Journal of Engineering Physics and Thermophysics, Vol. 70, No. 5, 1997

SPREADING OF A DROP OF AN ELECTRORHEOLOGICAL SUSPENSION IN AN EXTERNAL FIELD

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UDC 532.68:537.218

We analyze the effect of a constant electric field on the dynamics of the spreading of an electrorheological suspension drop. We discovered a strong effect of the electric field intensity on the speed of spreading and shape of the drop. An empirical relationship is established between the contact spot radius and droplet height and the magnitude of the voltage supplied to the electrodes.

Introduction. General Statement of the Problem. Investigation of the laws governing the process of the spreading of liquid over a horizontal surface is stimulated by the importance of the problem for a number of practical applications such as technology of painting, lubrication, and cleaning of surfaces, consideration of adhesion effects and of the processes occurring in electrophoto- and lithographic printing.

There are a great number of both experimental [1, 2] and theoretical [3, 4] works that are devoted to this problem starting from the investigation made by Hardy in 1919 [5]. Certain prospects in this field of investigation were opened up in recent years due to the development of new types of fluids with abnormal rheological properties that are determined by an external effect, for example, by an electromagnetic field.

It is known that spreading is stable if interphase surface tensions are governed by physicochemical processes [4]. For slow flows at each time instant the Young equation is valid

$$\sigma_{\mathrm{sg}} - \sigma_{\mathrm{s\,liq}} = \sigma_{\mathrm{liq\,g}} \cos(\theta_{\mathrm{st}}) , \tag{1}$$

where $\sigma_{\mathrm{s\,liq}}$, $\sigma_{\mathrm{liq\,g}}$, σ_{sg} are the surface tensions between solid and liquid phases, and liquid and gas phases, and solid and gas phases.

Under the spreading conditions considered, it is necessary to keep in mind, first, the change in the surface energy of solid bodies exposed to the influence of an electric field [6]. This effect was evoluated within the framework of an oscillatory model in [7]. It was shown in that work that in an electric field of strength $E \sim 10^6$ V/m the surface energy decreased only by a value of the order of 10^{-15} J/m^2. However, the polarization of an electrically conducting or semiconducting (the Jonson–Rabek effect) layer near the metal surface may create fields of strength $E \sim 10^8$ V/m. However, in this case calculation of the surface energy by the Lippman–Helmholtz equation gives a value of the order of 100 mJ/m, suggesting the possibility of a noticeable change in the surface tensions σ_{sg} and $\sigma_{\mathrm{s\,liq}}$ in formula (1).

Second, an electric field must noticeably affect the process of spreading of disperse liquids over a surface due to internal structural rearrangements. The molecules of virtually any liquid in an electric field are dissociated, polarized, begin to move to the electrodes, and form anisotropic structures. It was shown experimentally in [8] that these rearrangements are insignificant in "pure liquids" and give only a weak (several percents) increase in electrical viscosity. In this respect, electrorheological suspensions are of great interest, being distinguished by strong structure formations leading to a change in rheological indices by several orders of magnitude.

However, despite the 50-year history of the study of the electrorheological effect, the literature lacks any publications associated with the investigation of the specific features of flow of such media with an open boundary.

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus," Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 70, No. 5, pp. 766-770, September-October, 1977. Original article submitted August 14, 1995.

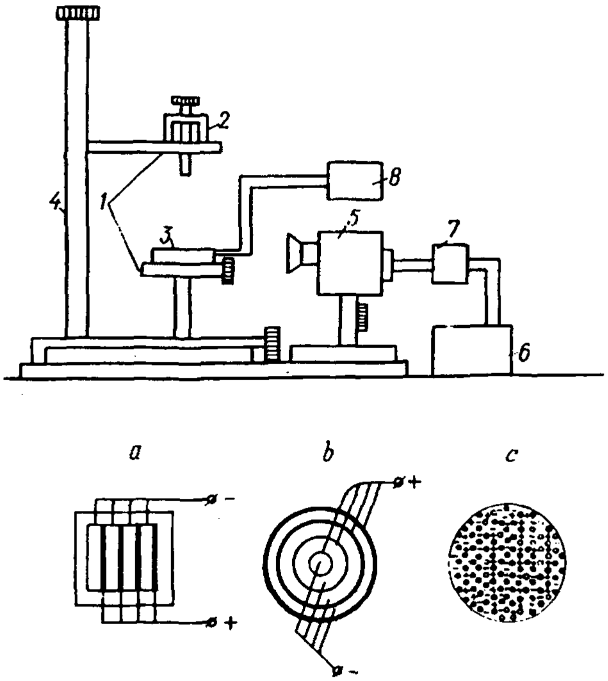

Fig. 1. Schematic diagram of experimental setup: 1) traverse mechanism, 2) microbatcher, 3) stage with electrodes (a) of planar type; b) of circular type, c) of pointwise type), 4) rack, 5) motion-picture camera (videocamera), 6) pulse generator, 7) power pack, 8) high-voltage source.

Up to the present time, only Poiseuille and Couette flows in closed channels have been considered. This seems to be due to the fact that the efforts of investigators and engineers were concentrated mainly on the optimum implementation of the well-known Winslow effect (increase of electrical viscosity of working media) in improved designs of hydraulic units. Such types of flow as film flows, as well as rivulet flows over a surface and in channels have been ignored. The necessity for stating such problems became evident only in connection with the development of new recipes for electrorheological suspensions for film coatings [9]. Their composition involves a quick-drying solvent of a dispersion medium and fine powders of oxides known as fillers for ordinary dyes.

The present work is the first in the series of planned comprehensive investigations of the process of spreading of electrorheological suspensions with an open boundary in electric fields. It is aimed at qualitative determination of the field effect on the basis of experimental evaluation of the change in the shape and dimensions of a drop from the time of contact with the surface to the attainment of an equilibrium state after the spreading terminates. It was intended to determine the functions $R(E)$, $h(E)$, $R(t)$, and $h(t)$ to perform subsequent estimations of the magnitude of surface tension for various external electric field strengths.

Experimental Investigations. As a working sample of electrorheological suspension, we selected a suspension based on the modification of silica (diatomite) activated with water in mineral oil with small additions of a surfactant, namely, oleic acid. The concentration of the solid phase varied from 5 to 60 wt.%.

To investigate the kinetics of the spreading of a drop after its fall onto a surface located horizontally in an electric field, we devised the setup whose schematic diagram is presented in Fig. 1.

The electric field was created by means of 4 mm-wide planar plane-parallel electrodes spaced 1.5 mm apart and imbedded into the dielectric flush with the surface of stage 3 (Fig. 1). Ten plates were mounted in the stage surface, with a positive potential being supplied to each even plate and a negative to each odd one. Such an electrode arrangement makes it possible to investigate the kinetics of the spreading of liquid drops that fall onto: a) the middle of a dielectric bridge; b) the middle of an electrode; c) several electrodes.

Calculation of the electric field outside the plane of the stage plates (in a drop) can be carried out using the Schwartz–Christoffel conformal transformation [10]

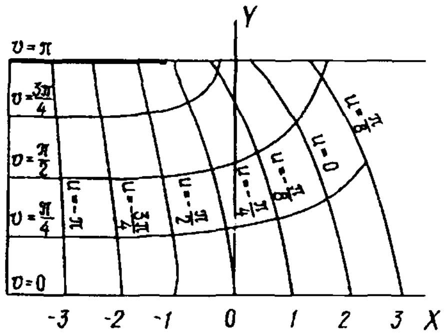

Fig. 2. Distribution of electric field in liquid drop.

$$z = w + \exp(z) . \tag{2}$$

Here, the complex potential of a two-dimensional field in the $z = x + iy$ plane is transformed into the mapping plane $w = u + iy$, and the linear coefficient of transformation is

$$du/dt = E(\exp i\xi) = du/dx + idv/dx . \tag{3}$$

The module E is the scalar field gradient in the plane z, ξ is the angle of clockwise rotation of the vector E in transition from plane z to plane w:

$$\tan(\xi) = -(du/dy)/(dv/dy) . \tag{4}$$

Differentiating (2) and substituting the values of the derivatives into formulas (3) and (4), we obtain

$$\begin{gathered} \mathrm{E} = \sqrt{(1 + \exp(2\mathrm{u}) + 2\exp(2\mathrm{u})\cos(\mathrm{v}))} , \\ \xi = \arctan(\exp(u)\sin(v)/(\cos(v)\exp(u) + 1)) . \end{gathered} \tag{5}$$

The static external electric field created in a drop by several pairs of electrodes can be calculated using the method of superpositions. In this case the vector sum of the intensities E from each pair of electrodes determines the magnitude and direction of the resulting field. The calculation of the electric field strength in the drop sectional plane is presented in Fig. 2 for the simplest case of its position between two electrodes.

The procedure for conducting the experiment is as follows. The electrorheological fluid is thoroughly stirred in the tank where it is contained and then it is poured into the cylinder of a microbatcher (2–3 ml). The microbatcher is positioned by coordinates at the desired height above the stage with the planar electrodes. A test drop of the electrorheological fluid is pressed out and is used for focusing the objective of the motion picture camera. For this purpose, a dummy target is set along with the drop with a millimeter scale, which is also a scale for estimating the dimensions of the drop on the developed film. The adjustment made, the microscrews of the traverse mechanisms and of the motion-picture camera are fixed by fastening screws. This makes it possible to keep the focal distance completely identical and the accuracy of the fall of a drop onto the same place on the stage.

To estimate the effect of the electric field on the shape of an electrorheological fluid drop falling from a prescribed height onto the stage and the dynamics of its spreading over the surface, the experiments were performed in two versions: without and with a field on the electrodes:

a) A motion-picture camera with a frame speed of 1 Hz/sec is activated. In 1–2 sec a drop of the electrorheological liquid is pressed out. The instant of contact is fixed by the camera and then the process of spreading is photographed for 90 sec. The readings of the frame counter are taken for further interpretation of the photographs;

b) Having selected all the above-indicated parameters (height of fall, mass of drop) the needed voltage is applied to the electrodes of the stage from a supply source. Then, the camera is switched on and the instant of contact of a new drop of the electrorheological suspension with the stage surface is fixed. At 30 sec after the drop contacts the surface, the field is switched off. The motion-picture photographs are taken continuously from the

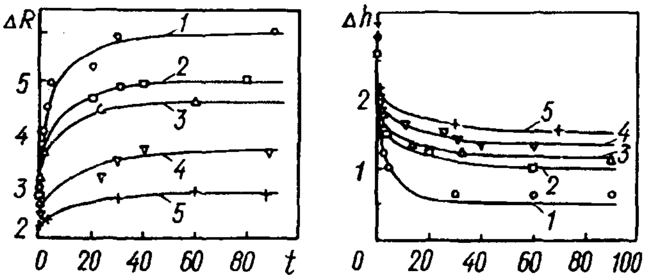

Fig. 3. Kinetics of change in radius of spot of contact with electrodes ΔR and height Δh of electrorheological liquid drop: 1) $U = 0$, 2) 250, 3) 500, 4) 1000, 5) 1500. h, R, mm; t, sec; U, V.

instant of contact for 120 sec. Experiments were made for four values of the voltage applied to the electrodes U: 250, 500, 1000, and 1500 V.

First of all we must say that we noticed an effect of the location of the point of contact of the drop center relative to the electrodes. When a drop falls between them in the middle of the dielectric bridge the drop spreads uniformly in all directions and its cross-section, which is parallel to the stage plane, is preserved in the form of a circle. When the middle of the drop plane coincided with the middle of the electrode, we observed deformation of the drop up to the cross-section in the form of a figure "eight" due to the strong inhomogeneity of the symmetric field. In other cases the symmetry was violated, the dimensions of the figure "eight" depended on the mass of the drop, the height of its fall, and the area of its contact with the electrodes. In order to ensure a more uniform spreading of the drop, other schemes of electrodes can be used, for example, such as shown in Figs. 1b and 1c. The experimental results presented in this paper were obtained for the version of the planar location of the electrodes and for the mass of the drop equal to 0.046 g.

Visual observations and analysis of the photographs showed that in the absense of an electric field the drop spreads continuously up to the development of an equilibrium state characterized by the parameters R_{st}, h_{st}, and θ_{st}.

The shape of the drop is identical to that obtained when a medium with a limited wettability spreads, when θ is larger than 90°. Power supply noticeably changes the pattern of drop spreading. Even at small voltages (250 V) we note a relative decrease in the dimensions of the drop, the parameters R, h and angle θ, which correspond to fixed periods of time.

For mean intensity fields (at $U = 1000$ V) we observed the formation of a thin film layer on the stage surface at the periphery of the drop. Beyond the limits of this layer (inside the drop) volumetric spreading occurs. In this case the profile of the drop is characterized by the angles θ and θ'. High-intensity fields ($U > 1500$V) create a situation in which the drop is kept on the surface without spreading for a certain time t. At this stage, the angle θ is smaller than 90°. However, the removal of the field leads to spreading; the magnitude of the drop radius attains the dimensions of the spot R_{st} only after a long period of time. Thus, electrorheological liquid is capable of preserving the elements of the internal structure created by the field, i.e., it possesses memory. Typical dependences of the parameters R and h on time and voltage are presented in Fig. 3. The change in the concentration of the filler preserves the type of spreading described.

The changes in time of the radius $\Delta R = R - R_0$ and height $\Delta h = h - h_0$ of the drop, where R_0 and h_0 are the initial dimensions of a drop exposed to a stationary external field for time $t \le t_{\text{ext}}$, are most adequately described by a power-law model of the form $\Delta h = At^{-n}$, $\Delta R = Bt^{m}$, which agrees with similar dependences for anomalous liquid media. The parameters of the model were evaluated by the least-squares method at a 95% confidence coefficient. For the case considered the values of the coefficients A, B, n, and m are presented in Table 1. It is seen that these dependences describe the dynamics of spreading for all of the investigated voltages U applied to the capacitor plates. The values of the coefficients A, B, n, and m follow the change in voltage U by a linear law:

$$A = a + bU\,, \quad B = a_1 + b_1U\,, \quad n = c + dU\,, \quad m = c_1 + d_1U\,. \tag{6}$$

TABLE 1. Characteristic Parameters of Spreading of an Electrorheological Suspension Drop

U, V	n	A	m	B
0	0.226	15.137	0.118	39.316
250	0.141	17.451	0.089	35.352
500	0.138	18.854	0.104	32.527
1000	0.128	24.476	0.066	27.520
1500	0.078	20.168	0.036	24.030

TABLE 2. Characteristic Parameters of Spreading of Electrorheological Suspension Drop

Parameter	a	b	c	d
Height	−0.0100	38.3291	0.1134	$-4.9 \cdot 10^{-5}$
Parameter	a_1	b_1	c_1	d_1
Radius	0.0034	16.3705	0.1937	$-8.1 \cdot 10^{-5}$

Statistical evaluation of the coefficients in relations (6) makes it possible to neglect the values of d, d_1 and a, a_1 in comparison with the values of c, c_1 and b, b_1, respectively. The general dependence of the considered process of spreading on time t and voltage U can be reduced to the following:

$$\Delta h\,(t, U) = bUt^{-c}\,, \quad \Delta R\,(t, U) = b_1 U t^{c_1}\,. \tag{7}$$

The values of the coefficients are presented in Table 2.

Conclusion. A specific feature of the effect of a stationary electric field on the spread of a limited volume (drop) of an electrorheological liquid consists in a change of its shape and speed of spreading when exposed to fields of different intensities. Here, one can distinguish the induction period and the period of aftereffect that are characteristic of the mechanical behavior of thixotropic media. The regressive dependence of the drop height h and the radius of spot contact R on time t and on the voltage U on the capacitor plates has a power-law form.

NOTATION

σ, surface tension; θ, angle between solid surface and tangent to the drop surface; θ', angle between solid surface and tangent to thin layer of drop being spread; k, coefficient of surface roughness; v, speed of contact spot propagation; S, contact area; t, time; R, radius; ρ, η, density and viscosity of liquid; E, electric field strength; x, y, Cartesian coordinates in plane z; u, v, coordinates in complex plane w; ξ, angle of rotation of vector of strength E on transition from plane z to plane w; n, m, indices in powers; A, B, C, D, coefficients; U, voltage. Subscripts: sg, s liq, g liq, values of quantities at the "solid body–gas,", "solid body–liquid," "gas–liquid" interfaces; 0, initial value; st, stationary values; ext, external effect.

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