CAPILLARY INSTABILITY OF LIQUID JETS IN THE CASE OF HEAT EXCHANGE WITH THE SURROUNDING MEDIUM

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We consider the effect of heat exchange on the capillary instability of a liquid jet. It is shown that the instability parameters differ from the standard values only when the rate of heat exchange is large.

In many technological devices, a flow of identical macroscopic particles is obtained by using the method of forced capillary break-up of liquid jets [1]. The diverse applications of this method have defined a whole class of problems connected with the study of the effect of different factors on the capillary break-up of liquid jets: electric, magnetic, acoustic, or other external fields can affect the characteristics of capillary break-up. In devices of cryodispersion technology, for example, the forced capillary break-up of the jet occurs in the presence of heat exchange with the surrounding medium [2]. Therefore it is important to study the parameters of a jet whose temperature differs from that of the external medium. Similar problems occur in the study of the capillary break-up of a jet with low vapor pressure in a vacuum [3]. A number of problems on the effect of heat exchange on the capillary instability of jets has already been considered in the literature [4, 5], however the influence of the thermocapillary effect induced by a longitudinal temperature gradient on the instability increment has not been established.

In the present paper we study the capillary instability of a cooled jet in the practically important case when the external medium does not exert a dynamical perturbation on the surface of the jet (this is the case for low gas pressure, for example) and when mass exchange is absent (i.e., we can neglect evaporation and condensation on the surface of the jet; this will be correct for liquid jets with low vapor pressure).

To analyze the capillary instability of the cooled jet, we need to determine the average temperature and velocity profiles, which then fix the state of the system whose stability is studied. We consider a nondeformable liquid jet flowing with velocity v_j from an aperture of radius R_j and having a temperature T_j which differs from the temperature of the surrounding medium T_s. The average temperature profile of the undeformed jet can be obtained from the heat equation written in dimensionless form:

$$\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}-\frac{\mathrm{Pe}}{2}\frac{\partial\theta}{\partial x}=0. \tag{1}$$

The boundary conditions are

$$\left.\frac{\partial\theta}{\partial r}\right|_{r=0}=0;\quad \left.\frac{\partial\theta}{\partial r}\right|_{r=1}=-\frac{\mathrm{Bi}}{2}\theta; \tag{2}$$

$$\theta|_{x=0}=1;\quad \theta|_{x\to\infty}=0. \tag{3}$$

The exact solution of the problem (1)-(3) can easily be obtained by expanding the unknown function in a series of Bessel functions. However, it is more convenient for our purposes to use the asymptotic representation of the solution for distances from the point of discharge which are larger than the radius of the jet, and for Biot numbers Bi < 1:

$$\theta(x,\ r)\approx\exp\left\{-\frac{2\,\mathrm{Bi}}{\mathrm{Pe}}x\right\}\left(1-\frac{\mathrm{Bi}}{4}r^2\right). \tag{4}$$

According to [6], for a free jet in air at atmospheric pressure Nu ≈ 0.43 and the ratio $\varkappa_s/\varkappa_j<1$, therefore Bi < 0.43. For materials with high thermal conductivities one can have the case Bi/Pe ~ 1 with Bi ≪ 1. This situation is possible for thin sodium jets, for example ($R_j = 10^{-4}$ m, Pe ~ 10^{-3}), flowing into a space filled with an inert gas at low pressure. It

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follows from (4) that in this case the problem of stability of the jet can be formulated by neglecting the dependence of the temperature on the radial coordinate and considering only the effect of the longitudinal temperature gradient. For other liquids (water, oil, and so on) the combination of parameters $\mathrm{Pe} \gg 1$, $\mathrm{Bi} < 1$ is more natural, and therefore in this case one can neglect the longitudinal temperature gradient and consider only its radial profile.

We consider the latter case first and study the capillary instability of a jet with the temperature profile

$$\theta_0(r) = \left(1 - \frac{\mathrm{Bi}}{4} r^2\right). \tag{5}$$

Using the approximation of an infinitely long liquid cylinder [1], we introduce the stream function ψ for axisymmetric velocity perturbations:

$$v_r = \frac{1}{r}\frac{\partial\psi}{\partial x}; \quad v_x = \frac{1}{r}\frac{\partial\psi}{\partial r}. \tag{6}$$

We write the laws of conservation of momentum and energy in dimensionless form and linearized in the neighborhood of the state $v_x = v_r = 0$ and $\theta = \theta_0(r)$:

$$\frac{\partial\Delta_1\psi}{\partial t} = \mathrm{Oh}\,\Delta_1^2\psi, \tag{7}$$

$$\frac{\partial T}{\partial t} + \frac{\mathrm{Bi}}{2}\frac{\partial\psi}{\partial x} = A\Delta T. \tag{8}$$

The boundary conditions on the axis of the jet are

$$\psi = \frac{\partial}{\partial r}\frac{1}{r}\frac{\partial\psi}{\partial r} = \frac{\partial T}{\partial r} = 0, \tag{9}$$

and on the perturbed surface of the jet $R(x, t) = 1 + \eta(x, t)$ we must have the kinematic boundary condition, the balance of the normal and tangential stresses, and the Cauchy condition for the temperature perturbation T:

$$\begin{gathered}
\frac{\partial\eta}{\partial t} = -\frac{\partial\psi}{\partial x};\\
P + 2\,\mathrm{Oh}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\psi}{\partial x}\right) + \eta + \frac{\partial^2\eta}{\partial x^2} - S\left(T - \frac{\mathrm{Bi}}{2}\eta\right) = 0,\\
\mathrm{Oh}\left(\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial\psi}{\partial r} - \frac{\partial^2\psi}{\partial x^2}\right) = S\left(\frac{\partial T}{\partial x} - \frac{\mathrm{Bi}}{2}\frac{\partial\eta}{\partial x}\right),\\
\frac{\partial T}{\partial r} - \frac{\mathrm{Bi}}{2}\eta = \mathrm{Bi}\left(T - \frac{\mathrm{Bi}}{2}\eta\right).
\end{gathered} \tag{10}$$

The pressure P can be found from the equation of motion

$$\frac{\partial P}{\partial x} = -\frac{\partial}{\partial r}\left(\frac{\partial\psi}{\partial t}\right) + \mathrm{Oh}\left(\frac{\partial^2}{\partial x^2}\frac{\partial\psi}{\partial r} + \frac{\partial}{\partial r}r\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial\psi}{\partial r}\right).$$

We assume the following form of the solution of (7) and (8), which satisfies (9):

$$\psi = \left[c_1 r\frac{I_1(kr)}{I_1(k)} + c_2 r\frac{I_1(lr)}{I_1(l)}\right]\exp(\gamma t + ikx), \tag{11}$$

$$T = \left[c_3\frac{I_0(\beta r)}{I_0(\beta)} - c_1\frac{ik\,\mathrm{Bi}}{2\gamma}r\frac{I_1(kr)}{I_1(k)} - c_1\frac{ik^2\,\mathrm{Bi}\,A}{\gamma^2 I_1(k)}I_0(kr) + c_2\frac{ik\,\mathrm{Bi}\,\mathrm{Oh}}{2\gamma(A-\mathrm{Oh})}r\frac{I_1(lr)}{I_1(l)} - c_2\frac{ik\,\mathrm{Bi}\,A\,\mathrm{Oh}^2}{\gamma^2(A-\mathrm{Oh})^2}\frac{I_0(lr)}{I_1(l)}\right]\exp(\gamma t + ikx). \tag{12}$$

The constants c_j are determined from the boundary conditions (10). Substituting (11) and (12) into (10), we obtain the dispersion relation (see Appendix).

Solution of the dispersion relation shows that the imaginary part of the increment is equal to zero and the unstable branch of the spectrum lies in the interval of wavenumbers

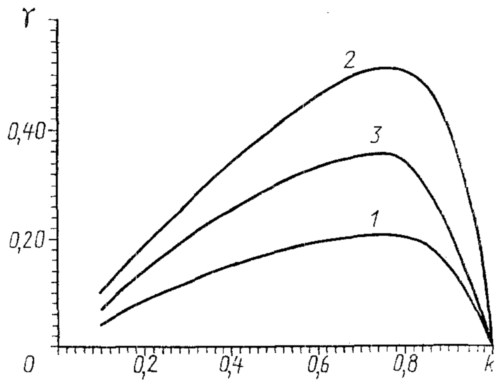

Fig. 1. Dependence of the instability increment on wavenumber for Oh = 0.01 and different values of the Biot number: 1) Bi = 1.0; 2) 10.0; 3) 20.0.

$0 < k < 1$. The calculations show that heat exchange with the surrounding medium affects the capillary instability of the jet only for very large Bi numbers and small Oh numbers, and shows up as a small shift in the maximum of the instability increment toward larger wavenumber. With increasing Bi number (Bi > 1) the increment first decreases, then increases. In the limit Bi ≫ 1 it approaches the value holding in the absence of heat exchange. As an example, Fig. 1 shows the dependence $\gamma(k)$ for a water jet with $R_j = 10^{-4}$ m for different values of Bi.

We consider the other limiting case Pe ≫ 1, when the temperature variation along the jet must be taken into account, while the radial profile can be neglected. To determine the structure of the flow in the jet we consider an infinitely long liquid cylinder in which a constant temperature gradient $\partial T_0/\partial x$ is created at the initial time. Tangential stresses are induced on the surface of the cylinder by the thermocapillary effect and they lead to a change in the velocity field. It can be shown that in this case the liquid moves with a velocity profile dependent on the radial coordinate:

$$u_0(r) = \frac{1}{\rho}\left(\frac{\partial\sigma}{\partial T}\right)\left(\frac{\partial T_0}{\partial x}\right)\frac{1}{\nu R_j}\frac{r^2}{2}.$$

We consider the stability of an infinitely long liquid cylinder with a nonuniform velocity profile as given above. We obtain the following equation for the stream function, introduced according to [6]:

$$\frac{\partial\Delta_1\psi}{\partial t} + \mathrm{Ma}\,\mathrm{Oh}^{-1}\frac{r^2}{2}\frac{\partial\Delta_1\psi}{\partial x} - \mathrm{Ma}\,\mathrm{Oh}^{-1}\frac{\partial\psi}{\partial x} = \mathrm{Oh}\,\Delta_1^2\psi. \tag{13}$$

The boundary conditions on the axis of the jet are

$$\psi|_{r=0} = \frac{\partial}{\partial r}\frac{1}{r}\frac{\partial\psi}{\partial r}\bigg|_{r=0} = 0. \tag{14}$$

On the perturbed surface of the jet $R(x, t) = 1 + \eta(x, t)$ we have the kinematic boundary condition and the condition of balance of the tangential and normal stresses:

$$\frac{\partial\eta}{\partial t} + \frac{1}{2}\mathrm{Ma}\,\mathrm{Oh}^{-1}\frac{\partial\eta}{\partial x} = v_r, \tag{15}$$

$$\frac{1}{2}\mathrm{Ma}\,\mathrm{Oh}^{-2}v_r = \frac{\partial v_x}{\partial r} + \frac{\partial v_r}{\partial x} + \mathrm{Ma}\,\mathrm{Oh}^{-1}\eta, \tag{16}$$

$$P - 2\,\mathrm{Oh}\frac{\partial v_r}{\partial r} = -\eta - \frac{\partial^2\eta}{\partial x^2}, \tag{17}$$

where P can be found from the relation

$$\frac{\partial P}{\partial x} = -\frac{\partial\varphi}{\partial t} - \mathrm{Oh}^{-1}\mathrm{Ma}\left(v_r + \frac{1}{2}\frac{\partial v_x}{\partial x}\right) + \mathrm{Oh}\,\Delta v_x.$$

Equation (13) is the Orr–Sommerfeld equation [4]. The difficulty of solving this equation is well known. However, it should be noted that the problem (13)-(17) differs from the Orr–Sommerfeld problem, which arises in the theory of stability of flows with a nonuniform velocity profile. The difference is the presence of a free deformable surface in our problem. In essence, the problem (13)-(17) can be considered as a problem on the instability of a cylindrical column of liquid with internal flow. The internal flow obviously affects the parameters of the instability, but the flow itself is stable. In the Orr–Sommerfeld problem we have the opposite situation in that the internal flow is unstable.

We look for the solution of (13)-(17) in the form

$$\psi(x,\ r,\ t) = f(r)\exp(\gamma t + ikx),\quad \eta(x,\ t) = \eta_h \exp(\gamma t + ikx).$$

From (13) we have the following equation for the function f(r):

$$\left[\gamma + \frac{1}{2}\,\mathrm{Ma}\,\mathrm{Oh}^{-1}\,ikr^2 - \mathrm{Oh}\left(r\frac{d}{dr}\frac{1}{r}\frac{d}{dr} - k\right)\right]\left(r\frac{d}{dr}\frac{1}{r}\frac{d}{dr} - k^2\right)f = ik\,\mathrm{Ma}\,\mathrm{Oh}^{-1}f. \tag{18}$$

Recalling the above discussion, we look for the solution of (18) in the form of an infinite series satisfying the condition (14):

$$f(r) = \sum_{j=1}^{2} c_j \sum_{n=1}^{\infty}\left[A_{2n-1}^{(j)} r^{2n-1} I_1(\varphi_j r) + A_{2n}^{(j)} r^{2n} I_0(\varphi_j r)\right], \tag{19}$$

where $A_1^{(j)} = 1$ since the constants c_j are arbitrary, and φ_1, φ_2 are given by

$$\varphi_{1,2} = \left[k^2 + \frac{\gamma}{2\,\mathrm{Oh}} \pm \left(\frac{\gamma}{4\,\mathrm{Oh}} - ik\frac{\mathrm{Ma}}{\mathrm{Oh}^2}\right)^{1/2}\right]^{1/2}.$$

Substituting (19) into (18) and collecting the coefficients of identical powers r^k, we obtain a system of linear equations for the coefficients $A_k^{(j)}$. For practical calculations we can put $A_{s+1}^{(j)} = 0$ beginning with the value of s for which the corresponding terms only slightly affect the solution. Calculations show that we can use this assumption with s = 6. Substituting (19) into the boundary conditions (15)-(17), we obtain the dispersion relation, whose explicit form is given in the Appendix (Eq. A.2).

The calculations show that in the case considered here, heat exchange with the surrounding medium affects the parameters of the capillary instability only for large longitudinal temperature gradients. As an example, Fig. 2 shows the calculated instability increment and oscillation frequency of a water jet of radius $R_j = 10^{-2}$ m. We see from the graphs that the value of the increment decreases as the longitudinal temperature gradient increases, and the maximum of the dependence $\gamma(k)$ shifts towards larger wavelength, while the oscillation frequency decreases, i.e., the instability becomes oscillatory (in the absence of heat exchange the frequency is equal to zero).

Our results show that the capillary instability of the jet can be affected by very intense heat exchange with the surrounding medium, which is rarely encountered in practice. However, in certain technologies, such as cryodispersion, the effect of heat exchange can be observed.

APPENDIX

In the approximation of large Peclet number the dispersion relation for the capillary instability of the jet can be written in the form

$$\gamma^2 + 2k\,\mathrm{Oh}\left[k\frac{I_1'(k)}{I_0(k)} + \frac{I_1(k)}{I_0(k)}\right] - k(1-k^2)\frac{I_1(k)}{I_0(k)} +$$

$$+\left[k(1-k^2)\frac{I_1(k)}{I_0(k)} - 2k\,\mathrm{Oh}\,\gamma\frac{I_1'(l)\,I_1(k)}{I_1(l)\,I_0(k)} - \mathrm{Oh}\,\gamma\frac{l^2+k^2}{k}\right] +$$

$$+\frac{I_1(k)}{I_0(k)}\left\{\left[\beta\frac{I_1(\beta)}{I_0(\beta)} - \mathrm{Bi}\right]\left[2k^2\gamma^2\,\mathrm{Oh} - k^3\,\mathrm{Bi}\,AS\frac{I_0(k)}{I_1(k)}\right] +\right.$$

$$+S\left[k^4\,\mathrm{Bi}\,A - k^3\,\mathrm{Bi}\,\gamma\frac{I_0(k)}{2I_1(k)} - \gamma k^2\frac{\mathrm{Bi}^2}{2} - k^3 A\,\mathrm{Bi}^2\frac{I_0(k)}{I_1(k)} -\right.$$

$$\left.\left.- k^3\gamma\frac{\mathrm{Bi}}{2}(1-\mathrm{Bi})\right]\right\}\left\{S\left[-\frac{k^2}{2}\frac{\mathrm{Bi}\,\mathrm{Oh}\,l\gamma}{2(A-\mathrm{Oh})}\frac{I_0(l)}{I_1(l)} +\right.\right.$$

$$\left.+\frac{k^2 l^2\,\mathrm{Bi}\,A\,\mathrm{Oh}^2}{(A-\mathrm{Oh})^2} + \frac{k^2\gamma\,\mathrm{Oh}\,\mathrm{Bi}^2}{2(A-\mathrm{Oh})} - \frac{k^2 l\,\mathrm{Bi}^2 A\,\mathrm{Oh}^2}{(A-\mathrm{Oh})^2}\frac{I_0(l)}{I_1(l)} - \frac{k^2\gamma}{2}\mathrm{Bi}(1-\mathrm{Bi})\right] + \left[\beta\frac{I_1(\beta)}{I_0(\beta)} - \mathrm{Bi}\right]\times$$

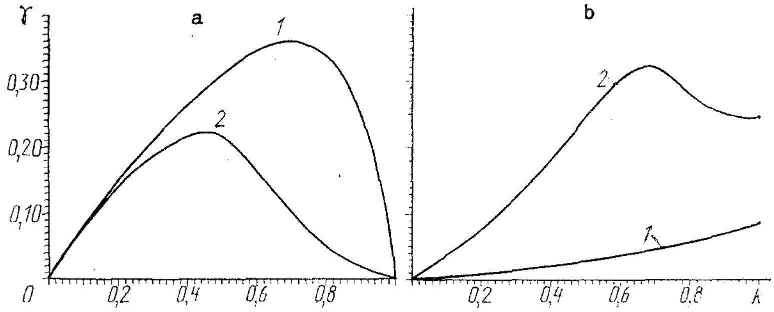

Fig. 2. Dependence of the instability increment γ (a) and the oscillation frequency ω of the surface of the jet (b) on wavenumber for Oh = $1.2\cdot 10^{-3}$ and different values of Ma: 1) Ma = $1.3\cdot 10^{-4}$; 2) $6.3\cdot 10^{-4}$.

$$\times\left[\gamma^2 \mathrm{Oh}\,(l^2+k^2)+\frac{k^2\,\mathrm{Bi}\,S\,\mathrm{Oh}\,\gamma}{2\,(A-\mathrm{Oh})}-\frac{k^2 l\,\mathrm{Bi}\,SA\,\mathrm{Oh}^2}{(A-\mathrm{Oh})}+\frac{I_0(l)}{I_1(l)}-\frac{k^2\gamma}{2}\mathrm{Bi}\,S\right]^{-1}=0. \tag{A.1}$$

In the approximation Pe ≪ 1 the dispersion relation is given by the expression

$$\left[\gamma+\frac{1}{2}k\,\mathrm{Oh}^{-1}\mathrm{Ma}\right]\Big\{\gamma\,(Y_2N_1+N_2)-ik\,\mathrm{Oh}^{-1}\mathrm{Ma}\,(X_1Y_2+X_2)+$$
$$+\frac{1}{2}ik\,\mathrm{Oh}^{-1}\mathrm{Ma}\,(Y_2N_1+N_2)-\mathrm{Oh}\,[P_1Y_2+P_2-k^2(Y_2N_1+N_2)]+$$
$$+2k^2\,\mathrm{Oh}\,(Q_1Y_2+Q_2)\Big\}=k^2(1-k^2)(X_1Y_1+X_2), \tag{A.2}$$

where

$$X_j=\sum_{n=1}^{\infty}A_{2n-1}^{(j)}I_1(\varphi_j)+A_{2n}^{(j)}I_0(\varphi_j);$$

$$Z_j=\sum_{n=1}^{\infty}A_{2n-1}^{(j)}\{I_1(\varphi_j)[4(n-1)(n-2)+\varphi_j^2+k^2]+4(n-1)\varphi_jI_0(\varphi_j)\}+$$
$$+A_{2n}^{(j)}\{I_0(\varphi_j)[4n(n-1)+\varphi_j^2+k^2]+2(2n-1)\varphi_jI_1(\varphi_j)\};$$

$$N_j=\sum_{n=1}^{\infty}A_{2n-1}^{(j)}[2(n-1)I_1(\varphi_j)+\varphi_jI_0(\varphi_j)]+A_{2n}^{(j)}[2nI_0(\varphi_j)+\varphi_jI_1(\varphi_j)];$$

$$Q_j=\sum_{n=1}^{\infty}A_{2n-1}^{(j)}[(2n-3)I_1(\varphi_j)+\varphi_jI_0(\varphi_j)]+A_{2n}^{(j)}[(2n-1)I_0(\varphi_j)+\varphi_jI_1(\varphi_j)];$$

$$P_j=\sum_{n=1}^{\infty}A_{2n-1}^{(j)}[8(n-1)(n-2)^2I_1(\varphi_j)+$$
$$+4(n-1)(3n-4)\varphi_jI_0(\varphi_j)+6(n-1)\varphi_j^2I_1(\varphi_j)+\varphi_j^3I_0(\varphi_j)]+$$
$$+A_{2n}^{(j)}[8n(n-1)^2I_0(\varphi_j)+4(n-1)(3n-1)\varphi_jI_1(\varphi_j)+2(3n-1)\varphi_j^2I_0(\varphi_j)+\varphi_j^3I_1(\varphi_j)];$$

$$Y_1=-\frac{Z^2+ik\,\mathrm{Ma}\,X_2/2}{Z_1+ik\,\mathrm{Ma}\,X_1/2};\quad H=-\frac{\mathrm{Ma}\,\mathrm{Oh}^{-1}}{Z_1+ik\,\mathrm{Ma}\,X_1/2};$$

$$Y_2=Y_1-ikH\frac{Y_1X_1+Y_2}{\gamma+ik\,(HX_1+\mathrm{Ma}\,\mathrm{Oh}^{-1/2})}.$$

NOTATION

$\theta=[T(x)-T(s)]/(T_j-T_s)$, dimensionless temperature; $\mathrm{Pe}=2\rho C_p v_j R_j/\varkappa$, Peclet number; $\mathrm{Bi}=2\bar{\alpha}R_j/\varkappa_j$, Biot number; $\mathrm{Nu}=\mathrm{Bi}\varkappa_j/\varkappa_s$, Nusselt number; C_p and $\varkappa_j$, heat capacity and thermal conductivity of the liquid, respectively; $\bar{\alpha}$, mean heat transfer coefficient; $\varkappa_s$, thermal conductivity of the surrounding medium; $x_* = r_* = R_j$, distance scale; $\Delta=(1/r)(\partial/\partial r)r(\partial/\partial r)+\partial^2/\partial x^2$, Laplacian; $\Delta_1 = r(\partial/\partial r)(1/r)(\partial/\partial r) + (\partial^2/\partial x^2)$, second-order differential operator; $A = \varkappa_j t_* / \rho c_p R_j^2 = 2 \quad (\mathrm{We})^{1/2}/\mathrm{Pe}$; $t_* = (\rho R_j^3/\sigma)^{1/2}$, time scale; $\mathrm{We} = v_j^2 \rho R_j/\sigma$; $S = (\partial\sigma/\partial t)(T_j - T_s)/\sigma$; $l^2 = \gamma/\mathrm{Oh} + k^2$; $\beta^2 = \gamma/A + k^2$; I_n, modified Bessel function of order n; $\partial T_0/\partial x$, temperature gradient along the jet; σ, surface tension; ν, kinematic viscosity; k, wave number; vj, mean velocity of the jet; ρ, density of the liquid; Rj, initial radius of the jet; $u_0(r)$, initial velocity profile; $\mathrm{Ma} = R_j(\partial\sigma/\partial T) + (\partial T_0/\partial x)/\sigma$; P, pressure perturbation; $\gamma = \gamma_r + i\omega$; Oh, Onezorg number.

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EXPERIMENTAL INVESTIGATION OF THE EFFECT OF THE SIGNAL-TO-NOISE RATIO ON THE CHARACTERISTICS OF FORCED CAPILLARY DISINTEGRATION OF A JET

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Dependences of the signal-to-noise ratio in a jet in the case of forced capillary disintegration of the jet (FCDJ) on the excitation signal, the mean jet velocity, the velocity distribution in the jet, and the jet diameter are derived. It is shown that, for equal excitation amplitudes, the signal-to-noise ratio in the case of FCDJ depends on the jet diameter and the velocity profile. A relationship between the relative scatter of diameters of the droplets formed as a result of FCDJ and the signal-to-noise ratio is derived.

The phenomenon of forced capillary disintegration of a liquid jet (FCDJ) is the basis of one of the most promising methods of generating an ordered flow of monodisperse (i.e., having similar dimensions) macroparticles. Such flow is finding increasingly wide application in technology and new techniques [1-3]. The basic advantages of this method include a high degree of monodispersity (a quantity which is the reciprocal of the coefficient of particle size variation), a considerable generation frequency, and a small angular divergence of the particle flux generated.

One of the most important problems in designing generators of monodisperse droplets characterized by a high degree of monodispersity is the provision of a maximum signal-to-noise ratio in the disintegrating jet. In the final analysis, this ratio determines the characteristics of the droplets generated, such as the standard deviation of sizes and velocities, the angular divergence, and the presence or absence of associated drops.

It should be mentioned that, until now, no attempt was made to determine experimentally the signal-to-noise ratio in the case of FCDJ. This is probably due to the difficulties in separating and recording the intensities of the many noise sources in the generator that are due to random frame vibrations, wall roughnesses in the outflow channel, relaxation of the velocity field in the jet, etc. The noise in the frequency band corresponding to the maximum gain increases the fastest, causing the jet to disintegrate into droplets.

For the criterion of the signal-to-noise ratio in FCDJ, we propose to use the ratio of the length Lj of the jet segment that has not disintegrated at a fixed level of the excitation

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