

BRIEF COMMUNICATIONS

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Onset and end of drop formation along the surface of turbulent liquid jets in still gases

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The onset and end of drop formation along the surface of turbulent liquid jets in still gases was studied for liquid/gas density ratios greater than 500 where aerodynamic effects are small. Measurements were correlated using a phenomenological turbulent breakup theory based on the interactions between the turbulence energy spectrum and the energy requirements for drop formation. The onset and end of drop formation along the surface generally was associated with turbulent eddies in the internal and large-eddy subranges of the turbulence spectrum, respectively, although breakup of the entire liquid column ends breakup along the surface in some instances, as well. © 1995 American Institute of Physics.

Drop formation along the surface of liquid jets in still gases is an important fundamental process relevant to liquid jet atomization. Earlier work has considered the onset of drop formation and the variation of drop sizes with distance from the jet exit for turbulent liquid jets, successfully correlating these properties based on a phenomenological turbulent breakup theory.¹⁻³ New measurements and phenomenological analysis were undertaken during the present study—emphasizing processes causing drop formation to end—in order to gain a better understanding of drop formation along the surface of turbulent liquid jets in still gases.

The test apparatus was the same as in previous works,¹⁻⁴ and involved vertically downward injection of various liquids in still air at normal temperature and pressure. The liquid injectors had rounded inlets followed by straight tubes, with tube length/diameter ratios, $L/d \geq 40$, in order to ensure fully-developed turbulent pipe flow at the jet exit.¹⁻⁴ Pulsed shadowgraphy was used for flow visualization and measurements. Measurements were averaged over five observations to yield experimental uncertainties (95% confidence) less than 25%, dominated by the statistical variations of drop and ligament separation from the liquid surface. Results considered include present measurements, as well as earlier data for similar conditions,^{1,2,5,6} yielding Weber numbers ($We_{fd} = \rho_f du_0^2 / \sigma$) of $1.0 \times 10^2 - 1.1 \times 10^6$, Reynolds numbers ($Re_{fd} = \rho_f du_0 / \mu_f$) of $3.4 \times 10^3 - 8.5 \times 10^5$ and Ohnesorge numbers ($OH_d = \mu_f / (\rho_f d \sigma)^{1/2}$) of 0.001–0.017, where ρ_f is the liquid density, u_0 is the average liquid velocity at the jet exit, σ is the surface tension of the liquid, and μ_f is the viscosity of the liquid. Aerodynamic effects were small over the test range because liquid/gas density ratios were larger than 500.³

Figures 1–3 are shadowgraphs illustrating the general

nature of drop formation for present test conditions. The positions noted in the figure captions refer to the distance, x , between the injector exit and the tip of the reference pin visible in each shadowgraph. At the lowest We_{fd} , Fig. 1, the liquid column does not generate drops until it breaks up as a whole; this behavior is conventionally called first wind-induced breakup.^{4,7} Different behavior is observed at larger We_{fd} , Fig. 2, where drop formation from the tips of ligaments starts along the liquid surface at $x/d \approx 10$, and the liquid column is surrounded by drops at larger distances from the injector exit; however, careful study of surface ligament behavior shows that drop formation along the liquid surface actually stops again at $x/d \approx 66$ which is before the liquid column breaks up as a whole. Finally, a third behavior is observed at even higher values of We_{fd} , Fig. 3, where drop formation from the tips of ligaments starts along the liquid surface at $x/d \approx 5$, and careful study of surface ligament behavior shows that this type of surface breakup persists over the whole liquid column (and even continues from the surface of the large ligaments formed by liquid column breakup). Naturally, once drop formation starts along the liquid surface, the liquid column is shrouded by drops to some extent, even when drop formation along the surface subsequently stops; therefore, the behavior illustrated in both Figs. 2 and 3 is conventionally called second wind-induced breakup regime.^{4,7}

The phenomena discussed in connection with Figs. 1–3 can be explained by extending the earlier turbulent breakup theory of Wu *et al.*^{1,2} to consider the large-eddy subrange of the turbulence spectrum, and combining these results with earlier liquid core length findings for turbulent liquid jets in still gases.^{1,5,6} Present considerations are limited to conditions where aerodynamic effects are small; therefore, the main hypothesis of the turbulent breakup theory is that drops are formed from turbulent eddies when the kinetic energy of radial fluctuations of the eddy is larger than the surface en-

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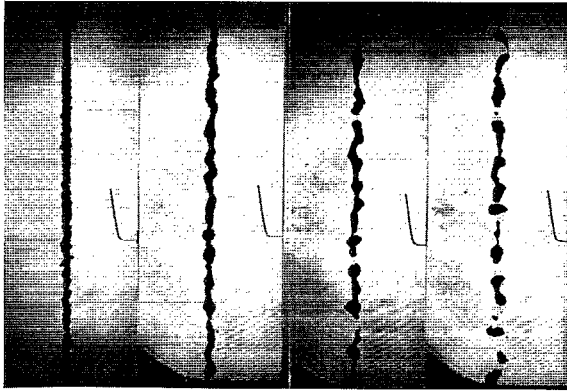


FIG. 1. Shadowgraphs of a turbulent water jet in still air at $We_{fd}=4940$ and (left to right) $x/d=20, 70, 120,$ and 170 .

ergy required to form a drop of corresponding size.^{1,2} This yields the following criterion for drop formation:

$$\rho_f v_l^2 (\pi l^3 / 6) / 2 \geq C_l (4 \pi l^2) \sigma, \quad (1)$$

where l is the characteristic eddy size, v_l is the radial fluctuation velocity corresponding to l , and C_l is an empirical factor of order of magnitude unity to account for various geometrical and scaling factors. Drop sizes observed over the test range were significantly larger than the Kolmogorov length scale; therefore, subsequent considerations will be limited to turbulent eddies in the large-eddy and inertial sub-ranges (although drop sizes after turbulent breakup comparable to the Kolmogorov length scale can be encountered in some instances and which merits attention). Then, the radial fluctuation velocity can be estimated as $v^2 \sim kE(k)$, where k is the wave number and $E(k)$ is the three-dimensional energy spectrum which exhibits slopes of 1 and $-5/3$ in the large-eddy and inertial subranges.^{1,8} For present purposes, the transition between these two regimes will be ignored and the spectrum will be approximated by straight lines following the power law fits for the large-eddy and inertial sub-ranges, illustrated in Fig. 4. Given these approximations, v_l can be related to the radial root-mean-square fluctuating velocity, v' , and the radial integral scale, Λ , as follows:

$$v_l / v' \sim (l / \Lambda)^n, \quad (2)$$

where $n = -1$ and $1/3$ for the large-eddy and inertial sub-ranges, respectively. The range of drop sizes that can be observed as a result of turbulent breakup can then be found by

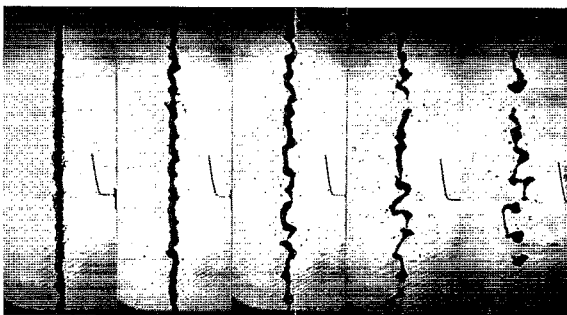


FIG. 2. Shadowgraphs of a turbulent water jet in still air at $We_{fd}=11\ 920$ and (left to right) $x/d=20, 75, 150, 200,$ and 250 .

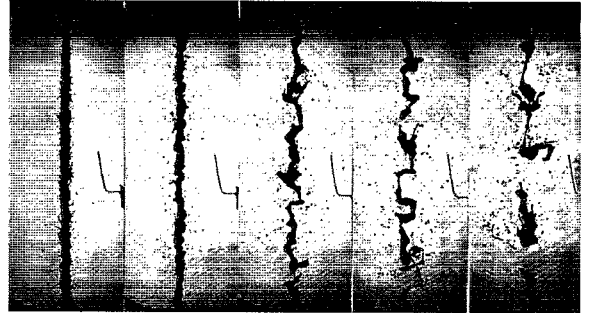


FIG. 3. Shadowgraphs of a turbulent water jet in still air at $We_{fd}=20\ 280$ and (left to right) $x/d=20, 70, 170, 230,$ and 255 .

substituting Eq. (2) into Eq. (1) and assuming that l is proportional to the Sauter mean diameter, SMD, of the spray, as follows:

$$C_{is} We_{fd}^{-0.6} \leq \text{SMD} / d \leq C_{es} We_{fd}, \quad (3)$$

where C_{is} and C_{es} are empirical constants associated with drop sizes at the onset and end of turbulent breakup along the surface. Notably, the onset drop size of Eq. (3) was in reasonably good agreement with the observations of Wu *et al.*,¹ yielding $C_{is}=2.37$.

The location of the onset and end of drop formation along the liquid surface can be found by estimating the time and distance from the jet exit that is required to form a drop of a given size, l . It was assumed that the time required to form a drop, τ , was proportional to the Rayleigh breakup time scale of an eddy of size l , i.e., $\tau \sim (\rho_f l^3 / \sigma)^{1/2}$, see Wu *et al.*¹ In the same way, it also was assumed that the growing disturbances at the surface of the turbulent liquid were convected with the mean streamwise injection velocity so that the distance from the jet exit to the breakup location, $x \sim \tau u_0$. Combining these ideas with Eq. (3) yields

$$C_{ix} We_{fd}^{-0.4} \leq x / d \leq C_{ex} We_{fd}^2, \quad (4)$$

where C_{ix} and C_{ex} are empirical constants associated with the locations of the onset and end of turbulent breakup, x_i and x_e , along the surface.

The feasibility of drop formation at the maximum energy condition of the turbulence spectrum is an important aspect of breakup along the liquid surface. From Fig. 4 the maximum energy condition occurs at $l=l_e$ where $l_e/\Lambda=4.3$ and the characteristic eddy velocity at l_e is $v_{le}/v'=1.6$.⁸ Introducing these factors into Eq. (1), then yields a critical Weber number for no turbulent breakup along the liquid surface of $We_{fd}^*=2450$.

Another interesting limit on conditions for drop formation along the surface of turbulent liquid jets is provided by the length of the liquid core, L_c . This length can be estimated by noting that breakup of the liquid core occurs when drop sizes formed by breakup along the liquid surface are comparable to the diameter of the liquid core itself, when aerodynamic effects are small, as follows:¹

$$L_c / d = C_c We_{fd}^{1/2}, \quad (5)$$

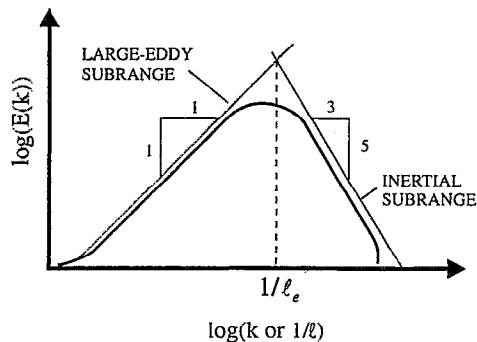


FIG. 4. Sketch of three-dimensional turbulent energy spectrum.

where C_c is an empirical constant of order unity. Grant and Middleman⁵ and Chen and Davis⁶ measured L_c for turbulent liquid jets in still gases, when aerodynamic effects were small, also finding L_c along the lines of Eq. (5).

The discussion of Eqs. (4) and (5) suggests that the onset and end of turbulent breakup along the liquid surface, and the length of the liquid core, all correlate in terms of We_{fd} . Thus present measurements of these properties, as well as the earlier results of Wu and coworkers,¹⁻³ Grant and Middleman⁵ and Chen and Davis⁶ are plotted as suggested by Eqs. (4) and (5) in Fig. 5. It is evident that fair correlations of x_i/d , x_e/d , and L_c/d can be obtained in this manner. The expression for the location of the onset of turbulent breakup along the surface is

$$x_i/d = 2000 We_{fd}^{-0.67} \quad (6)$$

with standard deviations of the coefficient and power of 10% and 12%, respectively, and the correlation coefficient of the fit equal to 0.91. The large value of the coefficient of Eq. (6) comes about because it is proportional to $(u_0/v_0')^{9/5}$, which is a large number of turbulent pipe flow.¹ The expression for the end of turbulent breakup along the surface is

$$x_e/d = 1.58 \times 10^{-5} We_{fd}^{1.68} \quad (7)$$

with standard deviations of the constant and power of 16% and 11%, respectively, and the correlation coefficient of the fit equal to 0.94. Finally, the expression for L_c is

$$L_c/d = 7.40 We_{fd}^{0.34} \quad (8)$$

with standard deviations of the constant and power of 4% and 3%, respectively, and the correlation coefficient of the fit equal to 0.98. The differences between the powers suggested by Eqs. (4) and (5) and the powers found from the empirical fits of Eqs. (6)–(8) are statistically significant but are not large in view of the approximations of the theory and the uncertainties of the measurements.

The correlations for x_i and x_e/d divide the flow into surface and no surface breakup regimes, and intersect each other at $We_{fd}^* \approx 2800$, which is close to the earlier prediction of $We_{fd}^* = 2450$. The measurements yield a higher value, $We_{fd}^* \approx 5200$, with the smaller predicted value resulting from the simplified power law approximation of the energy spectrum illustrated in Fig. 4. For $We_{fd} \leq 5200$, the jets do not undergo surface breakup which corresponds to the conventional first wind-induced breakup regime.^{4,7} For $5200 \leq We_{fd} \leq 17000$, the liquid jet exhibits both the onset and end

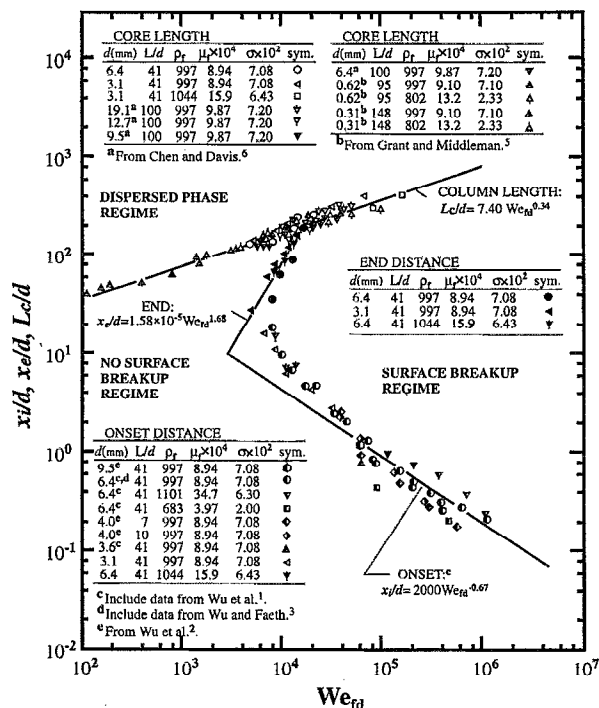


FIG. 5. Surface breakup regime map for turbulent liquid jets in still gases when aerodynamic effects are small.

of surface breakup before the liquid column breaks up as a whole. Finally, for $We_{fd} \geq 17000$, surface breakup continues beyond the end of the liquid column. For moderate values of $We_{fd} \geq 5200$, the onset of surface breakup begins at some distance from the jet exit and the flow would be described as second wind-induced breakup.^{4,7} With increased We_{fd} , however, turbulent liquid surface breakup begins progressively closer to jet exit, eventually reaching the criterion for the atomization breakup regime where surface breakup occurs close to the injector exit.^{4,7}

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