that, in the general three-dimensional case, if there is relationship (24) and condition (22) is satisfied at solid boundaries, we naturally assume, by analogy with exact solutions, that (22) holds throughout the flow field. In this case, MMPE are self-consistent, in contrast to MPE. Actually, (3) is then transformed into an ordinary Navier–Stokes equation with the viscosity coefficient $\mu + k/2$, while (7) is transformed into the Helmholtz equation for vorticity [in contrast to (7), expression (4) does not convert to the Helmholtz equation]. This indicates once again that the correct approach in describing the flow of a micropolar liquid must be based on MMPE.

NOTATION

σ_{ij}, stress tensor; m_{ij}, micromoment tensor; δ_{ij}, Kronecker tensor; ε_{ijk} Levi–Civita tensor; α, β, and γ, rotational viscosity coefficients; μ and k, viscosity coefficients; p, pressure, ρ, density; j, micromoment of inertia; V, velocity, Ω, angular velocity of microrotation; Φ, differential form; L_V, Lie operator; r, φ, z, cylindrical coordinates; ω, angular velocity of the disk; F, G, H, f, g, and h, dimensionless functions; C_1, C_2, C_3, and C_4, dimensionless constants; M, moment; ψ, stream function; a and λ, constants.

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CHARACTERISTICS OF THE RHEOLOGICAL BEHAVIOR OF ELECTROSENSITIVE DISPERSIONS OF DIFFERENT STRUCTURAL-RHEOLOGICAL TYPES

Yu. G. Yanovskii, E. V. Korobko, and V. V. Barancheeva

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A classification of electrosensitive dispersions of different structural-rheological types is made.

According to existing ideas electrorheological fluid systems (ERS), which are sensitive to the action of an electric potential, consist of dispersed compositions with a complicated formula, in which the solid phase (most often silicon dioxide) is insoluble in the dispersion medium – nonpolar organic substances, for example, oils. Such compositions also contain a number of other necessary components, in particular, stabilizers and activators. The stabilizers become adsorbed on the developed surface of the particles of the solid phase and encapsulate them, thereby preventing conglomeration and precipitation. The activators, by polarizing the particles, make ERS electrically active. Under the action of an external potential the particles of the solid phase, becoming dipoles, interact actively with one another. In the process they rotate, which rotation is recorded on speckle pictures, and move into the volume of the dispersion medium, and this motion is accompanied by entrainment of the medium and local turbulence. As the intensity of the electric action becomes stronger the particles of the solid phase are combined into separate associates and continuous fi-

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A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. A. V. Topchiev Institute of Petrochemical Synthesis, Academy of Sciences of the USSR, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 2, 219-224, August, 1989. Original article submitted March 17, 1988.

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bers, extended anisotropically along the intensity vector and the tips connecting the electrodes. When the content of the solid phase (fill) $C \leq 1\%$ they can be easily seen in transmitted light [1]. In ERS with a high concentration of suspended particles a unified framework is formed. The lifetimes of the separate elements and the strength properties of the framework depend on the ratio of the electric and shear forces and determine the structural-rheological state of highly filled ERS: viscoplastic, elastic, or quasisolid. The manifestation of the rheological characteristics of ERS have been studied in detail experimentally using different schemes and methods for producing deformation (shear, vibrational, and oscillatory rheometry [2, 3]) as well as in experiments on measuring the escape forces of the electrodes of the capacitor filled with the working medium [4], etc. In particular, it has been established that the intensity of the electrorheological effect depends strongly on the composition of the medium — one of the main factors determining the structural-rheological type of the ERS. If it is necessary to have an activator and it is desirable to have a stabilizer in the usual collection of ingredients of the ERS, then the amount of solid fill is determining for obtaining the necessary change in the physical-mechanical characteristics of the medium.

Our investigations [5, 6] of the deformation characteristics of ERS, as well as the investigations of others [7, 8], have made it possible to separate them into three basic structural-rheological groups whose properties determine their area of application in modern technology. This division is based on the ration of the concentrations of separate components in them and the degree to which they affect the electrorheological effect (ERE).

Electrorheological systems with low concentration ($C \leq 5\%$), which in a shear flow have structures that are mobile relative to the dispersion medium but are practically uncoupled with one another, manifest the properties of a Newtonian liquid. When an electric field is applied in a definite range of electric actions each level of such actions is associated with corresponding values of the viscosity, and virtually no anomalous effects are observed. Such media can be employed as heat carriers [9], as well as for creating controllable optical devices [10].

For compositions of ERS with average concentrations ($C = 5$-20%) and a dynamic framework, formed by spatially coupled structures, non-Newtonian properties are observed and the effective viscosity of the system increases in electric fields by several factors of ten. Under conditions of low-amplitude deformations, not leading to intense disruption of the structure, such suspensions exhibit elastic properties [3]. Their area of application is determined by the working media for different automatic hydraulic and robotic systems [11], water power systems [12], and viscous-friction dampers [13].

Highly filled ERS ($C > 20\%$) are distinguished by completed structure formation and as a result of this they have the highest increment to the effective viscosity and exhibit significant manifestation of elastic forces in the presence of electric fields; this makes it possible to use this group of suspensions as fixing pastes [4] or interlayers with varying acoustic characteristics [14].

We shall now discuss in greater detail the general characteristics of the rheological behavior of ERS of different structural-rheological types, manifested as a result of the combined actions of differently oriented force fields — electric and mechanical — in a wide range of variation of these parameters. We shall examine the data for a typical ERS — a suspension of finely pulverized diatomite in transformer oil with water as an activator and oleic acid as a stabilizer. The experimental results were obtained by varying over a wide range the intensity of the electric field and at room temperature in two traditional deformation regimes — continuous shear in steady state flow regimes and periodic (sinusoidal) shear — on a Reotest-2 rotation viscosimeter and a DKhP mechanical spectrometer [15], respectively. In the last case the tests were performed both in the linear region of deformation, i.e., under conditions of extremely low deformation amplitudes, which do not disrupt the internal structure of the system, and in the nonlinear region. The attainment of the linear region of deformation was monitored by well-known methods [3].

The concentration of the dispersed phase in the ERS affects primarily their behavior in the regime of continuous deformation, i.e., the character of the flow curves — the stress τ versus the rate of deformation $\dot{\gamma}$ (Fig. 1). The data were recorded in a regime with an established shear flow. One can see from the figure that the higher the concentration of the solid phase the higher the effective viscosity in the absence of a field (curves 1-3) and the greater the anomaly of the viscoelastic behavior accompanying the application of the electric field (curves 4-8) are.

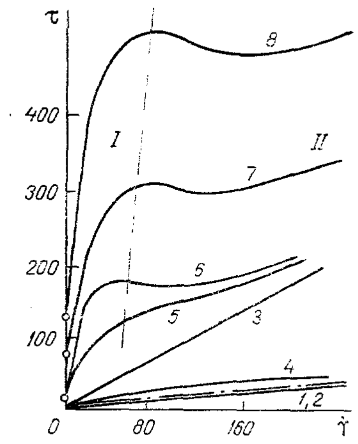

Fig. 1. Stress τ versus the rate of shear γ for ERS (diatomite – transformer oil) for different values of the electric field intensity E: 1) E = 0, C = 5.0; 2) 0 and 20; 3) 0 and 40; 4) 1.3 and 5; 5) 1.3 and 20; 6) 0.52 and 40; 7) 0.65 and 40; 8) E = 1.0 kV/mm, C = 40 mass %.

Summarizing, we note that for $C < 5\%$ (the value $C = 5\%$ can be adopted as the threshold value of the concentration that leads to the formation of the structural framework of the system) the flow process develops predominantly in the liquid phase without affecting the adsorption layers formed on the surface of the solid particles – the system behaves as a Newtonian liquid.

The introduction of more than 5% of a finely dispersed silicon dioxide fill into the ERS changes considerably the character of the flow of the medium when a field is applied (see curves 5-8). In these cases the ERS primarily acquires pseudoplasticity, characterized by a yield stress τ_0 (the values of τ_0 are denoted by dots on the coordinate axes). The yield stress τ_0 is a function of the concentration and the intensity of the electric field. In addition, increasing the intensity of the electric field leads to the appearance of distinct thixotropic properties, which is observed primarily in the irreversibility of the course of the curves $\tau(E)$ accompanying an increase and a decrease in E (not shown in Fig. 1). If, however, after such a cycle is completed, i.e., after the electric field is removed, the deformation of the ERS is continued with a constant rate of shear $\dot{\gamma}$, then the degree of structural organization returns to that present at the start, which existed before the electric field was applied, all the more quickly the lower the maximum value of E.

The transition through the maximum on the curves $\tau(\dot{\gamma})$, i.e., from the nonlinear region I into the linear region II (the boundary of these regions is denoted by the broken line in Fig. 1), corresponds to a transition from regimes of flow of a system with undisrupted structure to regimes of flow with deformation-induced disruption of the structure. The existence of a structural framework in ERS, which is stronger in strong electric fields, leads to the fact that the rates of shear corresponding to the maximum on the curves $\tau(\gamma)$ depend on the content of the solid phase.

The effect of the fill concentration on the characteristics of the process of structure formation in ERS is also observed in the regime of periodic deformation (dynamic tests). Thus, Fig. 2a shows the components of the complex dynamic shear modulus – the modulus of elasticity σ' and the modulus of losses σ'' – as a function of C; these curves were constructed in the linear region of deformation [15]. The strongest changes in σ', $\sigma'' \sim f(C)$ are observed in the region $C \cong 20$-30%. For compositions with concentration $C > 40\%$ the dependences $\sigma'(C)$ reach a plateau, while the values of the modulus of losses σ'' continue to increase. The latter behavior can apparently be explained by the definite increase in the number of defects in the structural framework formed in an electric field in systems with high fill concentration.

The effect of the electric field on the viscoelastic behavior of ERS with different compositions can be seen from the data presented in Fig. 2b in the form of the curves σ', σ'' – f(E). Curves of the tangent of the angle of mechanical losses $\tan\delta$ versus E are also shown here. As is well known, $\tan\delta = \sigma''/\sigma'$ is a measure of the ratio of the dissipated energy to the energy stored in the material over one cycle of periodic deformations. One can see that $\tan\delta$ varies most strongly for low values of E, i.e., in relatively weak electric fields. As E is increased the dependences $\tan\delta$ – f(E) become weaker and the values of $\tan\delta$ approach constants. The maximum values of σ' and σ'' and the minimum values of $\tan\delta$ depend on the fill concentration. For media with low concentration C (less than 5%) $\sigma'' > \sigma'$ and $\tan\delta > 0$ (not shown in Fig. 2), since a spatial structural framework is not formed in the system. As C is increased from 10 to 60% the values of σ' become significant-

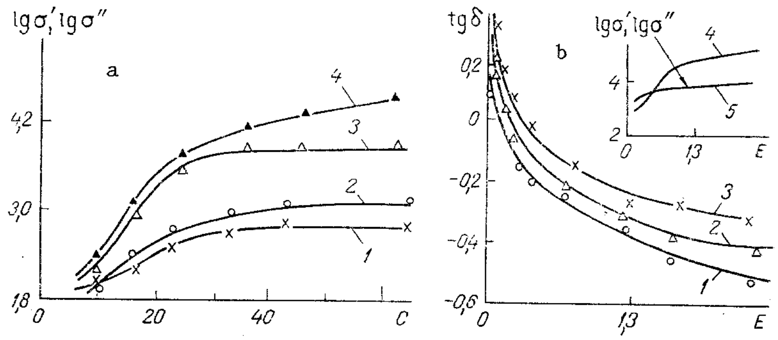

Fig. 2

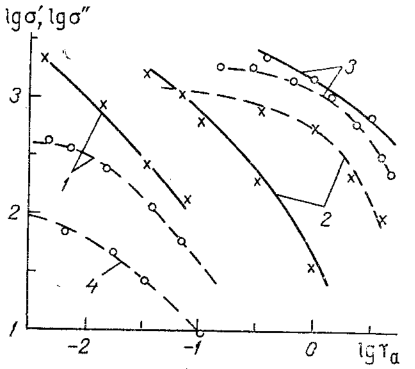

Fig. 3

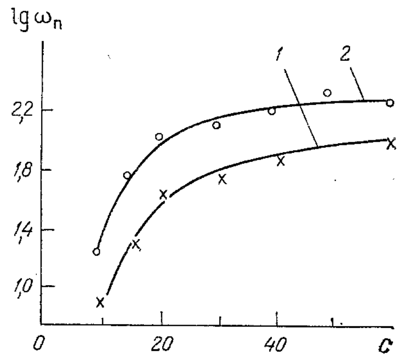

Fig. 4

Fig. 2. Components of the complex shear modulus σ' and σ" versus the fill content (a) as well as their ratio tan δ = log (σ"σ') versus the electric field intensity (b): a – 1) σ'; 2) σ", E = 0.1 kV/mm; 3) σ"; 4) σ', E = 2.6 kV/mm; b – 1) C = 60; 2, 4, 5) 40; 3) 10%, log ω = 0, γ = 0.0266.

Fig. 3. Modulus of elasticity σ' (solid curves) and the modulus of losses σ" (broken lines) versus the amplitude of the rate of deformation γ_a for ERS with diatomite concentration C = 40 mass % and different electric field intensities: 1-3) E = 1.3; 4) 0.13 kV/mm; 1, 4) log ω = 0; 2) 1.0; 3) 2.4, ω = 2πf. f, $\sec^{-1}$.

Fig. 4. Dependence of the threshold values of the frequency ω_{th} on the diatomite concentration in ERS: E = 0.13 (1) and 2.6 kV/mm (2).

ly higher than σ", in some cases by two orders of magnitude. Completion of the formation of the potentially possible spatial structural framework in ERS (all free dipoles are involved in the interaction) with a fixed level of deformation is achieved for E > 1 kV/mm.

The frequency dependences of the modulus of elasticity σ' and the modulus of losses σ" as well as their dependence on the amplitude of the rate of deformation $\gamma_a = \gamma_0\omega$, where ω is the circular frequency and γ_0 is the amplitude of the deformation, permit determining the starting shear stresses, corresponding to the deformation-induced boundaries of existence of the structural framework, i.e., bounding the region of linear deformation, depending on the composition of the medium, the value of E, and the deformations. Thus, two regions can be distinguished on the curves $\sigma'(\gamma_a)$ and $\sigma''(\gamma_a)$ (Fig. 3) for all compositions of the ERS – linear and nonlinear. In the linear region the curves $\sigma'(\gamma_a)$ and $\sigma''(\gamma_a)$ drop rapidly as γ_a increases, and these characteristics depend sharply on γ_a. This manifestation of the nonlinear properties of ERS as dispersed systems is a general behavior. It is significant that the modulus of elasticity σ' drops more rapidly than the modulus of losses σ", since "nodes" of the structural framework starts with stronger mechanical actions.

If the experiments are performed under conditions of strictly constant deformations γ_0, but with variable frequencies ω, then it is obvious that up to certain (threshold) values of the deformation frequencies $\omega = \omega_{th}$, which are unique for each composition of the medium and intensity of the electric field E, the moduli σ' and σ'' are constant. As the frequency $\omega > \omega_{th}$ is increased, however, σ' and σ'' change rapidly with time until they reach some constant values characteristic for one or another level of deformation. The dependence of ω_{th} on the fill concentration C is shown in Fig. 4. For ERS with a diatomite content C > 40% the zone where the structural framework is not disrupted is increased insignificantly. It was established that for all compositions studied, the behavior of the ERS under mechanical actions is determined not by the frequency, but rather the amplitude of the deformations, since the dependence of σ' and σ'' on γ_0 is clearly nonlinear over a wide range of values of γ_0.

Analysis of the viscoelastic behavior of ERS, performed based on comparing the results observed in periodic and continuous regimes of deformation with application of an electric field, shows that in the case of dynamic experiments (low-amplitude deformation) the structure is not disrupted and all concentration dependences and the character of the electric action are manifested more prominently.

Establishing the boundaries of the linear region of deformation for ERS with different compositions as a function of E makes it possible to justify the choice of optimal regimes for controlling the amplitude-frequency characteristics of oscillatory devices [16].

It can be concluded from the data presented that the characteristics of the mechanical behavior of ERS depend significantly on the concentration of the dispersed phase. However, the structural-rheological type of ERS and its ability to function in concrete devices are determined also by the intensity of the electric field and the frequency and amplitude of the mechanical load. Taking these factors together in aggregate makes it possible to develop hydraulic systems and units for robotic systems (grippers) with fixed working characteristics.

NOTATION

C, fill concentration in the electrorheological suspension, mass %; γ, rate of shear, sec^{-1}; τ, shear stress, Pa; τ_0, starting shear stress or the yield stress, Pa; E, electric field intensity, kV/mm; σ', modulus of elasticity, Pa; σ'', modulus of losses, Pa; $\tan\delta$, tangent of the angle of mechanical losses; γ_0, deformation amplitude; ω, circular frequency, rad; γ_a, amplitude of the rate of deformation.

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MOTION OF A HIGHLY VISCOUS NON-NEWTONIAN LIQUID IN RESERVOIRS

V. V. Mel'nichenko, B. M. Khusid, A. A. Dunets,
V. M. Postnikov, and O. I. Mikulin

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Self-similar solutions are found for the equation of spreading of a thin layer of high viscosity non-Newtonian liquid in the presence of a constant power source. Results are compared with experimental data.

It was shown in [1] that in the approximation of a geometrically thin layer ($h_0/L \ll 1$, where h_0 is the layer height) flow over a horizontal plane of a layer of high viscosity rheologically complex liquid $Re_h = (\rho gh/\eta)(h/L)^2 \ll 1$ can be described by using an equation for the change in layer height [$h = h(x, y, t)$] with time:

$$\frac{\partial h}{\partial t} = \nabla\left(\frac{\rho g h^3}{\eta_0}\beta\nabla h\right),\ \ \beta = \int\limits_0^1 (1-\xi)^2\Psi\left[\frac{\rho g h}{\tau_0}|\nabla h|(1-\xi)\right]d\xi. \tag{1}$$

For a Newtonian liquid $\Psi = 1$, $\beta = 1/3$, for a power model ($\tau = k\gamma^n$)

$$\Psi = \left(\frac{\tau}{\tau_0}\right)^{\frac{1}{n}-1},\ \ \beta = \frac{n}{2n+1}\left(\frac{\rho g h}{\tau_0}|\nabla h|\right)^{\frac{1}{n}-1},$$

where τ_0 is the value of the shear stress at which the viscosity is equal to η_0.

In a radial coordinate system Eq. (1) can be written in the form

$$\frac{\partial h}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\rho g h^3}{\eta_0}\beta\frac{\partial h}{\partial r}\right]. \tag{2}$$

For a power model, in particular, Newtonian, at n = 1 Eq. (2) has a self-similar solution describing spreading of a liquid with a constant supply at flow rate Q (Fig. 1). This solution can be found as in the analogous filtration problem [2]. The dependence of the height h on radius r and time t can be expressed in terms of self-similar dimensionless variables length ξ and time ζ in the following manner:

$$h = \frac{h_0 f(\xi)}{\Phi(\zeta)},\ \ \xi = \frac{r}{h_0\varphi(\zeta)},\ \ \zeta = \frac{t}{t_0}, \tag{3}$$

where $\Phi(\zeta)$, $\varphi(\zeta)$, $f(\xi)$ are some functions. Equation (2) must be solved simultaneously with the condition of linear increase over time of the liquid volume:

$$Qt = \int\limits_0^\infty 2\pi h r dr. \tag{4}$$

Substitution of Eq. (3) in Eq. (4) yields

$$Qt_0\zeta = 2\pi h_0^3\frac{\varphi^2(\zeta)}{\Phi(\zeta)},\ \ \int\limits_0^\infty f(\xi)\xi d\xi = 1. \tag{5}$$

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