate of pressurized air supply to the nozzle, i.e., liquid-to-air ratio, or LAR, was varied.
The LAR was chosen as the test variable based on the well-recognized correlation between mmd and this ratio (see, e.g., [13]). The results of the still-air tests are presented in Figure 8 using the open symbols, plotted as mmd vs. (1+LAR). Consistent with the literature, the mmd was found to increase linearly with LAR.

Another series of tests was performed in the ABT using the HVD facility, simulating aerial application of the airblast atomizer. The results of these experiments are also plotted in Figure 8, using the solid symbols. According to these results, the presence of high-velocity wind appears to considerably reduce the mass median diameter of water droplets compared to those generated under still-air conditions. The simulated flight results shown in Figure 8 were obtained using three different wind velocities, i.e., 150 mph, 170 mph, and 190 mph. It appears, however, that in this range of ambient airflow conditions, increasing air velocity from 150 to 190 mph does not provide any noticeable additional reduction in the spray droplet size. The MMD measured were on the order of 20 µm for the high-wind conditions used in this study.

In both cases, i.e., with and without high-velocity wind, there is a linear dependence of MMD on the LAR; however, as may have been expected, it is considerably less pronounced in the presence of high-velocity ambient airflow. Thus, the high-velocity wind conditions that develop around the nozzle during aerial application of agricultural chemicals were found to significantly contribute to the performance of airblast atomizers, and effectively lessening the influence of the nozzle’s own internal air flow characteristics.

With respect to the distribution of spray droplet diameters, the Nukiyama-Tanasawa distribution function (Eq. 5) was applied to several tests performed under this study, a typical example of which is shown in Figure 9. As can be seen, the maximum entropy method does not appear to be applicable to the airblast atomizer spraying water under still-air conditions, since the experimental droplet size distribution frequency is significantly broader than that based on the maximum entropy concept. As mentioned above, this is likely a result of some systematic processes that take place in the droplet formation mechanism.

As opposed to the still-air testing, the high-wind test conditions resulted in a reasonable agreement between the experimental droplet size distribution and that predicted using Eq. 5, which is illustrated in Figure 10. This agreement suggests that formation of spray droplets during spraying water under high ambient airflow conditions is controlled by more spontaneous phenomenology. In this case, in the presence of the high-velocity air flow, the nozzle specifics are less important in controlling the droplet formation phenomena, which is also consistent with the flatter dependence of mmd versus LAR shown in Figure 8.

4. CONCLUSIONS

Droplet size distributions were measured for the plain-orifice liquid-jet atomization process, using a 9.5 mm liquid discharge opening, in which jet velocities ranged up to almost 500 m/s. Eleven empirical correlations available in the literature were evaluated against data obtained in this work. Correlation developed by Elkotb [3] for calculating
the Sauter mean diameter \((\text{smd})\) was found to correlate reasonably well with the mass median diameter \((\text{mmd})\) measured in the experiments. It was also found that the log-normal distribution law describes our experimental droplet size distribution frequencies reasonably well, using a constant value of \(\sigma_g = 1.8\).

Another objective of this work was to investigate the effect of high-velocity ambient airflow on the performance of a prefilming airblast atomizer. Ambient velocities ranged up to 150 mph in these tests. The effect of high ambient airflow was found to result in a noticeable reduction in the \(\text{mmd}\) of spray droplets as compared to those obtained under still-air ambient conditions. Frequency distributions of the spray droplets generated under high velocity ambient conditions were well described with the Nukiyama-Tanasawa distribution function.

5. REFERENCES