NOTATION

T, temperature of the mixture; C, vector of molar concentrations of the mixture components; C', vector of concentrations converted according to relations (13); [D], matrix of multicomponent diffusion coefficients; ⌈D'⌋, a diagonal matrix of eigenvalues of matrix [D]; [G] and [L], fundamental matrices for the gaseous component and the liquid component, respectively; λ, thermal conductivity; κ, thermal diffusivity; q, heat flux; J, vector of diffusion fluxes of the mixture components; ⌈m⌋, p_1, p_2, parameters in the equilibrium relation (5); $\Delta\tilde{H}_i$, difference between molar enthalpies of the i-th component in the gaseous phase and in the liquid phase, respectively, carried by its mass flux across the interphase boundary; n, number of mixture components; h_0, thickness of the liquid film; R, pipe radius; u, velocity of the phases in directional motion; t, x, y, space coordinates; η_1, η_2, dimensionless coordinates; and ⌈I⌋, unit matrix. Subscripts i refers to the i-th component; L, liquid phase; G, gaseous phase; and 0, value of a quantity at the boundary.

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CRITERION FOR THE BREAKUP OF LIQUID DROPS AND JETS

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UDC 532.529

The conditions of the breakup of liquid drops and jets are determined using wave theory.

The breakup of liquids is accomplished pneumatically, in particular, for the intensification of physicochemical processes in engineering. The mechanism of this process has been studied in many investigations, much of which has been systematized in [1-3]. It has been established that irregularities of the wave type develop on the surface of a liquid with the motion of a gas stream relative to it. These travel and increase in size, separating from the liquid surface and being converted into drops of smaller size than the initial volume of liquid. Since no significant difference in the conditions of liquid breakup is noted with variation of the position of the gas–liquid interface in space, it can be assumed that the waves have a capillary nature, and the theory of the development of these waves at a gas–liquid interface [4] can be used.

Let us assume that capillary waves develop on the surface of a volume of liquid at its frontal point when a gas stream impinges on it. Their amplitudes grow with time and over the period τ_{gr} they become comparable with the wavelength $\alpha \approx \lambda$, and according to [4] this leads to separation of the wave from the surface of the liquid, i.e., to the breakup of its original volume. Since the waves move over the surface of the volume of liquid, it is obvious that such breakup becomes possible if the growth time of at least one wave is less than the time τ_{mo} of its motion over the surface of the volume. On the other hand, it is necessary that the length of at least one wave be less than the characteristic size ℓ of the volume of liquid being broken up.

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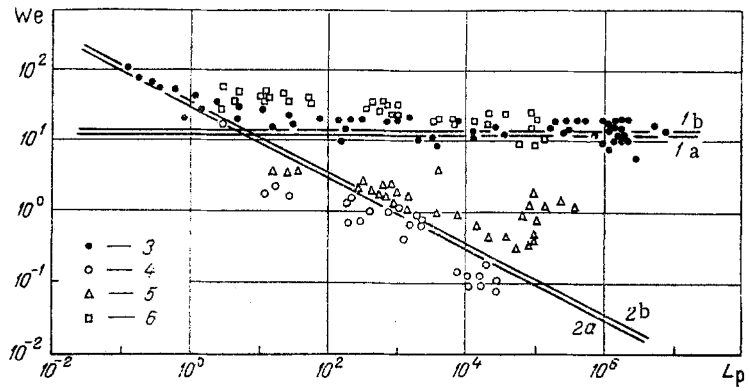

Fig. 1. Limiting conditions for the breakup of liquid drops and jets: 1a, 1b) based on Eqs. (8) and (10); 2a, 2b) on (9) and (11); 3-6) experimental data on the breakup of drops and on the axisymmetric and bending breakup and the atomization of liquid jets.

The expressions obtained in [4] for the lengths of the generated waves and their growth times can be represented in the form

$$\lambda = k_\lambda \pi (2)^{7/3} \frac{\mu_l^{2/3} \sigma^{1/3}}{\rho_l^{1/3} \beta^{2/3} (\rho v_{re}^2)^{2/3}}, \tag{1}$$

$$\tau_{gr} = \frac{(2)^{5/3} \mu_l^{1/3} \rho_l^{1/3} \sigma^{2/3}}{\beta^{4/3} (\rho v_{re}^2)^{4/3} \left(\frac{1}{k_\lambda^{1/2}} - \frac{1}{k_\lambda^2} \right)}, \tag{2}$$

while the time of motion of a wave over a segment S is

$$\tau_{mo} = \frac{(2)^{2/3} S k_\lambda^{1/2} \mu_l^{1/3} \rho_l^{1/3}}{\beta^{1/3} (\rho v_{re}^2)^{1/2} \sigma^{1/3}}. \tag{3}$$

Comparing (2) and (3), for the first breakup condition $\tau_{gr} \leq \tau_{mo}$ we obtain, after transformations,

$$(\mathrm{We})_{1re} \geqslant \frac{2}{\beta \left(1 - \frac{1}{k_\lambda^{3/2}} \right)} \left(\frac{D}{S} \right). \tag{4}$$

For the second breakup condition $\lambda \leq \ell$ we find, using Eq. (1),

$$(\mathrm{We})_{2re} \geqslant \frac{k_\lambda^{3/2} (2)^{7/2} \pi^{3/2}}{\beta (\mathrm{Lp})^{1/2}} \left(\frac{D}{l} \right)^{3/2}. \tag{5}$$

It has been established experimentally that the separation of drops from the surface of a liquid volume that is breaking up takes place approximately in the section from the frontal point to the equatorial plane of the latter. This is evidently connected with the separation of the gas stream in flow over the body and with the formation behind the latter of a wake in which the directional flow prevents the capillary waves from continuing to move beyond the equatorial plane into the rear part of the volume that is breaking up. In such a case $S \leq \pi D/4$, and for the most rapidly growing waves, for which $k_\lambda = (2)^{4/3}$ [4], the first breakup condition takes the form

$$(\mathrm{We})_{1re} \geqslant \frac{(2)^5}{3\pi\beta}. \tag{6}$$

One can assume that the maximum characteristic size of a volume that is breaking up is its half-perimeter, along which waves of the minimum size λ_{min} must fit, according to the second breakup condition. For the latter waves $k_\lambda = 1$, according to [4], and the second breakup condition (5) takes the form

$$(\mathrm{We})_{2re} \geqslant \frac{(2)^5}{\beta (\mathrm{Lp})^{1/2}}. \tag{7}$$

Since the theory of [4] was developed for a plane gas–liquid interface, the concept of the reduced velocity of the gas stream is introduced in application to the curved surface occurring in the breakup of liquid drops and jets. The solution using this procedure has an approximate character. Since for a sphere the tangential component of the relative velocity is $v_\theta = 3/2\ v \sin\theta$, for the first breakup condition in the section $0 \leq \theta \leq \pi/2$ the reduced velocity is $v_{re} = (3/\pi)v$, while for the second condition, when equal but oppositely directed streams act in the sections $0 \leq \theta \leq \pi/2$ and $\pi/2 \leq \theta \leq \pi$, flowing onto the upwind side and flowing over in the wake on the downwind side, $v_{re} = (6/\pi)v$. Substituting the expression for v_{re} into (6) and (7), for the initial breakup time we obtain

$$(\mathrm{We})_1 \geqslant \frac{(2)^5 \pi}{(3)^3 \beta} \quad (8)$$

and

$$(\mathrm{We})_2 \geqslant \frac{(2)^3 \pi^2}{(3)^2 \beta (\mathrm{Lp})^{1/2}}. \quad (9)$$

The breakup of a liquid escaping from a nozzle into a gas phase can take place in an axisymmetric, bending, or atomizing regime.

In the axisymmetric regime the waves forming at the frontal point of the escaping jet move along the surface of the liquid toward the nozzle. It can be assumed that for the jet to retain stability it is necessary that the minimum wavelength, which can increase with time, be greater than the half-perimeter of a drop formed as a result of axisymmetric breakup. Otherwise the formation of the drop is not completed and, as a result of the continuing entry of liquid, it grows into a cylinder of a length such that this condition is satisfied. The cylinder bends due to instability at the outflow velocities reached, and the breakup of the jet occurs in the bending regime. Since the minimum possible diameter of a drop corresponds to the nozzle diameter, the condition for the transition from axisymmetric to bending breakup is described by Eq. (9).

In the regime of bending breakup waves develop on the upwind side of each segment of the jet at the frontal generating line under the action of the oncoming stream while a wake develops on the downwind side as a result of separation of the gas stream. It is obvious that the transition from the bending regime of breakup to atomization will also occur when the two conditions described above are observed for a volume of the liquid. In contrast to a sphere, in flow over a cylinder $v_\theta = 2v \sin\theta$. If one assumes that the jet has the shape of a simple sinusoid in the regime of bending breakup, then at the point of a bend, where these conditions must be satisfied first of all, $v_{re} = (2)^{3/2} v/\pi$ for the first while $v_{re} = (2)^{5/2} v/\pi$ for the second. After substituting these quantities into Eqs. (6) and (7), we obtain

$$(\mathrm{We})_1 \geqslant \frac{(2)^2 \pi}{3\beta} \quad (10)$$

and

$$(\mathrm{We})_2 \geqslant \frac{\pi^2}{\beta (\mathrm{Lp})^{1/2}}. \quad (11)$$

Thus, the conditions (8) and (9) must be satisfied for the breakup of a drop in a gas stream. In the case of a jet escaping into a gas phase the transition from axisymmetric to bending breakup occurs when the condition (9) is satisfied, while the transition from bending to atomizing breakup occurs when (10) and (11) are satisfied.

In Fig. 1 we present experimental data on the conditions of breakup of liquid drops [5-10] and jets [1], as well as the expressions (8)-(11) found analytically. The agreement obtained between them can be considered satisfactory. The breakup of liquid drops and jets in the atomizing regime, of particular importance in engineering, evidently occurs when the first breakup condition is satisfied for nonviscous liquids and when the second condition is satisfied for viscous liquids, since for a given value of the Laplace number the values of the Weber number required for atomization prove to be higher than those needed to satisfy the second condition for nonviscous liquids and the first condition for viscous liquids. The critical value of the Laplace number, above which a liquid can be treated as nonviscous and below which it can be treated as viscous, is, for both liquid drops and jets.

$$(\mathrm{Lp})_{cr} = \frac{(3)^2 \pi^2}{(2)^4}. \quad (12)$$

NOTATION

λ, α, w_λ, length, amplitude, and velocity of motion of a wave; ρ_ℓ, μ_ℓ, σ, density, coefficient of dynamic viscosity, and specific surface energy of the liquid that is breaking up; k_λ, proportionality factor in the expression $\lambda = k_\lambda \lambda_{min}$; D, diameter of the liquid drops and jets breaking up; $We \equiv \rho_{amb}v^2D/\sigma$, Weber number; $We_{re} \equiv \rho_{amb}v_{re}^2D/\sigma$, reduced Weber number; $Lp \equiv \frac{\rho_\ell D\sigma}{\mu_\ell^2}$, Laplace number; ρ_{amb}, density of the oncoming gas stream; v, relative velocity of the oncoming stream; τ, time; S, path length traveled by the wave; t, characteristic size of the volume breaking up; θ, angle between the point under consideration and the frontal point on the surface volume breaking up in the polar coordinate system. Indices: ℓ, liquid; amb, ambient medium; gr, growth, mo, motion; cr, critical; min, minimum; 1, 2) first and second breakup conditions; re, reduced.

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ANALYSIS OF SELF-SIMILAR LAMINAR FLOWS IN SLOT CHANNELS WITH ONE PERMEABLE WALL

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An analysis is made of the fluid flows in a plane slot permeable channel. It is shown that for large numbers R (suction) self-similar solutions exist.

Plane and axisymmetric laminar flows are observed in many modern engineering elements [1, 2]. These are systems of "porous" effusion cooling, heat pipes, heat exchange sublimation apparatus, apparatus for thermostatic regulation of large-scale objects [3, 4], and distributive collectors of heat exchangers [5]. It is difficult to assume a uniform discharge distribution of the heat carrier in channels without analyzing the flows in such apparatus.

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