where t is the time.

In conclusion we note that, taking account of the hydrodynamic interaction of suspended particles by the method proposed in the present article, the rheological equations of state of weakly concentrated suspensions of deformable ellipsoidal particles (10) and the equation for the distribution function coincide in form with the corresponding equations for dilute suspensions of such particles. The hydrodynamic interaction of suspended particles manifests itself in a change in the rheological functions entering into these equations.

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INVESTIGATION OF THE DECOMPOSITION OF JETS OF RHEOLOGICALLY COMPLEX LIQUIDS

V. M. Entov, V. I. Kordonskii, V. A. Kuz'min, Z. P. Shul'man, and A. L. Yarin

UDC 532.522:532.135

1. Experimental Investigation of the Decomposition of Jets of Pseudoplastic Liquids

The investigated liquids were suspensions with different concentrations of acicular iron gamma-oxide (γ-Fe_2O_3) in AMG-10 hydraulic fluid.

The rheological characteristics of the investigated materials are given in Fig. 1. Curves 1-3 show the dependence of the effective viscosity η on the shear rate $\dot{\gamma}$, respectively, for 18, 25, 36% suspensions by weight of γ-Fe_2O_3. This same dependence for a suspension of clay is shown by curve 4. The curves of the flow have a form characteristic for the rheograms of typical pseudoplastic media with a strong dependence of the viscosity on the shear rate. With a sufficient degree of exactness, this dependence can be described by a power function

$$\tau = K\dot{\gamma}^n,\ \eta = K\dot{\gamma}^{n-1}. \tag{1.1}$$

In an experiment, the carefully degassed liquid from a tank, under the action of a piston, set into motion by compressed air, is fed vertically downward through a nozzle with a diameter of 1.28 mm. The rate of outflow of the jet formed was high enough so that the acceleration due to gravity could be neglected, and small enough so that, with the limits of the recorded section, there arose no significant aerodynamic perturbations. At the outlet from the nozzle, using a thin needle, which, at a right angle, touches the surface of the jet, and which is brought into motion by an electrodynamic vibrator, periodic perturbations, controlled in amplitude and frequency, are applied to the jet. For clay suspensions, perturbations were set up with excitation at the resonance frequency of a vibrator attached on the frame of the unit. The fully established periodic process of the decomposition of jets was recorded by photography of the jet with pulsed illumination against the background of a screen and a linear scale. The exposure time was 1 μsec.

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A detailed investigation of the evolution of the surface of the jet under real conditions on a real time scale was made using an opticoelectronic device, analogous to that used in [1].

At a given point, the jet is illuminated by an intense, uniform-density, parallel beam of light from a single-mode laser. Using a microscope, an image of the jet is projected on a narrow slit, following which a photoelectronic multiplier is installed. Since the width of the slit is far less than the linear dimensions of the projection of the image on the slit, the output signal of the FÉU is proportional to the diameter of the jet at a given moment of time. The signal from the FÉU is fed to the input of an electron-beam oscillograph, and is photographed on its screen. Using a two-beam oscillograph, and feeding direct and inverted signals to its inputs, the accuracy of the measurements can be raised and an image of the jet, reproducing its instantaneous form, can be obtained on the screen.

The process of the growth of the perturbations and the decomposition of jets of the investigated materials is shown in Fig. 2. In the case of weakly expressed non-Newtonian properties (suspension of 18% γ-Fe_2O_3), the rise in the perturbations at the surface of the jet and its decomposition under the action of capillary forces practically do not differ from the classical scheme, i.e., close-to-sinusoidal waves of gradually rising amplitude and decomposition of the jet into spherical drops (Fig. 2a, rate of outflow, 1.94 m/sec, frequency of perturbations 250 Hz).

Reinforcement of the non-Newtonian (pseudoplastic) properties of the liquid (a suspension of 25% γ-Fe_2O_3) considerably changes the character of the decomposition of the jet. The visible perturbations appear exclusively as systematic contractions of the jet. The further development of the perturbations (thinning of the jet) takes place only at the points of contraction, and the jets fall apart into columns, with a length equal to the length of a wave of the perturbations, and with a diameter close to the initial diameter of the jet (Fig. 2b, c). Under the action of the surface tension, the columns are gradually shortened, conserving their characteristic form and, in the final analysis, are converted into drops. With a further reinforcement of the plastic properties of the liquid (a suspension of 36% γ-Fe_2O_3), the jet, as before, divides into columns, which are practically not shortened during the observation time. Instead of this, there is a unique type of deformation, expressed in their curving (rotation) (Fig. 2d, e). An analogous character of the decomposition occurs also in jets of clay suspensions. The picture of the decomposition, typical for jets of pseudoplastic liquids, is well illustrated by data obtained by an opticoelectronic method. Localization of the perturbation at the point of the original contraction (Fig. 3a) and division of the jet into columns (Fig. 3b, c) can be clearly seen.

The characteristic form of the decomposition of jets of pseudoplastic liquids, observed in the experiments, opens up possibilities for evaluation of the rheological characteristics of the investigated systems. Actually, the shortening of the column takes place under the action of surface forces; here, the rate of shortening is determined by the relationship between the capillary pressure and the effective viscosity of the liquid. Neglecting inertial forces, we have

$$\alpha/a = -3\eta l^{-1}dl/dt, \tag{1.2}$$

where α is the coefficient of surface tension; a is the radius of a column; l is the length of a column; η is the effective viscosity.

All the kinematic quantities entering into relationship (1.2) can be measured directly from instantaneous photography of the regular decomposition of a jet, since, in view of the periodicity of the process, the individual columns of liquid on a photo can be regarded as successive positions of exactly the same volume of liquid at moments of time differing by a period.

The above method was used to determine the dependence of the effective velocity on the shear rate $l^{-1}\,dl/dt$; it was compared with corresponding data, obtained under steady-state deformation conditions in a coaxial-cylindrical viscosimeter (points 1 in Fig. 1). As can be seen, the results, obtained by these two fundamentally different methods, are in good agreement.

A more exact means for recording the process of the shortening of a column of liquid under the action of surface forces in a real time scale is based on an opticoelectronic method. An oscillogram of this process is given in Fig. 3c. The oscillogram gives the instantaneous value of the radius of the column and the rate of its change. From this, the deformation rate is equal to

$$\dot{\gamma} = 2a^{-1}\Delta a/\Delta t.$$

Values of the effective viscosity obtained by this method (see formula (1.1)) are also given in Fig. 1 (points 2). The coincidence of the results confirms the possibility of the use of the proposed methods for practical purposes. In the given case, two nontrivial facts are established simultaneously. First, the coincidence of the shear viscosity and the viscosity with monoaxial longitudinal deformation and, secondly, the coincidence of the values of the viscosity of the suspensions with steady-state flow and the viscosity of a material, which, before the measurement, has been subjected to intense deformation in a nozzle with the formation of a jet. In turn, this, to a certain degree, justifies the use of the steady-state rheological characteristics of a liquid in calculations of the dynamics of jets. Other data of similar form obviously do not exist. We note further that, the above approach can be found useful for the evaluation of the rheological characteristics of relaxing systems.

2. Theory of the Decomposition of Jets in a Quasi-One-Dimensional (Long-Wave) Approximation. Principal Equations.

As is shown by an analysis of the experimental data (see Fig. 2 and [2-4]), jets of sufficiently viscous Newtonian liquids, and jets of rheologically complex liquids, fall apart into segments, whose length is considerably greater than the initial diameter of the jet. This provides a basis for the construction of an approximate theory of the decomposition of jets, under the assumption of the "thinness of the jet."

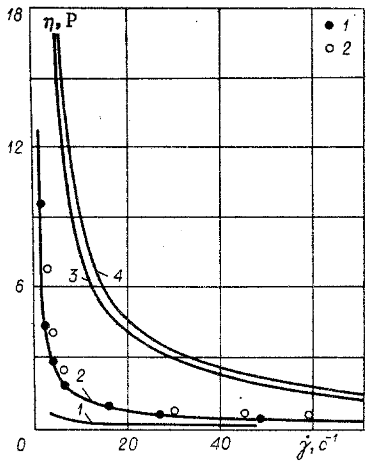

Fig. 1

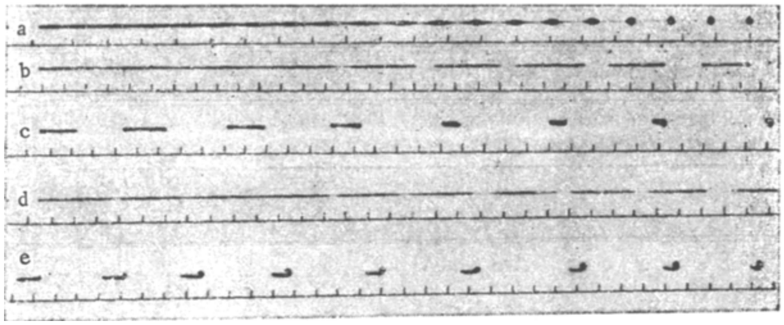

Fig. 2

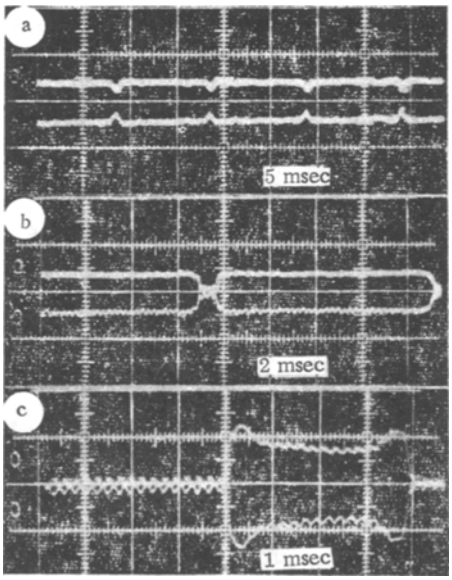

Fig. 3

We shall consider an axisymmetric form of the decomposition of the jet. Under these circumstances, the axial component of the velocity of the liquid $v_x = v$ is considerably greater than the radial v_r, and remains practically constant over the cross section of the jet; the tensors of the deformation rates D and the stresses σ are also constant over the cross section of the jet, and have a diagonal form

$$\mathbf{D}=\begin{pmatrix}\dot\gamma & 0 & 0\\ 0 & -1/2\dot\gamma & 0\\ 0 & 0 & -1/2\dot\gamma\end{pmatrix},\quad \sigma=\begin{pmatrix}-p+s & 0 & 0\\ 0 & -p-1/2s & 0\\ 0 & 0 & -p-1/2s\end{pmatrix},$$

where $\dot\gamma = \partial v/\partial x$; p is the hydrostatic component of the stress tensor; s is the deviator of the component of the axial stress.

The equations of continuity and momentum in a quasi-one-dimensional approximation have the form

$$\frac{\partial f}{\partial t}+\frac{\partial fv}{\partial x}=0,\quad f=\pi a^2; \tag{2.1}$$

$$\frac{\partial fv}{\partial t}+\frac{\partial fv^2}{\partial x}=fg+\frac{1}{\rho}\frac{\partial (s-p)f}{\partial x}+\frac{1}{\rho}\frac{\partial}{\partial x}\left[\frac{2\pi\alpha a}{[1+(\partial a/\partial x)^2]^{1/2}}\right], \tag{2.2}$$

where the last term takes account of the longitudinal force, due to the surface tension (the coefficient of surface tension α); g is the component of the acceleration of the mass forces along the axis); ρ is the density of the liquid.

From the condition of the equality of the radial component of the stresses at the lateral surface of the jet to the capillary pressure q_α with an inverse sign, we have

$$p = q_\alpha - 1/2s,$$
$$q_\alpha=\frac{\alpha}{a\,[1+(\partial a/\partial x)^2]^{1/2}}\left[1-\frac{a}{1+(\partial a/\partial x)^2}\frac{\partial^2 a}{\partial x^2}\right]. \tag{2.3}$$

On the other hand, the deviator component of the stress s is expressed in terms of the deformation rate $\dot\gamma$ in accordance with the adopted rheology of the liquid. Thus, for a power model and a Newtonian liquid, we have [5]

$$s = 2K3^{(n-1)/2}|\dot\gamma|\ \ \mathrm{sgn}\,\dot\gamma; \tag{2.4}$$

$$s = 2\eta\dot\gamma. \tag{2.5}$$

Substituting into Eqs. (2.1)-(2.3) an expression selected from expressions (2.4), (2.5) in accordance with the adopted rheology, we obtain a system of two equations for determination of $a(x, t)$ and $v(x, t)$. Giving the corresponding initial conditions and analyzing their subsequent evolution, we can investigate the dynamics of the development of the perturbations and the decomposition of a jet.

3. Numerical Investigations of Decomposition of Jet

The above system of equations was investigated numerically. Here, the motion was considered in a bounded section of the jet with a length of $(1/2)\lambda$ (λ is the length of a wave of the perturbation), and, at the end ot the segment of the integration, conditions were set assuring the periodic extension of the solution to the whole jet

$$v(0, t) = v(1/2\lambda, t) = 0,\ \partial a(0, t)/\partial x = \partial a(1/2\lambda, t)/\partial x = 0. \tag{3.1}$$

The initial perturbation was given in the form of a distribution of the radius which is not constant along the length of the jet without perturbations of the velocity

$$a(x, 0) = a_1(x),\ v(x, 0) - 0.$$

Different schemes can be used for numerical integration: a natural requirement here is that, for small deviations from the initial unperturbed state, the spectrum of the numerical scheme must correctly reproduce the spectrum of a linearized system of starting equations in a long-wave approximation. We note that, with a formal investigation of a difference scheme, it is found to be unstable, which does not mean at all that it is unsuitable, but only reflects the natural instability of the investigated physical process. Actual calculations were made by the method of straight lines, with division of the section of integration ($0 < x < (1/2)\lambda$) into 19 segments. After discretization of the derivatives with respect to x, the system of ordinary differential equations obtained was integrated by the Kutta–Merson method.

First, calculations were made of the decomposition of jets of Newtonian viscous liquids, with the aim of verifying the adequacy of the approximate method adopted for the set of existing data on the decomposition of capillary jets.

As a comparison has shown, the results of a numerical calculation from the rate of increase in the perturbations and from the decomposition time of a jet are in good agreement with the results of the linear theory and of experiment [2, 3] (this once again confirms the well-known fact of the "linearity" of the decomposition of jets of viscous liquids).

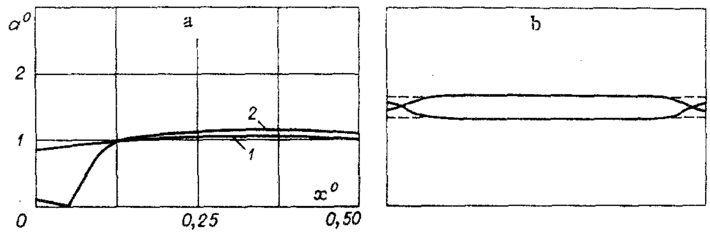

Fig. 4

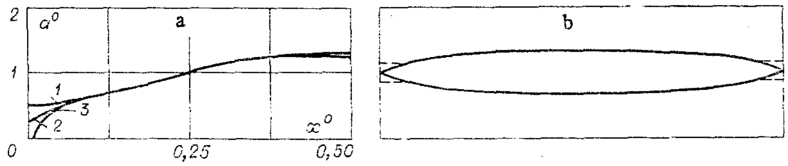

Fig. 5

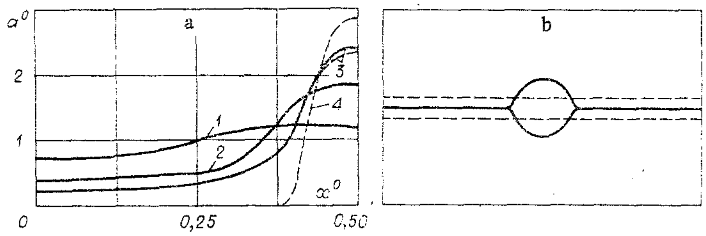

Fig. 6

Further calculations were made for several models of rheologically complex liquids. It was found that the form of the decomposition of a jet of a pseudoplastic liquid depends to a considerable degree on the form of the initial perturbation. The results obtained for a jet of pseudoplastic liquid of "moderate viscosity" (K/ρ = 8.16 cgs units, n = 0.5) are given in Fig. 4. Here the initial perturbation is taken in the form

$$a^0(x^0, 0) = 1 - \varepsilon(1 - 2x^0)\cos 2\pi x^0, \quad a^0 = a/a_0,\ x^0 = x/\lambda,\ \varepsilon = 0.05, \tag{3.2}$$

where a_0 is the initial radius of the jet. Expressions (3.2) simulates the perturbation of the surface of a jet from the impact of a needle. Figure 4a shows the development of the perturbation of the surface of the jet with time (curves 1 and 2 correspond to a time t^0 = 300 and 479.05; $t^0 = t/T$; $T = 0.229\cdot10^{-3}$ sec). It can be seen that the further change in the form of the jet is localized at the points of greatest intensity of the initial perturbation. The jet decomposes into segments, having a characteristic columnar form (Fig. 4b, where the volumes of liquid forming with decomposition are shown to scale; the dashed lines show the form of the unperturbed jet; t = 0.11 sec; a_0 = 0.06 cm; λ = 1.98 cm). With a transition to "more viscous" liquids, with a more strongly expressed pseudoplasticity (K/ρ = 127 cgs units, n = 0.1), which is characteristic for the liquids investigated in the experiment (see Sec. 1), the dependence of the picture of the decomposition on the kind of initial perturbations is expressed still more strongly, and the localization of the breakdown becomes clearer. In this case, the effective viscosities are so great that, in practice, the inertial properties of the liquid can be neglected. The calculations were made in an inertialess approximation; the left-hand part of Eq. (2.2) is discarded. The velocity v was determined by double integration with respect to x of the momentum equation obtained, taking account of the boundary conditions (3.1).

Figure 5 shows the evolution of a very large initial perturbation of a jet of pseudoplastic liquid (K/ρ = 127 SGS units, n = 0.1). The initial perturbation is taken in the form

$$a^0(x^0, 0) = 1 - \varepsilon(1 - x^0)\cos 2\pi x^0,\ \varepsilon = 0.5.$$

It can be seen that the whole evolution of the profile of the jet is located at the point of greatest contraction (see Fig. 5a); the curves 1-3 correspond to moments of time t^0 = 0, $0.517\cdot10^5$ and $0.519\cdot10^5$, respectively; $t^0 = t/T$; $T = 1.62\cdot10^{-4}$ sec. Here, considerable rates of deformation arise immediately at the points of contraction of the jet. It is obvious that, with a pseudoplastic rheology of the behavior, this rapidly leads to a fall in the effective viscosity of the liquid and, as a consequence, to a rapid localized progressive contraction. Figure 5b shows to scale the form of the jet at the moment of decomposition (t = 8.4 sec; a_0 = 0.1 cm; λ = 2.5 cm; the dashed lines show the form of the jet at the initial moment of time).

From this, by contrast, it is clear that, for dilatant liquids (n > 1) there should be "localization" of the perturbations and an increased stability of the material at the contractions. This postulate is completely confirmed by the calculations.

A comparatively rapid growth in the initial perturbation, of the form of (3.2), leads to an increase in the effective viscosity at the contractions of the jet and its conversion into a system of almost spherical drops, connected by thin filaments (Fig. 6). Here, as in the case of a "very viscous" pseudoplastic liquid, it is convenient to neglect the inertia of the liquid. In the initial stage of the development of the perturbation, the results obtained in an inertialess approximation and taking account of the inertia of the liquid coincided (curves 1 and 2, Fig. 6a; curves 1-4 correspond to the moments of time $t^0 = 5, 10, 13, 21, 85$; $t^0 = t/T$; $T = 6.08 \cdot 10^{-2}$ sec; the dashed lines show results obtained without taking the inertia of the liquid into consideration). The form of the jet at the moment of decomposition is shown to scale in Fig. 6b ($t = 1.325$; $a_0 = 0.06$ cm; $\lambda = 1.98$ cm; the dashed lines show the form of the unperturbed jet). Here $K/\rho = 9.43$ (SGS), $n = 1.5$.

4. Evaluation of Results

The experimental and theoretical investigation of the process of the decomposition of capillary jets of liquids in the region of a predominance of viscous forces over inertial forces, taking account of literature data, makes it possible to obtain a clear picture of the effect of the rheological special characteristics of the liquid on the picture of the decomposition of a jet. Above all, both for pseudoplastic and for dilatant systems, in distinction from Newtonian liquids, the decisive effect on the decomposition is that of the nonlinear stage of the development of the perturbations. However, the picture of the evolution of the jet itself is significantly different in these two cases. In pseudoplastic systems, at the points of increased initial values of the deformation rate, the effective viscosity falls, the local rates of deformation increase, and there is thus an avalanche-type process of the localization of the deformations. From this, there is a considerable dependence of the conditions of the decomposition on the value and form of the initial perturbation. In addition, it can be understood that, for sufficiently viscous systems with a strongly expressed pseudoplastic behavior, of the type of suspensions investigated in the experiment of Section 1, the whole picture of the decomposition depends to a considerable degree on the small initial rates of deformation which always occur in a vertical jet, thanks to the action of the force of gravity.

On the other hand, for systems with a well-expressed dilatant nature, there is a characteristic comparatively rapid transition to a quasi-steady state of deformation, with the formation of a beaded structure of drops of almost spherical form, connected by fine filaments (see Fig. 6). In this case, the initial perturbation is determined only by the distance between the drops (and, consequently, their volume), but not by the form of the decomposition or the time of conservation of the continuity of the jet. The dynamics of the thinning of the filaments is easy to investigate, if it is taken into consideration that the capillary pressure in the drops, equal to $2\alpha/R$ (R is the radius of a drop), with $R \gg a$ is small and can be neglected, as well as the stresses in the liquid in the drops in comparison with the capillary pressure in the filaments ($\approx \alpha/a$). Therefore, the axial component of the stress in a filament

$$\sigma_{xx} = 0,\ {}^3/_2 s = q_\alpha = \alpha/a,\ s = {}^2/_3 \alpha a^{-1}. \tag{4.1}$$

For a power liquid, we have from (2.4)

$$\frac{\partial v}{\partial x} = \left(3^{-\frac{n+1}{2}} \frac{\alpha}{Ka}\right)^{1/n} = -\frac{2}{a}\frac{da}{dt}; \tag{4.2}$$

$$\frac{\partial a}{\partial t} = -\frac{a}{2}\left(3^{-\frac{n+1}{2}} \frac{\alpha}{Ka}\right)^{1/n},\quad t = \left(3^{\frac{n+1}{2}} \frac{K}{\alpha}\right)^{1/n} 2n\left(a_0^{1/n} - a^{1/n}\right). \tag{4.3}$$

Thus, the time of the decomposition of a beaded structure

$$T^* = 2n\left(3^{\frac{n+1}{2}} \alpha^{-1} K a_0\right)^{1/n}. \tag{4.4}$$

A long extension of the final stage of the decomposition of a jet of a dilatant liquid in comparison with the initial stage is characteristic.

In conclusion, let us apply relationships (4.1)-(4.4) to an analysis of the decomposition of thin filaments of a solution of polyoxyethylene (such filaments are formed, e.g., with the rapid thinning of fingers, wetted by a solution of polyoxyethylene), having a diameter of fractions of a millimeter, and a lifetime of the order of a few seconds).

Assuming a solution of a viscous liquid, for its effective viscosity we obtain from (4.4)

$$\eta = \frac{\alpha T^*}{6a_0} \sim \frac{50 \cdot 1}{6 \cdot 0{,}01} \sim 10^3 \Pi.$$

Thus, to make the observability of thin filaments of a solution of polyoxyethylene compatible with the theory of decomposition, they must be assigned a viscosity exceeding by more than 4 orders of magnitude the viscosity of the solution in ordinary shear measurements. This fact is in need of further analysis; however, it points above all to a strong orientation of molecules of polyoxyethylene in an earlier stage of the formation of thin filaments with the formation of a "microfibrous" structure of the solution. Under these circumstances, the "elongational viscosity" of a longitudinally orientated high-molecular solution can exceed the viscosity of the solvent by several orders of magnitude [6, 7].

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EXPERIMENTAL INVESTIGATION OF THE DECOMPOSITION OF A CYLINDRICAL LAYER OF A MAGNETIZING LIQUID UNDER THE ACTION OF MAGNETIC FORCES

V. I. Arkhipenko and Yu. D. Barkov UDC 532.595:538.4

Questions of the stability of jet flows of liquid, in connection with their various technical applications, have attracted the attention of investigators in the field of the hydrodynamics of continuous media [1-9]. Magnetizing liquids hold out the possibility of effective action at an interface, using a magnetic field [6-9]. It has been established in theoretical work [10-12] that a homogeneous magnetic field tangential to a surface stabilizes jet and film-type flows, while at the same time, a field directed along a normal has a destabilizing action. For example, the field of the conductor with a current is always tangential to the surface of a cylindrical layer and, consequently, exerts a stabilizing effect on the surface of a magnetizing liquid. In this case, there arises the possibility of modeling a jet and studying its characteristics in a static statement [13]. The present investigation is a continuation of [9].

In a linear approximation, the process of the decomposition of a cylindrical layer of a magnetizing liquid can be described by a dispersion equation for infinitely small perturbations, under the assumption that the radius of the conductor is small [12]:

$$\omega^2 = I_1 \alpha k(\mathrm{Bo}_m - 1 + k^2)/I_0 \rho a^3,$$

where ρ is the density of the magnetizing liquid; I_0 and I_1 are Bessel functions of an imaginary argument; k is the wave number made dimensionless with respect to the radius of the column of liquid; α is the coefficient of surface tension at the interface of the magnetizing liquid with the surrounding medium; a is the radius of the cylinder of magnetizing liquid.

The dimensionless parameters $\mathrm{Bo}_m = \mu_0 M G a^3/\alpha$, in which μ_0 is the magnetic permeability of a vacuum; M is the magnetizability of the liquid; G is the gradient of the intensity of the magnetic field, and analogous to the well-known Bond number $\mathrm{Bo} = \rho g a^2/\alpha$; in [13] it was called the magnetic Bond number. This number is the ratio of the pressure induced by the volumetric magnetic force $\mu_0 MG$ to the pressure set up at the interface by the forces of surface tension. With $\mathrm{Bo}_m > 1$, the layer of perturbations is stable with any given arbitrary perturbations; if the condition $\mathrm{Bo}_m < 1$ is satisfied, the cylindrical layer falls apart into individual drops. For a conductor with a current $G = \mathcal{J}/2\pi a^2$ ($\mathcal{J}$ is the current through the conductor). Setting $M = \chi H$, which is valid with small values of the intensity of the magnetic field H, and writing H in the form $H = \mathcal{J}/2\pi a$, we obtain

$$\mathrm{Bo}_m = \mu_0 \chi \mathcal{J}^2/4\pi^2 a,$$

where χ is the magnetic susceptibility of the magnetizing liquid.

To describe the effect of an external homogeneous magnetic field on the stability of the cylindrical layer, we introduce the dimensionless complex $S = \mu_0 M^2 a/\alpha$, used in working up the results of an investigation of a suspended drop in a homogeneous magnetic field [14].

Experiments on the investigation of the stability of a cylindrical layer and of a study of the effect of an external homogeneous magnetic field perpendicular to the axis of the cylinder, on it, were made in a glass vessel with horizontal dimensions of 240 × 40 mm and a height of 40 mm. The action of an external magnetic force tangential to the surface of the cylinder was investigated in a vessel with horizontal dimensions of 40 × 40 mm and a height of 130 mm. Along the long axis of the vessels there was installed a horizontal hollow conductor with an external radius of 1 mm, made out of a nonmagnetic material and cooled by flow-through water with a constant temperature. The length of the cylindrical layer of magnetizing liquid in a horizontal vessel was 160 mm, and in a vertical vessel 80 mm.

The working liquid was a ferroliquid, whose saturation magnetization was 27 kA/m, density $\rho = 1.25 \cdot 10^3$ kg/m^3, and magnetic susceptability $\chi = 1.242$. The gravitational forces at the surface of the cylindrical layer was compensated by

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