Aerosol Atomization from Transonic Air Jets in Cross Flow

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Abstract

We investigate the droplet size distributions and concentrations produced by an aerosol generator driven by a high velocity air jet delivered in cross flow to an oil tube at Mach numbers of 0.1-1.0, and Weber numbers based on the air flow parameters between 1000 to 40000. Measured Sauter mean droplet diameters (SMD) from 1µm to 3.5µm were determined by an Electronic Low Pressure Impactor over the range of Weber numbers. The droplet sizes are shown to scale with the Weber number based on the air jet velocity according to SMD (µm) = 12.4 We0.223, where We is based on the air properties. The measured diameters were little sensitive to other variables tested under controlled conditions. Comparisons with previous correlations failed to capture the dependence on Weber number, or predicted very different diameters. The number density was found to increase with oil and air flow rates, with values clearly limited by the oil flow rate delivered. The narrow variation in diameters over the high range of velocities tested demonstrates why the present technique is effective in delivering suitable aerosols for a range of applications.

Introduction

The reliable generation of aerosols with a given range of droplet sizes is important in a number of industrial applications, such as fuel injection, spray coating, particle and gas analysis, as well as cleaning equipment and pollution control. Much of the information on methods of aerosol and droplet generation via shear has come from fuel injection studies, where droplets diameters of the order of tens of microns are desirable [12]. Aerosol generation for submicron diameter ranges often relies on growth from particles in slowly condensing environments. In the present case, we consider the high rate generation of micron-size droplets, which are often used in the measurement of flow velocities via light scattering methods. Here we consider a shear breakup method, where the liquid sheet is disrupted by high speed air colliding in cross flow. This is a common method for nebulisation of aerosols [4][5]. Surprisingly, there has been to date no published quantification of the typical droplet size or rate generated by such methods. Moreover, there has been no assessment of the sensitivity of droplet size or delivery rate to geometry or operating conditions. This gap in the knowledge base may be in part due to difficulties in the measurement of droplets in the submicron range. In this study, we investigate the rate of formation of droplets by high speed air in cross flow, as a function of the various physical parameters involved, and propose a correlation for the mean diameter obtained.

The breakup of a liquid stream or jet is traditionally described as composed of two phases: primary, where the liquid column or sheet becomes unstable due to the propagation of wave disturbances, and disintegrates through the stripping of ligaments into large droplets; and secondary, where the primary droplets or filaments break up into multiple smaller droplets, typically under the action of shear. In the latter, described in this work, shear forces acting on the liquid-air interface are very high, so that the liquid tends to break up promptly, rather than in stages [1, 6, 7, 8]. This prompt atomization means that the liquid viscosity and the injector geometry are expected to have little impact on the final droplet size relatively to the velocity of the air jet [1]. The atomization is controlled by the ratio of drag forces supplied by the cross flow air at density ρa and velocity Va on the liquid stream of characteristic diameter Da, to the surface forces keeping the liquid intact via the liquid-air surface tension, σ. This can be expressed as a Weber number based on the density and velocity of the air and a characteristic length scale, which can be the integral turbulence length scale or, as in the present case, the diameter of the air jet, Da,

\[ W_{e_{aa}} = \frac{\rho_a V_a^2 D_a}{\sigma} \]

Alternatively, one can also consider the characteristic dimension of the liquid jet instead for an air-oil (or liquid) Weber number \( W_{e_{aa}} = \frac{\rho_a V_a^2 D_a}{\sigma} \).

The vast majority of studies on droplet breakup have investigated high velocity liquids emerging into lower velocity air, as that is a common method for atomization in sprays such as in diesel engines. In those cases, the smallest droplet diameter is typically controlled by the liquid injector diameter and the shear generated by the momentum of the liquid jet [7, 9]. A number of correlations have been cited for a range of air blast atomizers [7], which can successfully represent the mean diameters obtained under those particular geometric conditions. Far fewer studies have been conducted under simple geometric conditions in which high velocity air is used to break up diameter for a stream of liquid, and only a few under cross flow. Of these, the studies Ingebo and Foster [10] and Weiss and Worsham [11] have quantified the effect of different flow and geometric parameters on droplet diameter for \( W_{e_{aa}} \) from 4000 to 8000. Ingebo and Foster [10] considered the breakup of hydrocarbon liquid streams by high velocity air in cross-flow for Weber numbers in the range of 1 to 1000. In that study, a particular location within the
dispersing stream was chosen for photographic determination of the droplet diameter, followed by a measure of the hydrocarbon concentrations. From these studies, a correlation was proposed involving the product \( Wean Rean \) (Table 1), showing the balanced importance of inertia, surface tension and viscosity. Similar studies were performed at different temperatures and pressures by Kihm et al. [12], Becker and Hassa [13], and Wu et al. [14]. These studies focused primarily on the trajectory of the liquid spray and the distribution of droplets as a function of location, rather than on the far field droplet distribution. Weiss and Worsham [11] considered liquid flows of a molten wax into heated air, and measured the size of the resulting droplets after cooling. The resulting droplet sizes were correlated as a function of the flow and fluid properties as listed in Table 1.

A few studies have produced correlations for mean droplet diameters as a function of flow parameters for high shear, dilute conditions: Hsiang and Faeth [15] studied the secondary breakup of droplets (rather than liquid jets) under prompt atomization high speed unsteady flows generated by sudden acceleration, for \( Wean \) in the range 1-1000. In this study, a correlation was generated based on the shear forces and characteristic viscous length in the liquid, without reference to surface tension, which is surprising. A correlation including surface tension was proposed, but in which the corresponding terms cancel out, as reproduced in Table 1. The work by Varga et al. [17] investigated the behaviour of a liquid stream in contact with a high speed co-flowing stream, over a similar range of Weber numbers. The work considers the amplification of Rayleigh-Taylor instabilities via shear, concluding with a correlation which connects the mean diameter to the wavelength of the most unstable mode, resulting in a dependence on the flow velocity, gas and liquid properties, including viscosity and surface tension as detailed on Table 1. A common feature of these widely different correlations is the negative power dependence of mean diameter on gas velocity, \( \langle d \rangle \propto V_a^{-n} \). The study of Weiss and Worsham [11] found the steepest dependence of \( n = 1.25 \), in agreement with the expectations of the amplified Rayleigh-Taylor instabilities, whereas the dependence found by Hsiang and Faeth [15] and Ingebo and Foster [10] is much shallower, with values of 0.75 and 0.50, respectively. Table 1 reformulates the original correlations onto a similar basis so that they can be suitably compared to the present results.

The study by Lemaire et al. [18] contrasts with previous work, as the size of the droplets produced by a similar air blast mechanisms were below 15 \( \mu \text{m} \) and the mean size was measured by optical diffraction. No independent correlations were offered, although a justification of the droplets obtained was provided by prior theory.

In the previous studies cited, droplet sizes of tens or hundreds of micrometres are typical, and a combination of optical such as photographic evidence or optical methods were used to determine droplet diameters. In the present study, the typical droplet sizes hover between 1 and 4 micrometres, and the concentrations are relatively large, so that usual optical methods are not precise, and different instrumentation must be arranged, as described further on. The particles are measured at a distance sufficiently far downstream so that the diameters are no longer large, so that usual optical methods are not precise, and different instrumentation must be arranged, as described.

In the present paper, we investigate the size distribution, number and mass flow rate of droplets formed by cross-flow droplet shattering using high velocity air flows at atmospheric conditions (Test A), as a function of the non-dimensional air and oil velocities. These are compared to existing correlations, and a new correlation is proposed for the present regime. Measurements made in a similar, pressurised aerosol generation unit for flow seeding (Test B) are also presented, showing that the mean droplet diameter is not significantly affected by the operating pressure over the range considered.

### Table 1. Relevant experimental correlations for mean diameter for high shear conditions.

<table>
<thead>
<tr>
<th>Author</th>
<th>( n^a )</th>
<th>Correlation(^b) for ( d_{32}/D_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingebo and Foster(^c) [10]</td>
<td>0.75</td>
<td>( 3.9 \left( \frac{D_a}{D_a} \right)^{-1/4} Wean Rean )</td>
</tr>
<tr>
<td>Varga et al. [17]</td>
<td>1.25</td>
<td>( 0.49 \left( \frac{D_o}{D_a} \right)^{-1/4} \left( \frac{D_o}{D_a} \right)^{3/4} Rean Wean^2 )</td>
</tr>
<tr>
<td>Weiss and Worsham [11]</td>
<td>1.25</td>
<td>( 0.61 \left( \frac{D_o}{D_a} \right)^{1/6} \left( \frac{D_o}{D_a} \right)^{1/6} \frac{D_a}{D_o} \left( \frac{D_o}{D_a} \right)^{1/4} \left( 1 + 10^4 \left( \frac{D_o}{D_a} \right) V_o^{1/2} Wean^{-5/6} \right) )</td>
</tr>
<tr>
<td>Hsiang and Faeth [15]</td>
<td>0.50</td>
<td>( 6.2 \left( \frac{D_o}{D_a} \right)^{1/4} \left( \frac{D_o}{D_a} \right)^{-1/2} \left( \frac{D_o}{D_a} \right)^{1/2} Wean^{-1/2} V_o^{1/2} )</td>
</tr>
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</table>

\(^a\) Exponent \( n \) in \( d \propto V_a^{-n} \).

\(^b\) Correlations modified from their original form to yield a similar expression for all cases. \( V_o = V_d \mu_o / \sigma \).

\(^c\) The expression given in Ingebo and Foster is for \( d_{30} \) rather than \( d_{32} \).
Materials and methods

Apparatus

Measurements of droplet sizes were made over two separate configurations using the same air and oil nozzle delivery systems. In one set (Test A), droplet sizes were measured for an atomising setup at atmospheric pressure into a large container. In these measurements, we have good control of the boundary conditions and particle collection locations. In the second setup (Test B), experiments were made in a practical device, where an aerosol is generated in a pressurised container, and fed into a flow system for purposes of flow seeding. Droplets in the latter setup are measured at the final point in the line at atmospheric conditions. Test B measurements are therefore relevant to assess the performance of a practical device, but not necessarily suitable for deriving correlations, as no correction was made to account for the role of baffles and expansion to atmospheric conditions.

The experimental setup for Test A is depicted in Figure 1a. Filtered laboratory air (7.5 bar, 290 K) was metered using a mass flow controller (Alicat, \( \pm 0.8\% \) accuracy) (MFC) connected to the aerosol generator by a system of stainless steel pipes. The air nozzle shown in Figure 1c consists of a delivery tube of diameter \( D_p = 9.5 \) mm, with a fitting welded onto one end, which contracts the diameter sharply to \( D_a \). Multiple nozzles were produced with a range of \( D_a \) values, as listed in Tables 3 and 4. Vegetable oil was used, and the properties used in calculations are listed on Table 2.

For Test A, a hypodermic tube of inner diameter from 0.77 to 1.41 mm delivered the oil to the cross flow air stream. The tube was positioned flush with the air nozzle exit, and the exit plane of the oil tube could be offset from the nozzle centreline by a distance \( r_s \). The oil flow rate was regulated by a syringe pump (NE-1010, New Era Pump Systems Inc), holding a 30 ml syringe with a Luer-lock fitting. A brass Luer adapter welded to a straight piece of hypodermic tube connected the delivery line to the syringe.

In the case of Test B, oil present in a pool at the bottom of the pressurised air vessel was delivered to the air jet via a Venturi effect, by connecting a 1.2 mm tube directly to the oil pool. The pressure differential produced by the high speed jet drove the flow rate of oil. This self-contained mechanism was part of the original generator, but had the disadvantage that the precise oil flow rate into the air jet could not be determined. The static absolute pressures were monitored, and ranged between 2-4 bar. The Weber numbers were approximated in the same manner as for Test A, from the pressure ratios and metered flow rates.

For Test A, the aerosol was sampled from the container at a point above the air jet along its centreline. To verify this was a representative measurement, additional tests were made at selected conditions with sampling at different radial positions across the jet.

For Test B, the aerosol from the generator exited via a delivery pipe of 12.7 mm and was passed into a dilution chamber at pressure, before exhausting to an overhead vent. The dilution chamber was supplied with an additional flow rate of metered clean air by a second MFC (Alicat, \( \pm 0.8\% \) accuracy). The two flows mix as they rise through the chamber, and a sample of 30 lpm is extracted from the top before the flows are delivered into the extractor hood. Dilution was necessary to deliver concentrations within the limits of the measuring device.

In both tests, the samples are then transferred to an Electronic Low Pressure Impactor (ELPI) device, through a 9.7-mm pipe, pumped by an Oerlikon Leybold Sogevac SV6SB vacuum pump maintained at 100 mbar. The sample aerosol moves to the exhaust after the pump and ELPI.

![Figure 1. Experimental setup](image)

(a) Test A setup: atmospheric
(b) Test B setup: pressurised
(c) Nozzle detail
Operating conditions
Operating flows and jet diameters were selected based on the geometry and conditions of an existing nebuliser used for aerosol production for flow seeding in particle image velocimetry. The full set of test conditions are shown in Tables 3 and 4.

For Test A, two different air nozzle diameters and three oil tube diameters were chosen, with a range of air flow rates from 50 to 600 slpm, and oil flow rates up to 1.0 ml/min giving exit velocities from 1-36 mm/s. The position of the oil tube exit relative to the centreline of the air jet was not varied in this set. For Test B, an additional two air nozzles were used, due to the observed dependence of aerosol properties on air jet Weber number, whilst only one oil tube size was selected since this property was observed to have no impact on particle size.

For the different oil delivery mechanism of Test B, the oil flow rate was controlled by the ejection velocity of the air, and the oil tube diameter was expected to influence the oil flow rate, so the tube size was selected from the available range based on a compromise between flow rate and manufacturing reliability. The tubes were required to have a 90 degree bend, which for the small tubes was often found to be too constricted to allow sufficient oil. For larger tubes, the oil flow rate was much too high, and so the 1.2-mm tube was used. Measurements at each condition were repeated three times, for about 60 seconds at 1 Hz sampling rate. All flows could safely be used undiluted without saturating the ELPI particle measurement system.

A key parameter in the liquid break up is the relative momentum of the incoming air cross flow. The bulk jet velocity was calculated from measurements of the static pressure upstream of the nozzle, as described below. The ambient temperature is 293 K, the air specific heat capacity was assumed to be constant and equal to 1005 J/kg K, and the ratio of specific heats was 1.4. Using the measured static pressure and the metered air flow rate \( Q_a \), we determine the jet Mach number \( M_a \) using isentropic calculations for the area ratio, and considering friction losses using the corresponding Fanno parameters and the length of the tube. For the sudden contraction, a discharge coefficient of 0.85 was estimated. These are then used to calculate the local velocities and corresponding Weber numbers at the jet outlet. Sample values for a fixed jet diameter are illustrated in Fig. 2.

**Particle Size Measurement**

The aerosol particle size distribution was measured using an Electronic Low Pressure Impactor (ELPI) (Dekati Ltd). In this instrument, aerosol particles in the constant pressure, constant flow rate sample receive an electric charge before entering a 12-stage impactor. Each stage forces the sample through successively tighter flow curvatures, which removes particles larger than a certain cut-off size. The particles which fall out of the flow accumulate on
collection plates, and the current onto these is measured and transmitted to a computer at a rate of one sample per second, for calibration and analysis. Data sets of 20-60 seconds were taken, depending on result variability. The data provided by the ELPI are in the form of a histogram of particle numbers per unit volume, over 12 size bins between 0.0283-10.08 µm, spaced logarithmically.

A two-way valve system with a tee is installed in the sampling line for Test B. This connects the sampling tube to the ELPI delivery pipe, with a third connection to the atmosphere. One valve is placed on the sampling tube, and the other on the atmospheric connection; they are maintained such that only one is open at a time. By switching the valves, either aerosol or atmospheric air can be supplied to the ELPI. This prevents oil from saturating the instrument when measurements are not being taken. For Test A, the oil flow rate was simply switched off at the pump to achieve the same result.

The impactor was cleaned whenever the accumulated mass indicator approached saturation, which limits accuracy due to particle bounce and other losses. All parts were cleaned with acetone and tissue, before being air-dusted. Virtanen et al. [18] estimated that for particles above 30 nm (the smallest measurable size), losses due to particle diffusion are below 2%. For particles above 0.2 µm, losses due to both diffusion and image force deposition combined are below 0.5%. For high concentrations of particles, space charge losses become significant, but are below 0.8% for particles smaller than 0.3 µm [18]. The lower cutoff diameter of the ELPI is 0.0283 µm - particles smaller than this value are not recorded. The collection efficiency curves for each stage have an average steepness ratio (ratio of values of \(d_p\) at 70% to those at 30% collection efficiency for a particular stage) of 1.19 [19]. For the present dataset, the uncertainty in droplet size and concentrations is affected to a far greater degree by the inherent variation in aerosol output due to the mechanism of generation than by the uncertainties introduced by the apparatus used to measure that output. Typical variations are discussed in the results section.

**Results and discussion**

**Test A - Droplet Size Distributions**

The droplet diameter probability densities shown in Figures 3-5 are area normalised, such that the value for each bin, \(f_i\), is related to the number density \(N_i\) (in particle numbers per cm\(^3\)) as recorded by the ELPI by:

\[
f_i = \frac{N_i}{\sum_{i=1}^{S} N_i \Delta d_{p50,i}}
\]

where \(d_{p50,i}\) is a cutoff diameter of a stage in the ELPI (each stage has an upper and lower cutoff), \(\Delta d_{p50,i}\) is the width of each size bin in the histogram, measured as the difference between the upper and lower cutoff diameters, \(d_{p50,i} = (d_{p50,u,i} - d_{p50,l,i})\), over the total number of bins, \(S\).

The distributions shown for selected cases are illustrative of the variation across the full set of results. Figures 3-5 showing the variation in the particle size distribution with oil tube diameter, oil mass flow rate, and \(W_{\kappa u}\), while keeping other parameters fixed. The oil tube diameter (Fig. 3) and flow rate (Fig. 4) have little effect on the droplet diameter distributions. There is slightly more variation in the lower particle size range than in the larger range, but this may be a result of the lower accuracy of the impactor in the lower size range, as well as the fact that the small droplets represent a much smaller fraction of the aerosol volume. The largest changes in the PDF of diameter are due to increasing relative velocity via \(W_{\kappa u}\).
Figure 3. Example of variation of particle size PDF with oil tube diameter, for oil flow rate of 1.0 ml/min, \( W_{e_{a-a}} = 26622 \)

Figure 4. Example of variation of particle size PDF with oil mass flow rate, for constant \( D_0 = 1.15 \text{ mm} \), \( W_{e_{a-a}} = 26622 \)

Figure 5. Example of variation of particle size PDF with \( W_{e_{a-a}} \), for constant \( D_0 = 1.15 \text{ mm} \), \( W_{e_{o}} = 0.00198 \) (\( D_a = 3.55 \text{ mm} \))

**Test A - Sauter Mean Diameter**

The SMD is obtained from the particle size distribution by summation over each bin, using the number of particles \( N_i \), and the geometric mean diameter \( d_{p,i} = \sqrt[50]{d_{p,50,i} \cdot d_{p,50,i}} \) within each bin:

\[
SMD = d_{32} = \frac{\sum_{i=1}^{S} N_i d_{p,i}^3}{\sum_{i=1}^{S} N_i d_{p,i}^2}
\]

The SMD value is clearly biased towards larger diameter values, so that the lower limit of 0.0283 \( \mu m \) of the ELPI does not affect the mean particle size significantly. However, the particle bin size is quite coarse (12 size bins in total), and spaced approximately logarithmically. The three largest size bin sizes register negligible numbers of particles for most of the test cases, so the uncertainty due to particle sizing at the largest diameters is limited. Figure 6 shows the typical repeatability of mean SMD between tests. The average standard deviation of SMD was 0.067 \( \mu m \) for Test A, and 0.040 \( \mu m \) for Test B. It is unclear whether the rise in SMD at the highest \( W_{e_{a-a}} \) is
representative, but for these transonic velocities, the temperature of the jet becomes significantly cooler, which may affect the viscosity of the liquid and thus atomisation. The liquid Weber number, $W_{e_o} = \rho V_o^2 D_o/\sigma$ does not appear to have any influence on the SMD.

\begin{equation}
    \text{SMD} (\mu m) = 12.4 \times W_{e_{aa}}^{-0.223}
\end{equation}

or as a non-dimensional version based on a non-dimensional viscous diameter $d_\mu = \mu_o^2/\rho_o \sigma$,

\begin{equation}
    \frac{\text{SMD}}{d_\mu} = 8.46 \times 10^4 W_{e_{aa}}^{-0.223}
\end{equation}

For the combined dataset in Test A, a best-fit correlation between $W_{e_{aa}}$ and SMD were obtained:

The jet air velocity has the highest effect on droplet size, over a range of operating and geometric conditions, as shown in Fig. 7. There is a clear and expected decrease in droplet diameter with increasing $W_{e_{aa}}$, but the range of variation is relatively small, given the wide range of $W_{e_{aa}}$. The rate of change in SMD with Weber number decreases with increasing air velocity, which suggests a saturation of the breakup mechanism. The dependence of SMD on other factors such as the oil jet diameter or velocity, expressed as $W_{e_{oa}}$, was found to be minimal within the range examined. The shear forces in the air jet are apparently sufficient to break up all the oil supplied into similarly sized droplets. Clearly, additional studies including variations in surface tension and viscosity could clarify additional functional dependences.
From the definition of $W_e a a$, this represents a dependence on velocity as $V^{-0.446}$. This is clearly different from the dependence found on all previous studies, with the exception of that of Hsiang and Faeth [15], which also showed negative exponent of 0.50. Their experiments were also made using droplets with negligible momentum relative to the blast air – similar conditions can clearly prevail in the current experiments. In the other sets of experiments, the momentum of the liquid jet is not entirely negligible, so this may play a role in the different scaling obtained. Figure 8 shows the comparison between the current correlation, and measurements from a range of different experiments. The resulting expected diameters vary by orders of magnitude, and the slopes are also rather different than the measured values obtained in the present experiments. Interestingly, the results of Test B are not significantly different than those for Test A, even though the pressures used in the vessels were different. The correlation of Varga et al. reproduces the results most closely, even though the dependence on the Weber number is different.

![Figure 8. SMD measurements, normalized by $d_{4a}$, for all operating conditions in Test A and B, and corresponding results for existing correlations from the literature.](chart.png)

**Test A - Particle number density**

The particle number density increases approximately as $W_e a a^{1/2}$, which means linearly with velocity as shown in Fig. 9. Higher jet velocities lead to a higher entrainment of droplets, as well as a larger number of smaller droplets entrained (Fig. 7). The number density is found to vary approximately linearly with the oil flow rate, for a given air flow rate. The measurements suggest that the number density is only limited by the rate of supply of oil in this regime: the blasting air both breaks up the droplets explosively and carries all droplets regardless of flow rate. The particle measurements above were all made at the centreline of the tank. The variations with distance from the jet exist, but are relatively minor towards the edges of the tank (Fig. 10). This could be attributed to the high velocities at the centerline, as well as the effect of coalescence away from the center in lower velocity regions of the air flow. The number concentrations decrease slightly towards the edges of the tank, as there is a dilution effect created by flow recirculation zones.

**Conclusions**

In the present study we have considered the prompt atomization of a low Weber number vegetable oil stream by a high Weber number cross stream air flow. The droplets produced are of the order of 0.1-3 micrometers, with a relatively small dispersion, and very typical of blast aerosolisers. The velocity of the air stream is the key parameter controlling the droplet diameter and the rate of transport of droplets from the source. A correlation based on the Weber number of the air stream and the air nozzle diameter was able to reproduce all the data points for the SMD over all conditions. The dependence on Weber number has a power exponent of $-0.446$, corresponding to an inverse dependence of diameter on air velocity. The values obtained for the diameter and the dependence on velocity are significantly different from most other correlations. However, this should not be surprising, as they were obtained in significantly different regimes. Further experiments should be conducted to elucidate the role of surface tension and a closer look at the mechanism of break up. The correlation obtained should be useful in designing variants to this very popular method of aerosolisation of liquids into very small droplets.
Figure 9. Test A, number density of particles. Colour coded symbols correspond to flow rates of oil: red, yellow and blue represent 0.1, 0.5 and 1.0 ml/min of oil respectively. Weber numbers for oil shown $\times 10^3$.

Figure 10. Variation of droplet SMD (left) and number density (right) over the width of the jet, 37 cm above the exit plane. $R_c$ is the radius of the container at its open end, and $r_s$ is the radial distance of the inlet of the sampling tube to the nozzle centerline.

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Nomenclature
\begin{align*}
d & \quad \text{droplet diameter [\mu m]} \\
d_{\mu} & \quad \text{Ohnesorge length scale } \mu^2/(\rho_o\sigma) [\mu m] \\
D & \quad \text{geometric diameter [m]} \\
M & \quad \text{jet Mach number [-]} \\
N & \quad \text{droplet number density [cm}^{-3}\text{]} \\
Q & \quad \text{volumetric flow rate [slpm]} \\
r_s & \quad \text{sampling position [m]} \\
R_c & \quad \text{radius of container [m]} \\
Re_{ao} & \quad \text{Reynolds number based on air properties and oil length scale [-]} \\
S & \quad \text{Number of bins [-]} \\
SMD & \quad \text{Sauter mean diameter [\mu m]} \\
V & \quad \text{velocity [m s}^{-1}\text{]} \\
V_o & \quad \text{non-dimensional velocity based on surface tension and viscosity (Table 1) [m s}^{-1}\text{]} \\
\end{align*}
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Weber number based on air properties and length scale [-]

Weber number based on air properties and oil length scale [-]

Weber number based on oil properties and length scale [-]

\[ \mu \text{ dynamic viscosity [kg m}^{-1} \text{s}^{-1}] \]

\[ \rho \text{ density [kg m}^{-3} \text{]} \]

\[ \sigma \text{ surface tension [N m}^{-1} \text{]} \]

Subscripts

- \( i \) running index
- \( a \) air (gas phase)
- \( l \) lower
- \( o \) oil (liquid phase)
- \( u \) upper
- 32 Sauter mean
- 50 median

References


