MONODISPERSE BREAKUP OF LIQUID JETS

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The monodisperse breakup of liquid jets with various physical properties is investigated experimentally and theoretically over a wide range of jet breakup parameters.

There is growing interest at the present time in the monodisperse breakup of liquid jets of various substances. The stimulus for such interest lies mainly in the application of flows of monodisperse macroparticles generated by this technique for various devices in electric-arc spray-jet technology, microdosing, granulation of mineral fertilizers, etc.

One of the physical phenomena underlying the generation of flows of macroparticles with a high degree of monodispersity is the forced capillary breakup of jets (FCBJ), which is induced by specially selected effects. The latter can be, e.g., acoustic, electromagnetic, or various periodic perturbations of the jet parameters (velocity, radius, etc.) in its initial cross section.

Many papers have been published on the capillary breakup of jets (see the surveys [1, 2]). However, several fundamental problems have been ignored to data. For example, experimental data on FCBJ over a wide range of jet parameters (diameter, velocity, excitation amplitude, etc.) are unavailable. In recent experiments, Chaudhary and Maxworthy [3, 4] were compelled to scan the wave numbers by varying the mass flow rate at a fixed oscillation frequency in their measurements of the length of the intact part of the jet, because the amplitude—frequency response of the generator exhibited a highly nonuniform behavior. Such a measurement procedure makes it difficult to readjust the operating modes of the generator when the orifice diameter is changed. The majority of theoretical papers (with the exception of [5, 6] and a few others; see [2]) are based on the assumption that the results of describing the capillary instability of an infinite liquid cylinder can be transferred to the instability of a finite jet by Galilean transformation. This assumption is incorrect in general [2], because different types of instability are involved in the indicated problems: Capillary instability is absolute for an infinite liquid cylinder and is convective for a semiinfinite jet emerging from an orifice [7]. Corrections for the convective nature of jet instability have been disregarded so far in processing of the experimental data, imparting ambiguity to the interpretation of the experimental data.

The present study is devoted to FCBJ over a wide range of variation of the jet parameters. The experiments were carried out for liquids with diverse physical properties (water and VM-1 vacuum pump oil at different temperatures) flowing from different types of nozzles (ranging from a die with ratio of duct length to diameter $L_N/D_N \sim 1$ to capillary tubes with $L_N/D_N \sim 80$). In the theoretical plan, we have investigated the convective instability of a viscous liquid jet in the long-wavelength approximation and attempted to correlate specific characteristics of the breakup of a small-diameter jet with the relaxation of surface tension during capillary breakup. A block diagram of the experimental arrangement used to investigated FCBJ is shown in Fig. 1. It includes a droplet generator and a system for diagnosing its parameters. The droplet generator consists of: the chamber 3, into which liquid is admitted under compressed-gas pressure; the piezoelectric modulator 2, which is placed between the base 1 and the chamber 3, both of which are heavy stationary objects. The die 4 is attached to the lower flange of the casing 3. The diagnostic system consists of a Michelson interferometer and the FÉU-85 photomultiplier 8; the interferometer is used for precision measurement of the amplitude of the die oscillations and is formed by the LG-52 laser 7 and the mirrors 5 and 6, the first of which is placed on the oscillating die, while the second is in a fixed position. In order to determine the average velocity of the jet in its cross

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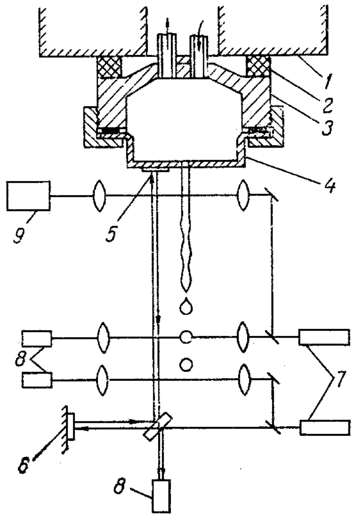

Fig. 1. Block diagram of the experimental arrangement for investigation of the monodisperse breakup of liquid jets. 1) Base; 2) piezoelectric modulator; 3) chamber casing; 4) die; 5, 6) mirrors of Michelson interferometer; 7) helium–neon laser; 8) photomultiplier; 9) sensing element of multichannel optical analyzer.

section, the profile of the undisturbed jet is measured by means of an LG-52 laser and the multichannel optical analyzer (MOA) 9, which operates on line with a microcomputer. The sensor of the MOA is a linear radiation detector using feedback instruments; it comprises a multielement (with the type 1300TsL2-2048 multicell photodetector used in our case) structure on a metal–oxide–semiconductor base made in the form of an integrated microcircuit with a transparent window in the casing for the transmission of optical radiation. Each element of the MOA sensing element has dimensions ~15 × 15 μm, a spectral sensitivity range of 300-900 mm, and a dynamic range of 10^3.

The channels are strictly positioned in the feedback detector system, so that absolute measurements of the jet diameter can be performed within 0.5 μm error limits at 50-fold magnification of the jet in projection onto the plane of the feedback detector system.

The characteristics of the generator are measured in the following sequence. An input is applied to the generator in the form of a periodic voltage signal, and the latter is converted by the piezoelectric modulator into mechanical oscillations of the die, which, in turn, induce periodic oscillations of the pressure and velocity in the generator. These pressure and velocity oscillations are converted at a certain distance from the generator output into surface oscillations, which (given the observance of several conditions) grow and cause the jet to break up. Precision measurement of the amplitude of the die oscillations is performed by means of the Michelson interferometer (Fig. 1) in order to monitor the amplitude of the initial perturbations in FCBJ.

The flow characteristics of the generator were determined by means of an AVN-200 analytical balance and a CAMAC timer. The relative error of measurement of the mass flow did not exceed 0.1%. The length of the intact part of the jet as a function of the generator oscillation frequency f was measured at fixed values of the oscillation amplitude and velocity of the jet. The length of the intact part was recorded within ±100 μm error limits by a microscope, which was moved along the jet in illumination by the light from a stroboscopic tachometer equipped with a device for varying the observation phase.

The measurements established the existence of a correspondence between the amplitude of the generator oscillations and the time of forced capillary breakup, making it possible to correlate the amplitude of the generator oscillations Δ_0 and the initial perturbations of the jet surface δ_0, e.g., by the relation [2]

$$L_j/D_j = \frac{1}{2\gamma_a} \ln\left(\frac{D_j}{2\delta_0}\right) \sqrt{\mathrm{We}}. \tag{1}$$

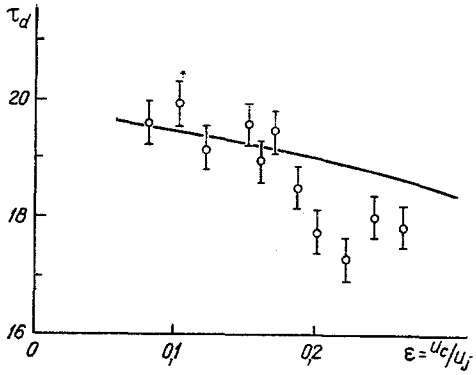

Fig. 2. Dimensionless breakup time τ_d vs ratio of surface strain rate to mean velocity of the jet for a generator with an orifice diameter $D_N = 118 \cdot 10^{-6}$ m.

Knowing the length of the intact part of the jet and introducing the time scale of capillary instability $\tau_* = (\tau R_j^3/\sigma_e)^{1/2}$, we determine the dimensionless breakup time τ_d:

$$\tau_d = \frac{L_j}{U_j \tau_*}. \tag{2}$$

Figure 2 shows an experimental graph of the dimensionless time of forced capillary breakup of a jet emerging from a nozzle with an orifice diameter $D_N = 4.06 \cdot 10^{-4}$ m as a function of the ratio of the surface strain rate to the mean jet velocity $\varepsilon = R_j/\tau_* U_j$ for a nozzle oscillation amplitude $\Delta_0 = 1.5 \cdot 10^{-7}$ m and a wave number k = 0.7. We see that when the jet velocity is decreased at a constant amplitude Δ_0 and wave number k = 0.7, the dimensionless breakup time decreases as ε is increased. Similar dependences were obtained for all the investigated nozzles with orifice diameters D_N in the interval from $4 \cdot 10^{-5}$ to $5 \cdot 10^{-4}$ m. It follows from Eqs. (1) and (2) that in order for the time τ_d to depend on the jet velocity U_j in this case, the instability growth rate γ must depend on the velocity U_j. However, such a dependence $\gamma(U_j)$ does not arise in the description of the capillary instability of jets according to the infinite liquid cylinder model, which is customarily used by several authors (see [2]) to investigate various characteristics of capillary breakup. This is attributable to the fact that the capillary instability of an infinite liquid cylinder is absolute, whereas the capillary instability of a real semiinfinite jet is convective [7] (or, in the terminology of [2], "spatial"). We introduce scales of the longitudinal coordinates $x_* = R_j$, the velocity $u_* = R_j/\tau_*$, and the surface strain $\eta_* = R_j$, and we write the system of equations of the long-wavelength approximation in a dimensionless form describing the convective instability of a viscous liquid jet in the laboratory frame:

$$\frac{\partial u}{\partial t} + V\frac{\partial u}{\partial x} = \frac{\partial \eta}{\partial x} + \frac{\partial^3 \eta}{\partial x} + 3\mathrm{Oh}\frac{\partial^2 u}{\partial x^2}, \tag{3}$$

$$\frac{\partial \eta}{\partial t} + V\frac{\partial \eta}{\partial x} + \frac{1}{2}\frac{\partial u}{\partial x} = 0, \tag{4}$$

where $\mathrm{Oh} = \nu\tau_*/R_j^2$.

We seek a solution of Eqs. (3) and (4) in the form ~ exp $[\varkappa(\omega)x - i\omega t]$, where $\varkappa(\omega) = \gamma_c(\omega) + ik(\omega)$, and we obtain the dispersion relation

$$(i\omega + \varkappa V - 3\mathrm{Oh}\,\varkappa^2)(i\omega + \varkappa V) + \varkappa^2(1 + \varkappa^2)/2 = 0. \tag{5}$$

In the limit V >> 1, the solution of Eq. (5) for the instability growth rate can be written in the form

$$\gamma_c = \frac{1}{V}\left[-\frac{3k^2\mathrm{Oh}}{2} \pm \sqrt{\frac{9k^4\mathrm{Oh}^2}{4} + \frac{1}{2}k^2(1-k^2)}\right]. \tag{6}$$

It can be shown that the ratio $\gamma_a/\sqrt{\mathrm{We}}$ in Eq. (1) coincides with the convective instability growth rate (6) in the long-wavelength approximation. With a decrease in the jet velocity (for water at V < 5), the approximation V >> 1 becomes invalid, and so it is necessary to replace the ratio $\gamma_a/\sqrt{\mathrm{We}}$ in Eq. (1) by the convective instability growth rate determined

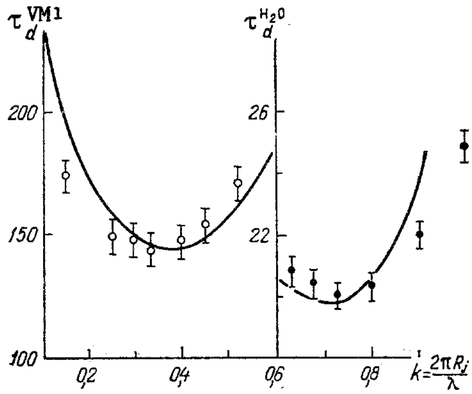

Fig. 3. Dimensionless breakup time τ_d vs wave number k for a distilled water jet at a temperature T = 20°C and a vacuum pump oil jet at T = 50°C; generator orifice diameter $D_N = 3\cdot 10^{-4}$ m, amplitude of die oscillations $\Delta_0 = 1.5\cdot 10^{-7}$ m.

from the solution of Eq. (5) in order to process the experimental data correctly. With an increase in the viscosity of the liquid, the corrections associated with the convective nature of the jet instability decrease. Figure 2 shows the dimensionless breakup time as a function of ε, where the solid curve is plotted according to the solution of Eq. (5), and the points represent the experimental data. It is seen at once that allowance for the convective nature of FCBJ gives the correct behavior of τ_d, indicating the important role of the type of breakup of jets. The discrepancy between the experimental and calculated data for $\varepsilon > 0.2$ can be attributed to two facts [2]: First, for such values of ε the velocity head $\rho U_j^2/2$ is commensurate with the capillary pressure $\sigma_e R_j$, i.e., the regime is transitional between jet and droplet flow; second, the jet flow can be highly unsteady at low velocities [2].

Figure 3 shows the dimensionless time as a function of the wave number k for jets of distilled water ($\tau_d H_2O$) at a temperature T = 20°C and vacuum pump oil (τ_dVM1) at T = 50°C flowing from nozzles with an orifice diameter D_N = 300 μm at an oscillation amplitude Δ_0 = $1.5\cdot 10^{-7}$ m. As before, the points represents the experimental data, and the solid curves correspond to the results of the calculations. The discrepancy, which is approximately of the same order as the breakup time, is attributable to the advent of the stabilizing role of viscosity [8].

Figure 4 shows the breakup time τ_d as a function of the orifice diameter D_N in FCBJ. An important feature of this dependence is the significant drop in τ_d when the nozzle diameter D_N is decreased. This effect can be attributed to surface tension relaxation, which sets in for small nozzle orifice diameters (the characteristic relaxation times of the surface tension are commensurate with the breakup time for D_N < 150 μm) [9].

To determine the influence of dynamic surface tension, we consider the system of equations [10]

$$\frac{\partial\eta}{\partial t} + \frac{1}{2}\frac{\partial u}{\partial x} = 0, \tag{7}$$

$$\frac{\partial u}{\partial t} = \int_0^t \sigma(t-\tau)\left[\frac{\partial^2\eta(\tau)}{\partial x\partial\tau} + \frac{\partial^4\eta(\tau)}{\partial x^3\partial\tau}\right]d\tau, \tag{8}$$

$$\frac{d\sigma}{dt} = -\beta(\sigma - 1), \tag{9}$$

where the scale σ_* coincides with the equilibrium value σ_e used to specify the time scale τ_*, $\beta = \tau_*/\tau_r$ and $\tau_r \approx 10^{-4}$ sec. Assuming that the coefficient of surface tension has the value $\sigma_0 = \sigma_I/\sigma_e$ (according to [9], $\sigma_I \approx 0.18$ N/m) and taking the Laplace transform of the system (7)-(9) with respect to time and its Fourier transform with respect to the coordinates, we obtain the dispersion relation

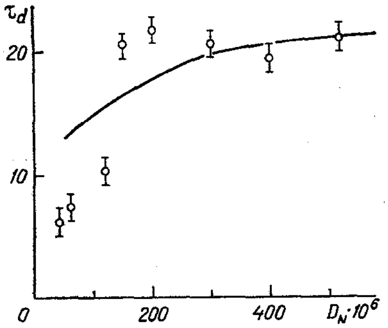

Fig. 4. Dimensionless breakup time τ_d vs generator orifice diameter D_N, mm, for a distilled water jet at T = 20°C; die oscillation amplitude $\Delta_0 = 1.5 \cdot 10^{-7}$ m.

$$p^2(p+\beta) = k^2(1-k^2)(\sigma_0 p+\beta)/2, \tag{10}$$

where p is the parameter of the Laplace transform.

The influence of surface tension relaxation on the jet breakup time can be investigated by analyzing relation (10). The results of such an analysis are represented by the solid curve in Fig. 4. Qualitative agreement between the experimental and calculated data is observed. On the other hand, the quantitative discrepancy is appreciable at $D_N < 100$. In our opinion, this can be attributed either to an inaccurate value of the dynamic surface tension or to a more complicated law than (9) governig its relaxation.

NOTATION

L_N, nozzle length; D_N, nozzle orifice diameter; Δ_0, amplitude of generator oscillations; δ_0, initial perturbations of jet surface; L_j, length of intact part of jet; D_j, mean jet diameter; γ_a, growth rate of absolute jet instability; We, Weber number, τ_*, time scale; R_j, mean jet radius; ρ, density of liquid; σ_e, equilibrium surface tension; τ_d, dimensionless breakup time; V_j, mean jet velocity; ε, small parameter; k, wave number; γ, growth rate of instability; x_*, coordinate scale; u_*, velocity scale; η, dimensionless surface strain; η_*, surface strain scale; $V = \varepsilon^{-1}$; Oh, Ohnesorge number; u, perturbation of jet velocity; ν, kinematic viscosity; ω, angular frequency of surface oscillations, γ_c, growth rate of convective instability, $\varkappa = \gamma_c + i\kappa$; T, temperature; σ, dimensionless surface tension; σ_*, surface tension scale; τ_r, surface tension relaxation time; σ_I, initial value of surface tension.

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