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The Effect of Turbulence on the Stability of Liquid Jets and the Resulting Droplet Size Distributions

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ABSTRACT

A study has been made of laminar and turbulent columns of liquids issuing from capillary tubes in order to determine the effects of turbulence on the stability of liquid jets and to establish the influence of liquid turbulence on the droplet size distributions after breakup. The droplet size distribution was measured using a digital imaging spray analyzer. Two capillary tubes were chosen with diameters $D_1 = 3.051\text{mm}$ and $D_2 = 1.194\text{ mm}$. The jet Reynolds numbers were varied between 1000 and 30000, and 400 and 7200 respectively. For water injection into stagnant air, the stability curve is bounded by a laminar portion characterized by a very low initial disturbance amplitude ($\ln(a/\delta_{o,L}) = 22$), where a is the jet radius and δ_o is the initial disturbance amplitude, and a fully developed turbulent portion characterized by a very high initial disturbance amplitude ($\ln(a/\delta_{o,T}) \sim 4.85$). In the transition region, $\ln(a/\delta_o)$ is not single valued; it decreases with increasing Reynolds number. It was also found that, in the absence of aerodynamic effects, turbulent jets are as stable as laminar jets. For this mode of breakup the sole effect of turbulence is to propagate initial disturbances with amplitudes that are orders of magnitude larger than those of laminar jets ($\delta_{o,T} = 28 \times 10^6 \delta_{o,L}$). The growth rates of initial disturbances are essentially the same for both laminar and turbulent columns; they are in agreement with the theoretical values derived by Weber. The droplet size distribution is bi-modal; the number ratio of large ($> D/2$), where D is the diameter of the tube, to small ($< D/2$) droplets is equal to 3 and is independent of the Reynolds number. For laminar flow conditions, the optimum wavelength (λ_{opt}) corresponding to the fastest growing disturbance is equal to $4.45D$, which is exactly the theoretical value derived by Weber. For turbulent flow conditions, the turbulent column was observed to segment. Typically, segments with lengths of one to several wavelengths, were observed to detach from the liquid jet. The long ligaments contract under the action of surface tension, resulting in droplet sizes larger than those predicted by Rayleigh and Weber. For turbulent flow conditions, $\lambda_{opt} = 9.2D$, which is approximately 2 times the optimum wavelength calculated by using Weber's theory.

and to establish the influence of turbulence when the aerodynamic effects are negligible. For comparison purposes, we also used a smaller diameter capillary tube, $D_2 = 1.194$ mm, with a length to diameter ratio of 255. The work is motivated by the desire to extend Weber's analysis of a laminar column of liquid, at least in the linear portion of the stability curve, to the case of a turbulent column. The large jet was turbulent throughout the linear portion of the stability curve. A comparative study between the breakup behavior of a turbulent jet and a laminar jet shows that turbulent flow propagates initial disturbances with amplitudes that are orders of magnitude larger than those for laminar flow. There are conflicting results in the literature regarding the effect of turbulence on the growth rate of initial disturbances. It is not known to what extent the presence of a contorted surface modifies the growth rate of an axisymmetric disturbance. This study shows that, when aerodynamic effects are negligible, the growth rate of the most dominant disturbance corresponding to laminar (α_L^*) and turbulent (α_T^*) flow conditions are identical $\alpha_L^* = \alpha_T^*$. The most prominent effect of turbulence is to propagate an initial disturbance that is orders of magnitude larger than that propagated by a laminar flow. The initial disturbance amplitude is larger for turbulent flow than for laminar flow. The breakup of a turbulent column results, however, in droplets that are significantly larger than droplets formed by the breakup of a laminar jet.

Rayleigh breakup is highly non-linear. A linear phenomenon will not produce satellite droplets. Satellite drops can be predicted from an analysis similar to that of Rayleigh; the ratio of the large drops to satellite drops was determined to be 2.8 [4]. In a study of the Rayleigh breakup mechanism, Duffie [5] investigated the diameter and size distribution of drops after the breakup of jets of liquid issuing vertically downward from capillary tubes into stagnant air. The jet Reynolds number was varied from 23 to 2230. Droplets were photographed below the point of breakup, and drop images were measured from projection of the negatives. The geometric mass mean drop size was correlated by the following empirical equation:

process occurs within the nozzle and that liquid turbulence may play an important part. Schweitzer [11] argued that growth of surface waves subsequent to discharge from a nozzle could not alone account for the high degree of atomization usually observed. He suggested that turbulence and vortex motion in the nozzle may reinforce the disintegration process. Reitz and Bracco [12] also identified breakup induced by liquid phase turbulence as one of the possible mechanisms contributing to the atomization process. This mechanism involves turbulent distortion of the liquid surface to form drops, with surface tension acting to stabilize the distortion, so that the maximum drop sizes should be comparable to the radial integral scales of the liquid turbulence. Bergwerk [13] argued that the turbulent velocity components, in the range of Reynolds numbers of interest, are not of sufficient magnitude to explain the atomization process. He suggested that liquid cavitation inside nozzles can create high amplitude pressure disturbances in the flow that lead to the atomization process.

Rupe [14] observed that high velocity laminar jets could actually be more unstable and breakup in an extremely violent fashion much sooner than fully developed turbulent jets. He argued that the decay of the laminar parabolic profile results in the creation of radial velocity components. He commented that the radial velocity led to the disintegration of the jet. On the basis of measurements of the centerline stagnation pressure in jets initially in fully developed laminar flow, Rupe suggests that the jet length required for the velocity profile to relax from a fully developed laminar profile to a uniform velocity profile (the relaxation length) is comparable with the entry length for laminar flow in a pipe. This agrees quite well with the theoretical results of Duda and Vrentas [15].

Recent work on the effect of turbulence on the disintegration process was conducted by Faeth and co-workers. Ruff et al. [16] observed significant effects of jet exit conditions on the rate of spread of the outer mixing layer in high speed pressure atomized jets. They found that pressure-atomized sprays are sensitive to the degree of flow development and

$$\alpha^2 F_1 + \alpha F_2 \frac{3\mu\zeta^2}{\rho a^2} = \frac{\sigma}{2\rho a^3} (1 - \zeta^2) \zeta^2 \quad (4)$$

F_1 and F_2 are ratios of Bessel functions whose arguments contain α and k , a is the tube radius and ζ is the dimensionless wave number ($\zeta = 2\pi a/\lambda$). Solution of the characteristic equation shows that the curve of α vs. ζ goes through a maximum and thus there is a disturbance that grows the most rapidly.

The droplet size (a measure of the wavenumber of the most unstable disturbance) and the breakup length (a measure of the growth rate of the disturbance) are the properties of most interest. For infinitesimal disturbances of the same initial magnitude, the droplet formation is controlled by the particular wave which grows the most rapidly. We denote the growth rate of the most dominant disturbance by α^* . Thus, the breakup time is given by

$$\delta(0,t) = a = \delta_0 e^{\alpha^* T} \quad (5)$$

Here it is assumed that breakup occurs when δ acquires a value equal to the jet radius a . The breakup length is $BL = U_{av}T$ or

$$BL = (U_{av}/\alpha^*) \ln(a/\delta_0) \quad (6)$$

Equation 4 is complex and cannot be solved analytically. However, for small arguments, the Bessel functions can be approximated by the leading terms of their expansions. For low speed jets, it can be shown that the solution to Eq.4 can be obtained with a good approximation by setting $F_1 = F_2 = 1$. This approximation corresponds to the conditions of practical interest, i.e. Rayleigh type of instability, where the wavelengths of disturbances are much greater than the radius of the unperturbed jet. In this case, the wavelength of the fastest growing wave can be obtained by implicit differentiation of Eq.4, and letting $d\alpha/dk = 0$. The fastest growing rate, α^* , can, in this way, be obtained from the following equation.

Weber's analysis also predicts that the optimum wavelength (λ_{opt}) corresponding to the fastest growing disturbance is given by

$$\lambda_{opt} = \sqrt{2} \pi D \left[1 + \frac{3\mu}{\sqrt{\rho \sigma D}} \right]^{0.5} \quad (11)$$

For the breakup of a laminar water column, λ_{opt} is calculated to be $4.44D$. Assuming that a segment of length equal to the optimum wavelength contracts after breakup to yield a spherical droplet, the diameter of such a droplet is then calculated to be $d = 1.88D$. Eq.11 is valid for low speed liquid jets when the aerodynamic effects are negligible. Weber examined the effects of air resistance on the disintegration of liquid jets (Eq.10) and found that air friction shortens the optimum wavelength for drop formation.

EXPERIMENTAL CONDITIONS

Apparatus

The apparatus consisted of a high pressure reservoir and a nozzle assembly. The primary objective in the design of the flow apparatus was to obtain a steady flow of liquid at the jet exit. Liquid flow rate was measured by a Micro-motion model D-6 flow meter having a full range error not exceeding 1%. Uncertainty in mean total liquid flow rate was 1.5% due to unsteadiness over longer time scales. Special care was taken to eliminate disturbances in the supply system and maintain an undisturbed and relatively quiescent flow field upstream of the nozzle. The nozzle assembly was anchored to a 1200 lb rugged three dimensional traversing mechanism. The nozzles were constructed from stainless steel hypodermic tubing, square cut on both ends and burr free. The injection orifices were examined under a 15x microscope and carefully deburred with a jeweler's broach, with particular care taken to avoid beveling corners. For the large capillary tube setup, the liquid entered a large cylindrical chamber followed by a 22:1 contraction. This was followed by an injector tube, $D_1 = 3.051$ mm diameter with a length to diameter ratio $L_1/D_1 = 36$. For

A digital image analyzer (Greenfield) was used to make droplet size measurements. The instrument setup and optical configuration is shown in Fig.1. The video imaging system includes: a CCD camera, microscope lens, fast strobed light, image processing hardware and software. The light source is on the opposite side of the jet from the CCD camera, so that the camera records back-lit images. The strobe light is synchronized with the camera and emits a flash of about 200 nanosecond duration, just before the camera begins a frame scan. The camera scans two 240-line fields and interlaces them to produce a 480-line frame. The time duration for scanning a full frame is 33 milliseconds. Drops appear as dark objects on a white background. A digitizer on the image processing board turns each picture into an array of 640 by 480 pixels, each of which has a gray scale level of 0 (black) to 255 (white). The frame scan algorithm sums up the dark pixels in each drop representation, and computes a pixel diameter based on that area, assuming circularity. The software transforms the pixel diameter into a diameter in microns on the basis of a prior calibration using objects of known size. For non spherical droplets, the software computes the diameter of a circle of an equivalent area. Often the droplets, acting as spherical lenses, contain a white center or optical hole due to light refraction effects. The scanning algorithm fills in these optical holes during the computation of area. At any one particular optical setting, the dynamic range of the instrument can extend to 150:1, with an overall range covering 1 to 18000 μm .

Test Conditions

Test conditions are summarized in Table I. The large injector Reynolds number was varied between 1200 and 29000, corresponding to $0.009 < We_g < 4.35$. The small injector Reynolds number was varied between 400 and 7200, corresponding to $0.0022 < We_g < 0.709$. This yielded conditions that are predominantly in the Rayleigh and the first wind-induced breakup regimes. Ranz[8], Miesse[6], and Reitz [20] recommend the following criteria for establishing the regimes of breakup:

liquid tends to laminarize due to viscous dissipation of turbulent energy. As can be seen in these photographs, the effect of increasing the Reynolds number results in an extension of the large wave number end of the spectral distributions. The fine-grained distortions appear to be the effect of the power spectrum of liquid turbulence, where the kinetic energy available to distort the liquid surface increases as the Reynolds number is increased [16]. These small scale disturbances decay at a faster rate than the larger ones. The large disturbances show a high degree of permanence and continue to exist well beyond $X/D = 50$, particularly for the higher Reynolds number conditions.

Velocity Measurements

Figure 3 shows the axial velocity ($U_{o,c}$) on the centerline normalized by the average velocity (U_{av}) at an axial location of $X/D_1 = 0.3$ as a function of Reynolds number. Figure 3 is divided into 3 subregions: laminar flow, turbulent flow without expansion, and turbulent flow with expansion. At $Re = 1000$, the ratio $U_{o,c}/U_{av} = 1.6$; this is less than the value of 2 for fully developed laminar flow. Kays [21] gives an estimate for the length of tube necessary for the development of a laminar profile as $X_e/D = Re/20$. The L_1/D_1 ratio for these experiments is 36; for $Re = 1000$ the tube length is less than that required for achieving a fully developed laminar profile. Thus, the flow in the tube does not reach fully developed laminar flow conditions, even for the lowest Reynolds number. $U_{o,c}/U_{av}$ decreases in the range of Reynolds number between 0 and 6000. This ratio tends towards a value of 1.17 at a Reynolds number of 6000. In the turbulent flow region without expansion ($6000 < Re < 21000$), the ratio $U_{o,c}/U_{av}$ has a value of approximately 1.17, which is less than the value of 1.2 for fully developed pipe flow over this range of Reynolds numbers. The discrepancy can be best explained by the relaxation that occurs in the distance from the tube exit to the point of measurement (i.e., $X/D_1 = 0.3$). The slight downward slope of $U_{o,c}/U_{av}$ in the range, $6000 < Re < 21000$, is due to the flattening of the velocity profile with increase of the Reynolds number. At a Reynolds number of about

Reynolds number of 1683, marks the beginning of the impact of the air resistance on jet stability and is solely dependent on the relative velocity between the liquid surface and the surrounding gaseous medium. Other investigators attributed this effect to the onset of turbulence. Haenlein [23], hypothesized that point B on the stability curve corresponds to the change in the breakup from varicose to sinuous. Weber offered a possible explanation for this observation. He showed that the aerodynamic forces at the jet surface tend to propagate both symmetric and transverse disturbances. Since the aerodynamic forces acting on the jet surface become increasingly important as the jet velocity increases, the departure from linearity at point B could be ascribed to aerodynamic forces.

Large magnification of the small diameter jet on the computer screen showed relatively large lateral oscillations of the jet, about the axis of symmetry, at the nozzle exit, in the region between points B and C. The lateral oscillations become more pronounced in the downstream direction. The breakup however is always varicose in nature. At point B, the jet surface also showed some degree of ruffling at the nozzle exit. It was not possible to identify whether the reduction in breakup length between points B and C is caused by the transition to turbulence or whether the aerodynamic effects play an important role. It should be mentioned however that throughout the transition region, the droplet size increased with increase in the Reynolds number, indicating that the aerodynamic effects played a secondary role. Weber examined the effect of air resistance on the development of a liquid jet and found that air friction shortens the optimum wavelength for drop formation. If the aerodynamic effects were important in the region between B and C, we would expect a reduction in the wavelength and thus a reduction in droplet size, which is contrary to the experimental observation. The droplet sizes are shown to increase in this region (see Drop Size Measurements). Point C corresponds to $U_{av} = 2.16$ m/s and $Re = 2578$. At point C, the surface becomes very ruffled. Point C also marks the complete disappearance of the lateral oscillations of the jet. If the aerodynamic effects were important in the region B-C, they would be even more important at velocities greater than 2.16 m/s. We would then

The breakup length of the small capillary jet should be contrasted to the breakup length of the large capillary jet, which had a fully developed turbulent profile in the range of velocities $U_{av} > 2$ m/s. The L_1/D_1 ratio for the large capillary is 36; for $U_{av} < 2$ m/s, the tube length is less than that required for achieving a fully developed laminar profile. Thus, the flow never reaches fully developed laminar flow conditions, even for the lowest Reynolds number. It is seen in Fig.4a that the large capillary jet exhibits a linear range similar to the small capillary jet, but throughout the range of Reynolds numbers studied, there is no maximum in the breakup length curve. No sinuous waves were observed in the velocity range $1 < U_{av} < 9$ m/sec, corresponding to $3154 < Re < 29000$, either. At the point of transition to turbulence, the laminar profile is not fully developed; the velocity profile rearrangement is less intense. The formation of sinuous waves is suppressed, and the breakup length increases continuously with increase in velocity or Reynolds number. From this it should be obvious that the maximum of the stability curve is not solely related to the onset of turbulence, for if this were the case we should expect a maximum in the stability curve of the large capillary at about $U_{av} = 2$ m/s (transition to turbulence).

Eq.8, which is derived directly from Weber's theory of the breakup of a laminar viscous jet in vacuum, suggests the form of the dimensionless correlation of the low speed linear portion of the breakup curve. We will assume that Webers analysis holds for the breakup of a turbulent column as well. Fig.4b shows the breakup length data of both liquid columns plotted according to Eq.8. A line of unit slope, in agreement with Eq.8 gives an intercept of 22 for the laminar portion of the small capillary jet, with a correlation coefficient $R^2 = 0.991$. This value of $\ln(a/\delta_{0,L})$, where L refers to laminar flow conditions, compares favorably with the values of 24 calculated from Grant and Middleman's correlation (Eq.9) for a water column. For the fully turbulent region of the small capillary, a line of unit slope, in agreement with Eq.8 gives an intercept of 4.85, with a correlation coefficient $R^2 = 0.988$. This value of $\ln(a/\delta_{0,T})$, where T refers to turbulent conditions, compares unfavorably with the value of 22 derived from the breakup data in the laminar

Fig.4b shows 2 transitional states. In the laminar portion of the stability curve, $\ln(a/\delta_{o,L})$ is single valued and the stability curve should follow the straight line of unit slope which has an intercept of $\ln(a/\delta_{o,L}) = \text{constant} = 22$. In the absence of aerodynamic effects, in the turbulent region the stability curve should follow the straight line of unit slope which has an intercept of $\ln(a/\delta_{o,T}) = \text{constant} = 4.85$. And finally in the transition region, $\ln(a/\delta_o)$ is not constant; it decreases with increasing Reynolds number and thus the breakup length decreases accordingly. Contrary to the assumption made by Sterling and Sleicher [24], $\ln(a/\delta_o)$ is not universal for a single nozzle. This value varies between 22 for the fully developed laminar flow case and 4.8 for the fully developed turbulent flow case. In the transition region $\ln(a/\delta_o)$ is bounded by those two values ($4.8 < \ln(a/\delta_o) < 22$). This means that in the transition region between points B and C, the reduction in the breakup length is not necessarily connected to a reduced stability of the liquid jet, it is merely the result of the increase in the initial disturbance amplitude. Beyond $(We^{1/2} + 3We/Re) = 30$, corresponding to a liquid velocity $U_{av} = 4.7$ m/s, the slope of the breakup length data changes, probably due to the onset of aerodynamic effects. At these conditions Eq.8 is not valid and the solution of the full dispersion equation, accounting for the aerodynamic effects is necessary.

Figure 4c shows the growth rate for the of the initial disturbance (α^*) for both laminar and turbulent flow conditions. This data is derived from the breakup length data and $\ln(a/\delta_o)$ according to Eq.6. For the small capillary tube, the intermediate region between points B and C is not included, for in this region $\ln(a/\delta_o)$ is not constant. The theoretical values derived from Eq.7, which do not account for aerodynamic effects, are equal to 205.8 and 50.55 for the small and large capillary tubes respectively. It is shown that for the small capillary tube the growth rate for an axisymmetric disturbance is nearly independent of the Reynolds number. The theoretical and experimental growth rates are identical within the range of experimental errors. This is to be expected since throughout the range of Reynolds numbers studied, the aerodynamic effects were negligible. For the large

size distribution. Increasing the Reynolds number, results in the flattening of the second peak. The maximum of the secondary peak shifts to lower values of d/D . The Reynolds number does not appreciably affect the formation of the larger droplets (i.e., the fundamental peak is centered at $d/D_1 = 2.4$, irrespective of the Reynolds number), but it does have a greater effect on the formation of the smaller droplets. At high Reynolds number conditions, the breakup process at the neck of the liquid jet and the formation of satellite droplets is less ordered giving rise to a wider distribution of smaller droplets. It is also seen that at the lowest Reynolds number (i.e, $Re = 3154$), the fundamental peak occurs at $d/D_1 = 1.9$ instead of 2.4. This compares favorably with the breakup of a laminar column in the Rayleigh mode.

For turbulent flow conditions, the fundamental peak is at $d/D_1 = 2.4$. This does not conform to the classical theory of Weber[2] which predicts $d/D = 1.88$ and $\lambda_{opt} = 4.44D$. The turbulent column was observed to segment. Typically, multiple values of one wavelength were observed to detach from the liquid jet. The long ligaments contract under the action of surface tension, thus leading to increase in droplet size over that predicted by Rayleigh and Weber. Based on $d/D_1=2.4$, $\lambda_{opt} = 9.2D_1$ for this particular case, which is approximately 2 times the optimum wavelength value calculated by using Weber's theory.

Figure 6 shows the cumulative percentage of droplets smaller than a certain diameter as a function of Reynolds number. In general the ratio of the number of the large droplets to the number of the small droplets is not constant and is a function of the Reynolds number. However if we define a satellite droplet as a droplet whose diameter is smaller than one half the diameter of the liquid jet ($d < D_1/2$), then it possible to conclude that the ratio of the large to the satellite droplets is constant and is equal to 3 and is independent of the Reynolds number. It is also shown in Fig.6 that, within the range of Reynolds number studied, the effect of increasing the Reynolds number results in an increase in the relative

disturbances is essentially the same for both laminar and turbulent columns. Both growth rates are very close to the theoretical value derived by Weber.

3. Marked differences were found to exist between the breakup behavior and droplet formation patterns of both laminar and turbulent jets. For laminar jets, single waves were observed to detach from the liquid column in a very ordered and repeatable fashion. The breakup length was generally unambiguous, very reproducible and readily measurable on the computer screen. For laminar flow conditions, the optimum wavelength (λ_{opt}) corresponding to the fastest growing disturbance is equal to $4.45D_1$ which is exactly the theoretical value derived by Rayleigh and Weber. For turbulent flow conditions, the turbulent column was observed to segment. Typically, multiple values of one wavelength were observed to detach from the liquid jet. The long ligaments contract under the action of surface tension, thus leading to increase in droplet size over that predicted by Rayleigh and Weber. Based on $d/D_1=2.4$, $\lambda_{opt} = 9.2D_1$ for this particular case, which is approximately 2 times the optimum wavelength value calculated by using Webers' theory.

4. The droplet size distribution is bi-modal; the number ratio of large ($d>D/2$) to small ($d<D/2$) droplets is equal to 3 and is independent of the Reynolds number.

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LIST of FIGURES

Fig.1 The Digital Image Analyzer

Fig.2 Characteristic Development of the Large Liquid Jet at Different Reynolds Numbers,
a) $R = 6308$, b) $Re = 14195$, c) $Re = 17349$, d) $Re = 22080$, e) $Re = 28390$.

Fig.3 Normalized Average Velocity at $X/D_1 = 0.3$, $R = 0$, at Different Reynolds Numbers

Fig.4a Breakup Length BL/D vs. Liquid Velocity ($D_1 = 3.051$ mm, $D_2 = 1.194$ mm)

Fig.4b Breakup Length BL/D vs. $(We^{1/2} + 3We/Re)$ ($D_1 = 3.051$ mm, $D_2 = 1.194$ mm)

Fig.4c Growth Rate of Axisymmetric Disturbances.

Fig.5 Normalized Droplet Size Distribution at Different Reynolds Numbers.

Fig.6 Cumulative Percentage of Droplets Smaller than a Certain Diameter as a Function
of Reynolds Number.

Fig.7 d_{10} , d_{20} , d_{30} , d_{32} at Different Reynolds Numbers ($D_2 = 1.194$ mm).

Fig.8 d_{10} , d_{20} , d_{30} , d_{32} at Different Reynolds Numbers ($D_1 = 3.051$ mm).

ρ	Density
σ	Surface tension
ν	Kinematic viscosity of jet
μ	Viscosity

Subscripts

1	Refer to large capillary tube
2	Refer to small capillary tube
c	Centerline property
e	Entry length
g	Gas phase property
G	Geometric mass mean diameter
j	Jet property
L	laminar condition
l	Liquid phase property
o	Ex'l. condition
opt	Refers to optimum wave length for Rayleigh Breakup
T	Refers to turbulent condition

Superscripts

*	Refers to the most dominant disturbance
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Fig.2 Characteristic Development of the Large Liquid Jet at Different Reynolds Numbers, a) $Re=6308$, b) $Re=14195$, c) $Re=17349$, d) $Re=22080$, f) $Re=28390$.

Fig.4a Breakup length BL/D vs. Liquid Velocity ($D_1=3.051$ mm, $D_2=1.194$ mm)

Fig.4c Growth Rate of Axisymmetric Disturbances.

Fig.6 Cumulative Percentage of Droplets Smaller than a Certain Diameter as a Function of Reynolds Number.

Fig.8 d10, d20, d30, d32 at Different Reynolds Numbers ($D_1 = 3.051 \text{ mm}$).

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