FEATURES OF THE CAPILLARY BREAKUP OF JETS OF DIELECTRIC VISCOUS LIQUIDS WITH SURFACE CHARGES

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An investigation is reported of the forced capillary breakup of a jet of charged viscous liquid in a corona discharge field.

Recently there has been increasing interest in the production and the use in various fields of technology of ordered and controlled streams of uniform (monodisperse) droplets [1]. The most promising method of producing such streams is the method of the forced capillary breakup of jets of liquid (FCBJ) which is accomplished by the action of a periodic signal on the jet. This makes it possible to produce a stream of uniform droplets of dimensions 10-1000 μm with only a small scatter of the parameters (velocity, diameter, etc.). This defines a very wide field of application for the FCBJ: high-speed jet printers, devices for the precision dosing of materials, techniques for the creation of monodisperse powders of various materials, etc. Most often, control of the motion of the stream is carried out by means of the interaction of charged droplets with external electric fields. Various methods have been developed for the electrification of the droplets [2]; the simplest and most widely used method is the induced method for conducting liquids or the use of a corona discharge (CD) for dielectric liquids.

The FCBJ method in a CD field has been used in the present work for producing uniform charged droplets of oil VM-1. The FCBJ of viscous liquids has a number of special characteristics compared with liquids of low viscosity (water, for instance): the jets of viscous liquid have a greater length of the unbroken part, and the perturbations are more unstable with longer wavelengths than in the case of water [1, 3, 4]. In addition, both the dynamic effects of the CD and the surface charges which the jet acquires influence the hydrodynamic parameters of the jet under charging conditions.

The objective of the present work was to investigate the features of the capillary breakup of jets of VM-1 oil under conditions in which a steady CD acts on the jet.

For the experimental investigation of the parameters of the FCBJ use was made of a test rig the main features of which are shown in Fig. 1. The functional elements of the equipment can be separated into a number of autonomous systems: the feed, droplet generator, charging arrangement, and devices for recording the parameters. The feed system includes, firstly, the preparation of the liquid before use, which includes the removal of impurities, degassing, removal of water, and thermostabilization, and secondly provides for its supply to the droplet generator with simultaneous control of the output parameters (temperature and pressure). The droplet generator consists of a reservoir in the lower part of which a nozzle is arranged. Under the action of the excess pressure set up in the reservoir, a jet of the liquid flows vertically downwards through the opening of the nozzle. In addition by using a piezoelectric transducer in the droplet generator periodic fluctuations of the pressure are set up, which lead to the appearance of periodic perturbations on the surface of the jet which in turn cause its breakup into uniform droplets. The droplet generator pulsations are recorded by means of a KD-39 accelerometer having linear characteristics over the frequency range 0-10 kHz. In this way it was possible to control not only the amplitude of the pulsations but also shape deviations relative to the sinusoidal signal fed to the piezoelement. The charging system consisted of a sharp corona-inducing electrode and a spherical counterelectrode of diameter ~7 mm placed on a mobile platform which could be moved in the vertical and horizontal directions. The selection of the CD conditions and the optimum relative positions of the jet and electrodes have been discussed in detail in [5].

In the course of carrying out the experiments measurements were made of the following parameters: the corona discharge current; the entrained current (i.e., the charge per unit

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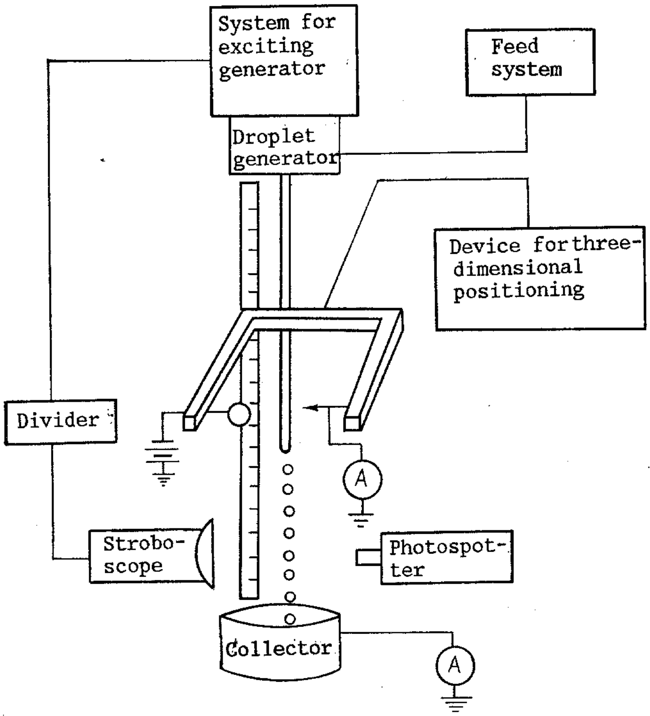

Fig. 1. Flowsheet of experimental equipment.

time which settles on the jet surface in the zone covered by the CD); the length of the unbroken part of the jet, which was recorded optically to an accuracy of ~0.5 mm in the illumination of a strobotachometer synchronized with the droplet generator. In order to control the upward leakage of charge along the jet, the body of the droplet generator and the liquid feed channels were made of dielectric materials, while the metallic nozzle was connected to an ammeter. It was found that under the operating conditions of the droplet generator which were used the current leakage was less than 10^{-9} A, which amounted to ~2% of the entrained current.

In order to reliably find the effect of the surface charges on the hydrodynamic parameters of the jet it was necessary to make very accurate observations of the flow conditions of the jet with and without surface charges. For this purpose, corona-inducing electrodes were placed on the movable platform, and the measurements were carried out in the following sequence. The length L of the unbroken part of the jet was first measured without a corona discharge. The CD conditions were then established and the system of electrodes was shifted relative to the jet so as to add the required entrained current, and the length of the unbroken part of the jet was measured again. The electrodes were then retracted, and the measurement of L was repeated. This procedure made it possible to clearly establish the effect of the surface charges on the jet characteristics.

The results of the investigations are shown in Figs. 2 and 3. The measurements were carried out for a constant amplitude of the pulsation of the droplet generator for jets of liquid preheated to ~40°C flowing out of an opening of diameter 0.44 mm at a velocity of 7 m/sec. The corona-inducing electrodes were placed at a distance of 20 mm from the nozzle, which was much smaller than the length of the unbroken part of the jet. The charge density was determined from the value of the measured entrainment current and the known geometric characteristics and velocity of the jet. The relative elongation of the jet was determined for the wave number corresponding to the minimum in the relationship L(k). The curves shown in Figs. 2 and 3 indicate that the length of the unbroken part of the jet with surface charge is greater than for the uncharged jet, so that the charge on the surface of the jet stabilizes the capillary instability. This fact is at variance with previous results on the stabilities of conducting and dielectric charged jets of liquid (see the review [1] and ref. [6]).

In order to explain the effect which has been observed, let us consider the capillary instability of an infinite cylinder of viscous dielectric liquid with surface electrical charge. It should be noted that in this problem an important question arises concerning the possibility of charge movement along the jet surface. The fact is that very often a liquid is a dielectric (i.e., possesses a small electrical conductivity) as a result of the

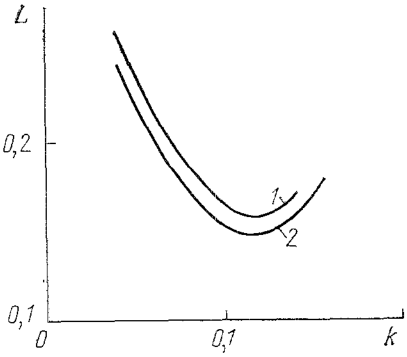

Fig. 2

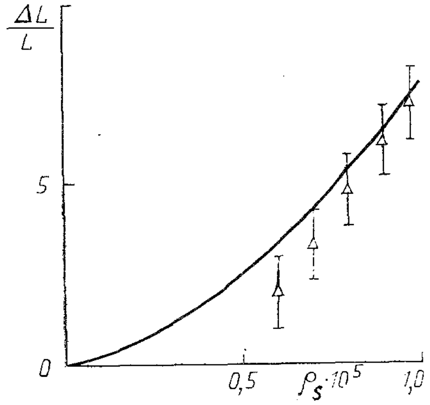

Fig. 3

Fig. 2. Experimental relationship between the length of the unbroken part of the jet and the wave number: 1) $\rho_s = 0$ C/m^2; 2) $\rho_s = 10^{-5}$ C/m^2. The parameter L is given in meters.

Fig. 3. Relative elongation of the jet as a function of the surface charge density. The solid line represents the calculated results; the points represent experimental data. The parameters $\Delta L/L$ and ρ_s are measured in % and C/m^2, respectively.

fact that the energy of activation for the formation of ions is very large, and consequently, there is a very small concentration of natural charge carriers. If an uncompensated charge is placed on such a liquid with a concentration exceeding the concentration of the natural carriers, then the electrical conductivity of the liquid will be proportional to the density of the introduced charge, $\sigma_e = \mu\rho_e$. To this approximation, the equation for the relaxation of a surface charge of density ρ_s will have the form:

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial}{\partial \tau}\left(\rho_s \mu E_\tau + \rho_s v_\tau - D\frac{\partial \rho_s}{\partial \tau}\right) = 0,$$

where the subscript τ denotes the tangential component of the vector. It should be noted that obviously the problem of the capillary instability of a jet with charge relaxation was first considered in [7]. However, this treatment dealt with a jet of ideal liquid with a simple equation for the charge relaxation with a current density $j=\sigma_e E$. Consequently, the results in [7] must describe the capillary instability of a jet of electrodes with charge carriers of different signs in feeble electrical fields, where it is possible to use the approximation of constant conductivity.

In order to describe the capillary instability of the jet let us consider an infinite cylinder of viscous incompressible liquid with surface charge. The transition from a real semibounded jet to the infinite cylinder being considered is valid for jets having high velocities [1, 3, 4].

As the base state for the infinite cylinder whose stability is being considered, the velocity of the liquid is equal to zero, the charge is uniformly distributed over the surface with a density ρ_{s0}, the electrical field strength in the jet is equal to zero, and outside the jet the latter is defined by the relationship $E_r = +\rho_{s0}/(\varepsilon_0 r)$. The scale factors of the coordinates $x_* = r_* = R_j$, the time $t_* = \rho R_j/\sigma$, and the electrical field potential $\varphi_* = \rho_{s0}R_j/\varepsilon_0$ are introduced. In addition, the components of the velocity perturbation are expressed in terms of the stream function ψ:

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

The following equations are then obtained for the dimensionless stream function and perturbation of the electrical field potential caused by the deformation of the jet surface:

$$\frac{\partial \tilde{\Delta}\psi}{\partial t} = \mathrm{Oh}\,\tilde{\Delta}^2\psi, \tag{1}$$

$$\Delta\varphi_1 = 0. \tag{2}$$

The subscript 1 refers to the perturbed quantities. The boundary conditions for the system of equations (1)-(2) linearized near the base state have the form:

on the jet axis r = 0,

$$\psi = \frac{\partial}{\partial r}\frac{1}{r}\frac{\partial\psi}{\partial r} = 0; \tag{3}$$

at infinity $r \to \infty$,

$$\varphi_1 = 0; \tag{4}$$

on the surface of the jet $r = 1 + \eta(x, t)$:

$$\frac{\partial\eta}{\partial t} = -\frac{\partial\psi}{\partial x}; \tag{5}$$

$$P + \mathrm{Oh}\frac{\partial^2}{\partial x\partial r}\left(\frac{\psi}{r}\right) - H\left(\frac{\partial\varphi_1}{\partial r} + \eta\right) + \eta + \frac{\partial^2\eta}{\partial x^2} = 0; \tag{6}$$

$$\frac{\partial\varphi_1}{\partial r} + \eta = -\rho_{s_1}; \tag{7}$$

$$\frac{\partial\rho_{s_1}}{\partial t} + \frac{\partial^2\psi}{\partial r\partial x} - E\left(\frac{\partial^2\varphi}{\partial x_1^2} - \frac{\partial^2\eta}{\partial x^2}\right) = \mathrm{sh}\frac{\partial^2\rho_{s_1}}{\partial x^2}; \tag{8}$$

$$\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial\psi}{\partial r} + k^2\psi = -\frac{H}{\mathrm{Oh}}\left(\frac{\partial\varphi_1}{\partial x} - \frac{\partial\eta}{\partial x}\right), \tag{9}$$

where the perturbation of the pressure P can be obtained from the equation of motion

$$\frac{\partial P}{\partial x} = -\frac{\partial}{\partial t}\left(\frac{1}{r}\frac{\partial\psi}{\partial r}\right) + \mathrm{Oh}\frac{1}{r}\frac{\partial}{\partial r}(\tilde{\Delta}\psi). \tag{10}$$

Dimensionless groups are defined by the following relationships

$$H = \frac{\rho_{s_0}^2 R_j}{\sigma\varepsilon_0};\ \mathrm{Sh} = D\left(\frac{\rho}{\sigma R_j}\right)^{1/2};\ E = \frac{\mu\rho_{s_0}}{\varepsilon_0 R_j}.$$

It is necessary now to go in more detail into the description of the boundary conditions (5)-(9). The relationship (5) represents the kinematic condition on the surface of the jet. Equation (6) defines the balance of normal stresses on the surface of the jet: P is the perturbation of the pressure, the second term is the viscous normal stress on the surface of the jet, the third is the perturbation of the electrical pressure related to the deformation of the jet surface, and the last two terms represent the linear part of the capillary pressure perturbation. From Eq. (9) it is clear that the jump in the normal component of the electrical field on the charged surface is proportional to the surface density of the charge. Equation (8) is a linearized equation for the relaxation of the charge, which was discussed earlier. Equation (9) is a balance of the tangential stresses on the jet surface.

According to (3), (4), Eqs. (1), (2) are converted into the form

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

$$\varphi_1 = c_3\frac{k_0(kr)}{k_0(k)}\exp(\gamma t + ikx). \tag{12}$$

By substituting (11), (12) into Eqs. (5)-(10) the following dispersion relationship is obtained after simple but extensive rearrangements:

$$\begin{aligned}&\gamma^2 + 2k^2\gamma\,\mathrm{Oh}\frac{I_1'(k)}{I_0(k)} - \frac{H\gamma k^2}{B(\gamma,k)}c(\gamma,k) = A(k) + \\ &+\left[2k\gamma\,\mathrm{Oh}\frac{lI_1'(l)I_1(k)}{I_0(k)I_1(l)} - \frac{H\gamma kl}{B(\gamma,k)}\frac{I_0(l)I_1(k)}{I_1(l)I_0(k)} + \frac{I_1(k)}{I_0(k)}c(\gamma,k) - A(k)\right]\times \\ &\times\left[2k^2 + \frac{Hk^2}{\mathrm{Oh}\,B(\gamma,k)}\frac{k_0(k)I_0(k)}{k_1(k)I_1(k)} - \frac{k_0(k)}{k_1(k)}\frac{c(\gamma,k)}{\gamma}\right]\times \\ &\times\left[l^2 + k^2 + \frac{Hkl}{\mathrm{Oh}\,B(\gamma,k)}\frac{k_0(k)I_0(l)}{k_1(k)I_1(l)} - \frac{k_0(k)}{k_1(k)}\frac{c(\gamma,k)}{\gamma}\right]^{-1}.\end{aligned}$$

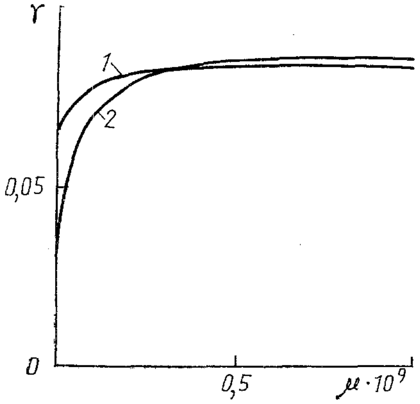

Fig. 4

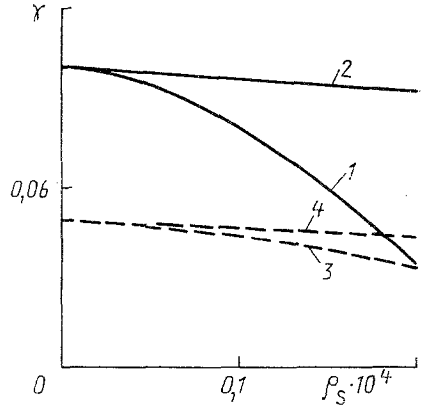

Fig. 5

Fig. 4. Increment of instability of the jet as a function of the charge mobility for a wave number k = 0.4: 1) $\rho_s = 10^{-5}$ C/m²; 2) $\rho_s = 2 \cdot 10^{-5}$ C/m². The units of the horizontal axis are μ, m²/(V·sec).

Fig. 5. Increment of instability of the jet as a function of the surface charge density (the solid lines are the calculated results for k = 0.4, while the dashed lines are for k = 0.8). 1, 3) μ = 0; 2, 4) $2 \cdot 10^{-10}$ m²/(V·sec).

The results of a numerical analysis of the dispersion relationship which has been obtained show that the presence of a surface charge on the jet with a small mobility of the charge $\mu \approx 10^9$ m²/(V·sec) stabilizes the capillary instability (i.e., the increment of instability is decreased). Here the maximum of the relationship γ(k) is shifted towards the zone of smaller wavelengths. For other liquids with $\mu > 10^{-9}$ m²/(V·sec) the surface charge leads to an increase in the increment of instability. It is obvious that the case of small values of μ occurs under the conditions of our experiment. The question of the mobility of the charge on the surface of the oil jets requires more detailed study.

By way of example, Figs. 3-5 show the results of the calculations of the characteristics of the capillary instability of the jet compared with the experimental data (the value $\mu = 10^{-10}$ m²/(V·sec) is used in the calculations, which corresponds to the mobility of ions in the bulk liquid for silicone oils [8]). The relative elongation of the jet is calculated from the formula

$$\frac{\Delta L}{L} = \frac{\gamma - \gamma^*}{\gamma^*}.$$

This definition of the relative elongation of the jet is obtained from the formula of Rayleigh for the length of the unbroken part of the jet:

$$L = \frac{v_j (\rho R_j/\sigma)^{1/2}}{\gamma(k)} \ln\left(\frac{R_j}{\delta_0}\right).$$

The small deviation between the experimental and calculated results can be explained by the fact that in the experiments the jets were charged at some distance from the efflux point, while the calculations, which do not take this fact into account, give results which are somewhat larger than the experimental values.

Further analysis of the dispersion relationship shows that the relationship γ(μ) for various values of the surface charge density has a monotonically increasing character (compare Fig. 4), and that the value of the increment γ* must exceed the quantity γ for the uncharged jet. It can be concluded from Fig. 5 that for various values of μ the relationship $\gamma(\rho_s)$ is also monotonic.

NOTATION

μ, mobility; D, diffusion coefficient; σ_e, conductivity; R_j, jet radius; σ, surface tension coefficient; Δ, Laplacian; $\mathrm{Oh} = \nu t_*/R_j^*$: Ohnesorge number; $\tilde{\Delta}$, differential operator of the second order; $\tilde{\Delta} = r\partial/\partial r(1/r\partial/\partial r) + \partial^2/\partial x^2$; $A(k) = kI_1(k)(1-k^2)/I_0(k)$; $B(\gamma, k) = \gamma + k^2\mathrm{Sh} + E_k K_0(k)/k_1(k)$; $C(\gamma, k) = EHk^2[K_0(k)/k_1(k) - k]/B(\gamma, k)$; $l^2 = \gamma/\mathrm{Oh} + k^2$; γ*, γ, increment of capillary instability of the jet with and without surface charge; δ_0, initial amplitude of deformation of jet surface; E, electrical field stress; ρ_{s0}, initial surface charge density; v_r, v_x, velocity components; x, r, longitudinal and radial coordinates; t, time; H, Sh, E, dimensionless constants; x_*, r_*, t_*, φ_*, scale factors for coordinates, time, and electrical field potential; P, pressure; ρ_{s1}, perturbation of the surface charge density; , perturbation of the electrical field potential; η, surface deformation; r, radial coordinate; k, wave number; ε_0, absolute dielectric permeability; E_r, radial component of electric field; c_1, c_2, c_3, constants; $\ell = \gamma/\mathrm{Oh} + k^2$; I_1, modified Bessel function; L, length of unbroken part of jet; ρ_s, surface charge density; ρ_c, charge density; j, current density; ψ, stream function; ΔL, increase in length of unbroken part of jet; v_j, jet velocity; ρ, liquid density.

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EFFECT OF AN ELECTRIC FIELD ON THE CAPILLARY BREAKUP OF ELECTROLYTE JETS

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The results are presented of a theoretical and experimental investigation of the forced capillary breakup of jets of electrolytes in an electric field. It is shown that in some cases there is a nonmonotonic dependence of the length of the unbroken part of the jet on the electrical field stress.

Recently there have been considerable advances in the investigation and utilization of streams of charged monodisperse particles. Such streams have found wide utilization in the new chemical technologies, in electrical droplet spraying, printing, and marking devices, in cryogenic systems, etc. An important condition of the operation of such systems is the controllability of the droplet streams by means of an external field, so that it is necessary to place an electrical charge on the particles. A very promising method of placing a charge on a droplet of a conducting liquid is the induction charging of droplets during the forced capillary breakup of jets (FCBJ) of the liquid.

The induction charging of particles during the FCBJ is a complex process and depends on many parameters [1]; there are considerable experimental difficulties in connection with its study. Hence, in spite of quite a large number of theoretical and experimental papers dealing with the FCBJ in the absence of a field, there has been clearly insufficient investigation of the effect of an electrical field on the FCBJ process. Among the theoretical investigations it is necessary to mention papers [2-4], in which by way of a model there is consideration of the problem of the effect of an electric field on the capillary instability of an infinite cylinder, which does not correspond to the real FCBJ process in a limited jet. There are still fewer experimental studies, and the investigation of the effect of an electric field on the FCBJ has been pursued to a qualitative level only in them. For these rea-

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