we have $F_z > 0$ and the particle of fluid accelerates near the wall of the pipe up to the complete establishment of the velocity W corresponding to Poiseuille flow. The maximum value of ω^2 for which the inequality (23) holds for any value of z, is $\omega^2 = 5.77$. Obviously the function on the right hand side of (23) is less than the function y(z/Re) shown in Fig. 2 for any value of z.

Hence we conclude that when $\omega^2 > 25.91$, the force F_z changes sign at a certain distance z, and in this case a particle of fluid slows down and changes direction at $z = z_0$. For the region of twist parameters $5.77 < \omega^2 < 25.91$, the distance at which a fluid particle braked near the wall of the pipe is not large enough to lead to back flow near the wall.

The study of the behavior of F_z as a function of the distance z can be used in an experimental verification of the appearance of back flow near the wall.

NOTATION

r, z, coordinates of a point in the cylindrical coordinate system; v_r, v_φ, v_z, components of the velocity vector in cylindrical coordinates; P, pressure of the liquid; V, W, U, Π, dimensionless components of the velocity vector and pressure, respectively; P_0, v_0, pressure and velocity of the liquid entering the pipe; g, acceleration of gravity; ν, kinematic viscosity; R, radius of the pipe; ω_0, angular velocity of rotation of the pipe; Re, Fp, ω, Reynolds number, separation factor, and twist parameter, respectively; q(z), Q(z), dimensionless functions in the formula for Π; ε, a, b, expansion parameters of the function U; p, parameter in the Laplace transform; $\bar{W}$, $\bar{q}'$, $\bar{Q}'$, Laplace transforms of the function W and the derivatives q' and Q'; I_0, I_2, Bessel functions of imaginary argument of order zero and two; J_0, J_2, Bessel functions of real argument or order zero and two; μ_n, zeros of the Bessel function J_2.

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DROPLET FORMATION FROM A JET OF ONE LIQUID ENTERING ANOTHER

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Wave theory has been used to derive expressions for the droplet sizes under various flow conditions.

When a jet of one liquid enters another but does not mix with it, waves are formed at the interface, which govern the break-up into droplets. If the jet is vertical, the break-up occurs in droplet, jet axisymmetric, jet bending, and spraying modes.

In droplet mode, the drops form at the end of the nozzle, which may be considered as a gravitational wave, length λ_g. As a drop forms, a capillary wave λ_σ forms at the surface, which moves over it towards the nozzle. If we neglect the efflux speed and assume that droplet formation ends when the capillary wave has traveled half the perimeter and reaches the axis, while the gravitational wave at the same time has traveled the nozzle radius, we have,

$$\pi D/(2)\, w_\sigma = d/(2)\, w_g. \tag{1}$$

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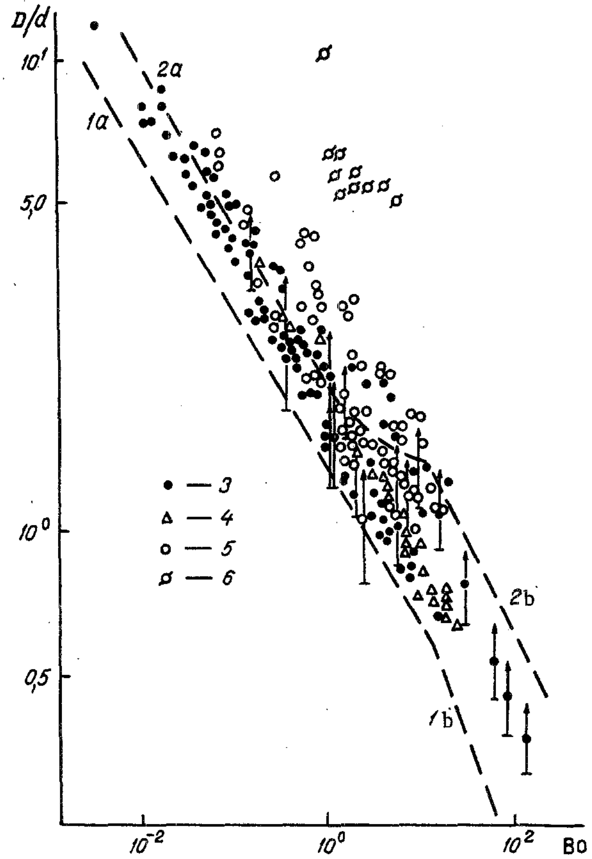

Fig. 1. Droplet (bubble) sizes in droplet (bubble) efflux for one liquid entering another when gravitational waves are significant: 1 and 2) theory (1a from (2), 1b from (3), 2a from (5), and 2b from (6)); 3-6) measurements correspondingly for liquid in liquid, liquid in gas, gas in a liquid from an advanced nozzle, and from a hole in the wall.

We substitute for the capillary and gravitational-wave speeds in (1) and assume $\lambda_\sigma = d/2$, $\lambda_g = \pi D$ to get

$$D/d = (2)/\pi^{1/3}\,(\mathrm{Bo})^{1/3}. \tag{2}$$

If $d > \pi(\sigma/\Delta\rho g)^{1/2}$, the surrounding medium will flow into the nozzle [1]; we assume then that the liquid emerges through a hole having diameter $d' = \pi(\sigma/\Delta\rho g)^{1/2}$, and define

$$D/d = (2)/(\mathrm{Bo})^{1/2}. \tag{3}$$

Then (2) can be used for $(\mathrm{Bo}) \leq \pi^2$ and (3) for $(\mathrm{Bo}) \geq \pi^2$.

If w_1 cannot be neglected and we assume that there is potential flow within the drop along the boundary at a speed equal to the speed of efflux from the nozzle, (1) becomes as follows as it applies for $(\mathrm{Bo}) \leq \pi^2$:

$$\pi D/(2)\,(w_\sigma + w_1) = d/(2)\,w_g, \tag{4}$$

while (2) and (3) correspondingly become

$$D/d = (2)^{1/3}\,[(2)\,\pi^{1/2} + (\rho_1+\rho_2)^{1/2}\,(\mathrm{We})_1^{1/2}/\rho_1^{1/2}]^{2/3}/\pi^{2/3}\,(\mathrm{Bo})^{1/3}, \tag{5}$$

$$D/d = (2)^{1/3}\,[(2)\,(\mathrm{Bo})^{1/4} + (\rho_1+\rho_2)^{1/2}\,(\mathrm{We})_1^{1/2}/\rho_1^{1/2}]^{2/3}/(\mathrm{Bo})^{2/3}. \tag{6}$$

The droplet flow mode evidently goes over to the jet one for

$$w_1 + w_g \geqslant w_\sigma, \tag{7}$$

and the drops begin to form not at the end of the nozzle but at the end of the jet section. For $(\mathrm{Bo}) \leq \pi^2$, (7) becomes

$$(\mathrm{We})_1 \geqslant \rho_1\,[(2)\,\pi^{1/2} - (2)^{1/3}\,(\mathrm{Bo})^{1/3}/\pi^{1/6}]^2/(\rho_1+\rho_2), \tag{8}$$

and for $(\mathrm{Bo}) \geq \pi^2$

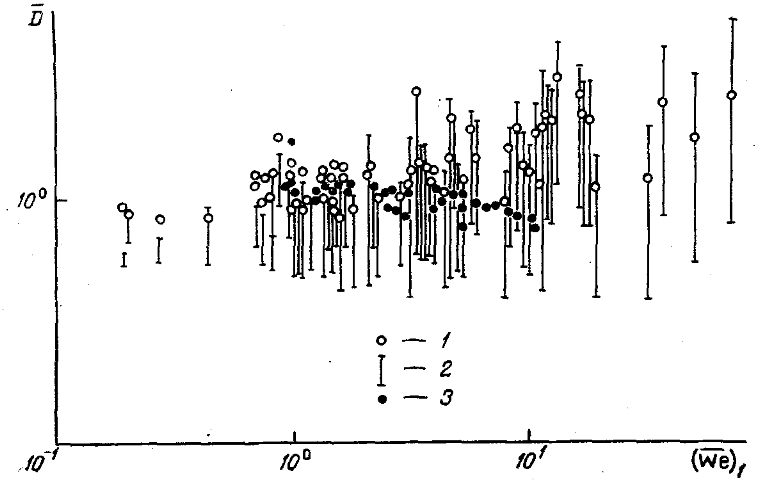

Fig. 2. Maximum droplet sizes in axisymmetric and bending break-up for a jet of one liquid entering another: 1) $\bar{D}_{ax}$; 2) $\bar{D}_{1be}$-$\bar{D}_{2be}$; 3) $\bar{D}_d$.

$$(We)_1 \geqslant \rho_1 [(2)(Bo)^{1/4}/\pi^{1/2} - (2)^{1/3}(Bo)^{1/3}/\pi^{1/6}]^2/(\rho_1 + \rho_2). \tag{9}$$

One applies (9) when the difference in the square brackets is positive, i.e., for $(Bo) < (2)^8/\pi^4$; as this quantity is less than π^2, it is clear that the efflux is always of jet type for $(Bo) \geq \pi^2$, and (9) is then inapplicable.

In jet mode, capillary waves arise at the end of the jet part, whose minimal length is defined by an expression derived in [2]. If the wave amplitude increases at a rate derived in [2] and becomes $\alpha = d/2$ during the advance of the end of the jet by a distance equal to the wave length, one gets a drop formed at the end of the jet part having size

$$D/d = (3)^{1/3}(\rho_1/\rho_2)^{2/9}[1/(2)^{1/2}\pi^{1/2}\beta(We)_1^{1/2} + (2)^{7/2}\pi^{3/2}/\beta(We)_1(Lp)_1^{1/2}]^{2/9} \tag{10}$$

for $(Bo) \leq \pi^2$ or

$$D/d = (3)^{1/3}(\rho_1/\rho_2)^{2/9}[\pi^{1/2}/(2)^{1/2}\beta(We)_1^{1/2}(Bo)^{1/2} + (2)^{7/2}\pi^{3/2}/\beta(We)_1(Lp)_1^{1/2}]^{2/9} \tag{11}$$

for $(Bo) \geq \pi^2$.

These conditions correspond to axisymmetric break-up.

As [2], $\lambda \gtrsim \alpha$, axisymmetric break-up persists while $\lambda \geq d/2$, since otherwise drop formation does not go to completion. For $\lambda < d/2$, there is a transition from axisymmetric mode to bending decomposition because the jet loses stability. If $(Bo) \leq \pi^2$, this occurs for

$$(We)_1 \geqslant \rho_1/\pi^{1/2}\beta\rho_2 + [\rho_1^2/\pi\beta^2\rho_2^2 + (2)^5\pi^{3/2}\rho_1/\beta(Lp)_1^{1/2}\rho_2]^{1/2}, \tag{12}$$

and if $(Bo) \geq \pi^2$, for

$$(We)_1 \geqslant (Bo)^{1/4}\rho_1/\pi\beta\rho_2 + [(Bo)^{1/2}\rho_1^2/\pi^2\beta^2\rho_2^2 + (2)^5(Bo)^{3/4}\rho_1/\beta(Lp)_1^{1/2}\rho_2]^{1/2}. \tag{13}$$

In bending mode, one gets short waves, $\lambda = 3\pi d(\rho_1 + \rho_2)/(We)_1\rho_2$ [3], and long ones, $\lambda = \pi d$ [4], no matter what the direction of motion. One can assume that the liquid emerging into a gas, where $\rho_1 \gg \rho_2$, allows one to neglect α by comparison with λ, whereas $\alpha = d/2$ for a liquid emerging into a liquid [4].

If one approximates the sinusoidal wave profile in the last case as straight-line segments joining the nodes and antinodes, the drop size formed on spheroidization for short waves is

$$D/d \approx (3)^{2/3}\pi^{1/3}(\rho_1 + \rho_2)^{1/3}/(2)^{1/3}\rho_2^{1/3}(We)_1^{1/3}, \tag{14}$$

and for long ones

$$D/d \approx (3)^{1/3}(4 + \pi^2)^{1/6}/(2)^{1/3} \approx 1.78, \tag{15}$$

which is somewhat less than the more accurate solution.

The drops move in the surrounding liquid with a speed equal to that of the wave moving on the nozzle axis in bending break-up. If the length of the wave sinusoid is l, the wave is displaced by λ when the liquid travels that distance at the nozzle speed w_1, so correspondingly for short and long waves

$$w_{je} \approx w_1, \tag{16}$$

$$w_{je} = \pi w_1/(4+\pi^2)^{1/2}. \tag{17}$$

The following is the condition for droplet break-up in an inviscid liquid moving in another liquid [5]:

$$(\mathrm{We}) \equiv \rho_2 w_{je}^2\, D/\sigma \geqslant (2)^5\, \pi/(3)^3\, \beta, \tag{18}$$

and on substitution for the droplet size from (14) and (15) and for the speed from (16) and (17) we get for short and long waves correspondingly

$$(\mathrm{We})_1 \geqslant (2)^8\, \pi\, [\rho_1^3/\rho_2^2\,(\rho_1+\rho_2)]^{1/2}/(3)^{11/2}\, \beta^{3/2}, \tag{19}$$

$$(\mathrm{We})_1 \geqslant (2)^{16/3}\, (4+\pi^2)^{5/6}\, \rho_1/(3)^{10/3}\, \pi\rho_2. \tag{20}$$

The $(\mathrm{We})_1$ defined by (20) are less than those that (12) and (13) show should be attained for bending break-up. Then drops formed by such break-up from long waves should themselves break up during subsequent movement. Calculations from (19) and (12)-(13) show that droplets formed at short wave lengths begin to break up for $(\mathrm{We})_1$ somewhat larger than those for bending break-up. As the break-up occurs in a time during which the drop is retarded, the right sides in (19) and (20) should be considered somewhat underestimates, and one cannot obtain a solution in explicit form for the maximum stable diameter from (18).

In spraying mode, not only do the drops formed by bending break-up themselves break up but so does the jet by a wave closure mechanism, with the waves formed at the surface as a result of the motion relative to the medium at w_{je} [5].

Then if bending break-up sets in and $(\mathrm{We})_1$ rises further, the large drops first break up and then the small ones, and the jet soon degenerates to a spray. The resulting hydrodynamic processes are complicated, and the results cannot be evaluated theoretically.

These expressions have been compared with measurements on drops formed by vertical jets of liquid in liquid [6-14], horizontal liquid jets entering gases [3, 6, 15-19], vertical ones entering gases [10, 20-22], vertical gas streams entering liquids at very low speeds from nozzles inserted in the liquid [23-30], or from nozzles placed on a level with the wall [31-34], as well as with data on the modes of interaction and their changes in liquid—liquid systems [7, 35-37], and liquid—gas ones [38, 39].

In [14], an attempt was made to unify the theory of drop and bubble formation for a jet of one liquid entering another on the basis of force balance. In Fig. 1, the wave theory is used for droplet (or bubble) outflow where gravitational forces are significant. The measurements for liquid—liquid, liquid—gas, and gas—liquid systems [23-34] mainly fall between lines 1a and 2a or 2b, which have been derived for the maximum possible $(\mathrm{We})_1$ corresponding to this flow mode. When one knows the $(\mathrm{We})_1$ dependence of D/d (indicated by arrows), the measured values for low efflux speeds lie near the lower theoretical limit, and for high speeds near the upper one. Such information is lacking for most of the data here, so one supposes that the position close to the upper boundary is related not only to theory errors but also to the data being obtained for fairly high efflux speeds. For $(\mathrm{Bo}) > \pi^2$, as $D < d$, one should take w_1' as the speed of the liquid that accelerates the capillary wave, which is the larger than w_1 the smaller the drop diameter by comparison with the nozzle one. As we have only restricted information on the flows within the drops, it is not possible to correct (6); to a first approximation, it is likely that $w_1' \sim w_1 d^2/D^2$.

For gas bubbles formed at a nozzle with a fairly thick wall, it is found that the base of the bubble slides over the wall during formation, and this applies even more to holes in a wall. Then the path traveled by a gravitational wave and ending in bubble formation is not the d/2 supposed for (1) but a somewhat larger distance, which increases the formation time and size for the resulting bubble (Fig. 1). If one knows the relation between the bubble base radius and the wetting angle for a particular outflowing liquid, surrounding liquid, and wall system, one can use the bubble (droplet) dynamics to derive D/d as a function of (Bo) for a gas (liquid) entering from a hole in the wall.

Then if $w_1 \to 0$ and one has to consider gravitational waves, the expressions derived from wave theory describe the droplet and bubble flow modes. Previously, the wave theory has been used [40] to derive expressions for the subordinate state in bubble flow where increase in w_1, size reduction, and increased capillary-wave speed enable one to neglect gravitational waves. It has proved impracticable to perform a generalization for these speeds and larger ones for gas entering a liquid and for a liquid entering a gas, when one factor here is evidently the relation between the inertia factors for the interacting media, which differ by several orders of magnitude, particularly when the efflux speed is decisive.

As the efflux speed for a liquid increases, there is a transition from droplet to jet flow under certain conditions [7, 9, 35, 38, 39], and one gets a jet section with a certain length. These conditions have been described empirically [9, 38] or from certain theoretical concepts [35, 39].

From the wave-theory viewpoint, the transition to jet flow occurs when (8) is met, which for a liquid entering a liquid or a gas describes the upper limit to the observed relation between $(\mathrm{We})_1$ and (Bo), as is evident from [7, 9, 35] as well as [38, 39]. One can compare the transition conditions provided by (12) with those found in [36, 37] for the transfer from axisymmetric to bending break-up; it is found that (12) describes the lower limit to the measurements. For (Bo) < 0.26-0.28, the $(\mathrm{We})_1$ derived from (12) are less than those from (8), which causes a delay in the transition to bending break-up and leads to degeneration in axisymmetric break-up. For $(\mathrm{Bo}) \to \pi^2$, which occurs for $\sigma \to 0$, as in experiments [13], the droplet formation appears to degenerate into turbulence, which also delays the transition to bending break-up.

Figure 2 shows the droplet size in axisymmetric and bending break-up for a liquid—liquid system. We have taken the ratio of the actual $(\mathrm{We})_1$ to the value required by (12) for transition to bending break-up, $(\mathrm{We})_{be}$, as index. The observed maximum sizes have been referred to the diameters calculated from (10), (14), and (15) for the axisymmetric case $\bar{D}_{ax}$, the bending case due to short waves $\bar{D}_{1be}$, and long waves $\bar{D}_{2be}$. In the latter two cases, the sizes are represented by ranges. For $(\mathrm{We})_{be} < (\mathrm{We})_{je}$, when there is delay in bending break-up, the efflux occurs in droplet mode, and the ratio of the observed maximum size to that calculated from (5) is denoted by $\bar{D}_d$.

Figure 2 shows that in the axisymmetric state, with $(\overline{\mathrm{We}})_1 \leq 1$, $\bar{D}_{ax}$ is close to one, so (10) describes the maximum drop sizes for these conditions satisfactorily.

In bending break-up for $(\overline{\mathrm{We}})_1 \simeq 1$-3, the largest droplets are formed mainly by the jet breaking up into segments corresponding to the length of the short waves, as is clear from the upper limit to $\bar{D}_{be}$ corresponding to $\bar{D}_{1be}$ being close to one. For these conditions, the maximum drop size is given by (14). For $(\overline{\mathrm{We}})_1 < 3$, the values given by (10) and (14) are similar.

For $(\overline{\mathrm{We}})_1 > 3$ in bending break-up, the sizes are in a range whose lower limit is provided by (14) and the upper by (15); the higher $(\overline{\mathrm{We}})_1$, the closer are the maximal sizes to the upper limit found in measurements, and calculations from (15) are justified for $(\overline{\mathrm{We}})_1 \geq 10^1$-$10^2$. Then the larger $(\overline{\mathrm{We}})_1$, the more likely it is that drops are formed by long-wave break-up. The calculation accuracy is here lower than previously because of break-up in the droplets on attainment of the $(\mathrm{We})_1$ defined by (19) and (20).

For $(\mathrm{We})_{je} > (\mathrm{We})_{be}$, Fig. 2 shows that $\bar{D}_d \simeq 1$, and the jet emerges in droplet mode for all available measurements, while the size can be determined from (5) at least up to $(\overline{\mathrm{We}})_1 \simeq 10$.

For the liquid—gas case, nearly all the maximum-size measurements for axisymmetric and bending break-up relate to horizontal jets and small (Bo).

Here axisymmetric break-up implies that (10) gives very large drops because ρ_2 is small (curves 2a-2c in Fig. 3). On the other hand, the Rayleigh break-up [1] occurs more rapidly and the droplet sizes are much less. Therefore, in [3, 6, 15, 16], in most cases the maximum size was close to the theoretical $D \simeq 1.89d$. However, in some measurements

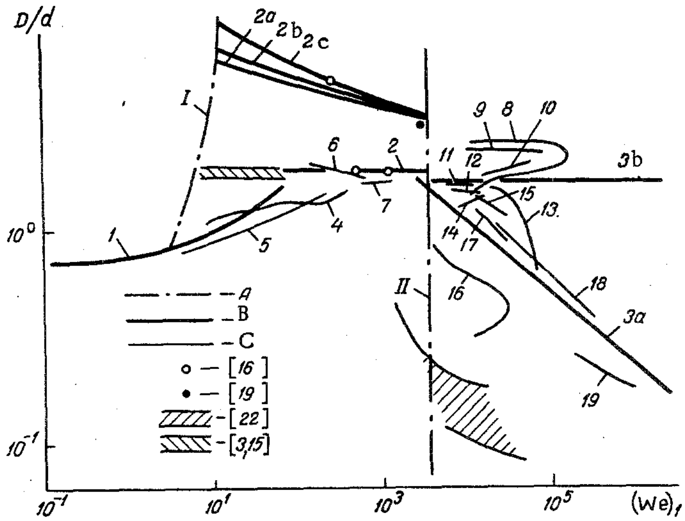

Fig. 3. Droplet sizes for a liquid flowing into a gas: A) flow state bounds (I according to (8) for $\rho_1/(\rho_1+\rho_2)\to 1$; II from (12) for $\rho_1/\rho_2 = 10^3$ and (Lp) = 10^2-10^6); B) calculated maximum sizes (1 from (5) for (Bo) = π^2; 2 according to Rayleigh [1]; 2a-2c from (10) with (Lp) = 10^6, 10^4 and 10^2 correspondingly; 3a from (14); and 3b from (15)); C) data from: [20] (4); [21] (5); [16] (6); [15] (7); [18] (8-16); [17] (17-19).

[16] and [19], larger drops were obtained corresponding to the (10) sizes. In fact, Rayleigh axisymmetric break-up is accompanied in some cases by axisymmetric break-up due to capillary waves, which can be described by (10), and experiment reveals this as occasional doubled or tripled droplets.

Jet flow in vertical jets means that the (5) sizes are less than the (10) ones because ρ_2 is small; therefore, even in jet mode, droplets can be formed via gravitational waves if the capillary waves are less significant because of the low surface tension. Measurements [20, 21] at high (Bo) give maximal sizes for vertical jets corresponding, as regards order of magnitude and dependence on $(\mathrm{We})_1$, to (5). Consequently, in axisymmetric break-up, the Rayleigh state does not always apply, which had been assumed previously.

In bending break-up for a liquid emerging into a gas, the maximal sizes found in [17] agreed well with (14) (curve 3a in Fig. 3), whereas the measurements of [18] for the same $(\mathrm{We})_1$ corresponded mostly to (15) (curve 3b) and only in isolated cases tended to those from (14). The variation in mean size with $(\mathrm{We})_1$ according to [22] is qualitatively in accordance with (14) but with sizes less than the maximal ones by an order of magnitude. Therefore, the jet breaks up on long and short waves, as for a liquid entering a liquid.

It is evident that the break-up occurs in the same way in bending mode. The drops spheroidize, and as (20) is always obeyed, while (19) is so when the $(\mathrm{We})_1$ given by (12) and (13) slightly exceeds the value for bending break-up, these drops themselves split up to form a size spectrum.

The wave theory enables one to classify all the cases of break-up for a jet of liquid entering another liquid or a gas. At very low efflux speeds, gravitational waves participate. Then the droplet and bubble states can be combined in one model described by (2)-(5). In axisymmetric break-up for a liquid entering a liquid, the jet splits up because capillary waves grow, as (10) and (11) show, while when a liquid enters a gas, the model describes the formation of duplicated and triplicated droplets, which are characteristic of Rayleigh break-up in that state. If the surface tension is very low and the Bond number is large, gravitational waves may be important for values of the Weber number characteristic of axisymmetric break-up, and then one can calculate the maximum size from (5); this also occurs when there is a delay in transition to bending break-up. In bending break-up, the jet splits up into segments corresponding to short and long waves (see (14) and (15)). When a liquid enters a liquid, the second will at first predominate as the Weber number increases, while the first evidently will predominate for a liquid entering a gas. When bending break-up occurs, the first droplets split up into secondary smaller ones, and this becomes more pronounced as the Weber number increases. These processes evidently determine the droplet sizes in spraying.

NOTATION

$(We)_1 \equiv \rho_1 w_1^2 d/\sigma$; $(Bo) \equiv \Delta\rho g d^2/\sigma$; $(Lp)_1 \equiv \rho_1 d\sigma/\mu_1^2$; λ, α, and w, wavelength, amplitude, and speed; d, nozzle diameter; $\bar{D}$, ratio of actual drop diameter to theoretical value; D, drop diameter; w_1, jet efflux velocity; ρ and μ, liquid density and viscosity; Δρ, density difference between liquid and medium; σ, interfacial tension; w_{je}, speed of jet element along nozzle axis in bending mode; $(\bar{We})_1$, ratio of actual value to that calculated from (12); β, constant from [1, 2] (β ≈ 0.3). Subscripts: g, gravitational; σ, capillary; l, emerging liquid; 2, surrounding medium; je, jet; d, drop; ', within drop; ax, axisymmetric; be, bending.

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