STUDY OF THE TIME SPECIFIC FEATURES OF THE RHEODYNAMICS OF WEAKLY CONDUCTING FLUIDS IN ELECTRIC FIELDS

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Results are presented on a study of the rheological response of electrosensitive dispersions to an electric action in channel-condensers and rotation devices. The display of the time-specific features of ERFs against the deformation and the field strength is found.

The problem of designing hydraulic drives capable of controlling the external force or the displacement with a high rate and considerable power of the response requires a liquid semiconductor to be used as the working medium in such systems. Liquid dispersed compositions or electrorheological fluids (ERFs) [1, 2] sensitive to electric fields can be successfully used as the working medium.

Up to now, definite progress has been attained in analyzing the distinctive features of flow of ERFs [1, 3], their commercial use [4-6], and in revealing factors that affect their sensitivity to the electric action [7, 8]. In the main the results have been obtained for steady-state flow, aiming at optimizing the ERF properties by the parameter $K = \Delta\tau/\Delta E$ [9]. Although this aspect is of importance for a number of technologies, the future of the ER effect with reference to the needs of high-speed facilities is concerned with studying time-specific features in unsteady transient processes in electric fields. The description of ERF behavior under these conditions requires an additional time parameter to be included in the main rheological laws. Of special interest is the electrohydraulic time constant t*, which means the time difference between the moment of applying the electric voltage and the start of the mechanical reaction (varying initial shear voltage or pressure drop in a channel) [10].

The specific features of the structure formation which is specified by the rheological response of ERF under shear have been studied by direct visualization of coarse model particles moving in a capacitor gap and by microscope high-speed photography, allowing a minimal process time of the order of 0.01 sec alone to be fixed. In the shear-free state, a typical ERF response to an electrical disturbance occurs much more rapidly. We used the speckle-interferometry method [1] to investigate the kinetics of ERF structure formation over this time range.

As the object of study, we selected low-concentrated (1-5 wt.%) fluids: DM based both on the dielectric dispersed medium – dried transformer oil – and on the natural silica modification – diatomite; PS, lithium polymetacrylate in silicon oil PMS-100. The fluid was poured into a flat vessel 2 mm thick, 30 mm high, and 15 mm wide. Two flat electrodes were immersed in the fluid with a 1-5-mm spacing between them, to which a high-volt rectangular pulse with a duration up to several seconds was supplied from the voltage source. The maximum pulse amplitude was 5 kV. The leading front occurred for $1.5 \cdot 10^{-4}$ sec. In the experiments, several radiation sources were used and had different power N and wavelength λ of the light signal: helium–neon laser (N = 50 MW, λ = 0.63 μm), argon laser (N = 100 MW, λ = 514 μm), and pulse ruby laser (λ = 0.63 μm and W = 0.5 J with a 30 msec duration).

The ERF illuminated by the laser radiation yields pictures of randomly moving spots or speckles resembling Brownian motion of particles on a screen behind the vessel. These are a result of the different-phase light waves scattered by the moving microparticles of a medium. This light field formed by an ensemble of the particles randomly distributed in size and position is statistical in nature. It is adequately described by a space–time correlation intensity function. For the simplest Gaussian distribution of the scattered light wave phases the width of the correlation function at the visualization point characterizes the mean speckle lifetime, i.e., it determines the mean time interval for which no substantial change in the space distribution of the particle ensemble occurs.

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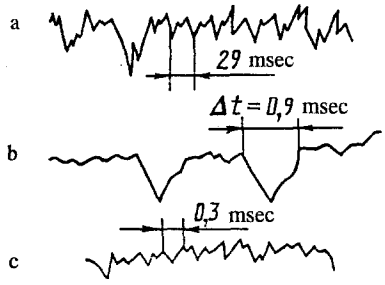

Fig. 1

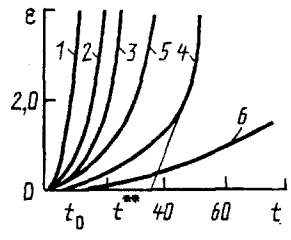

Fig. 2

Fig. 1. Oscillograms of the photoflux under 2% ERF (PS) illumination: a) at no field; b, c) E = 2.5 kV/mm; b) t_d = 11 μsec; c) $2 \cdot 10^5$ μsec.

Fig. 2. Time variation of ERF deformation t (sec) with changes in mechanical stress and electrical voltage: 1) E = 0.05 kV/mm; 2) 0.125; 3, 5, 6) 0.25; 4) 4) 0.5; 1-4) τ = 2.24 Pa; 5) 1.12; 6) 0.48; DM concentration is 40%.

To record the medium-scattered radiation the photomultiplier FÉU-65-7 was utilized. The diaphragm located before it had a 0.3-mm-diameter hole. The mean speckle size in the recording plane was 4 mm. The pulse generator allowed photoflux recording to be delayed discretely by a digital oscilloscope from 0.01 μsec to 1 sec in 0.1 μm. The oscilloscope was connected to a computational complex, whose software permitted the space–time correlation functions of the recorded random processes to be constructed.

Figure 1 plots oscillograms with a typical shape of the recorded random fluctuations of the photoflux at no field and as well as at electric field with E = 2.5 kV/mm at different measuring moments Δt after it is applied. It is seen that the external electric action does not change the signal amplitude noticeably, i.e., the speckle brightness almost does not change. However, a sharp (by two orders) reduction of the characteristic time interval Δt between the photoflux overshoots is noted. So, whereas at no field the interval time was 29 and 0.3 msec for fluids containing silica and polymer, at a field with E = 2.5 kV/mm it amounts to 0.3 and 0.018 msec, respectively. Thus, for times of the order of 10^{-4}-10^{-5} sec after the electric signal has been supplied, the particles or the particle ensembles change their position in the ERF. These changes have been recorded already during the first measurement, corresponding to the delay t_d = 11 μsec with an electric field. The quantity Δt for the ERFs tested at $t_d > 10^3$ μsec starts to sharply grow and attains a constant value for $t_3 = 10^4$-10^5 μsec. Apparently, such a relationship is determined by the shape and the time of the front of the high-voltage signal and its amplitude. The minimal time of the response to the electric signal corresponds to the strength E > 1 kV/mm.

This run of experiments has shown that the response of the silica and polymer particles to an electric signal with no flow can be considered almost instantaneous. For times of the order of 10^{-4}-10^{-5} sec these particles advance and turn slowly, and then for times of 10^{-3} sec they move more markedly, which results in intense structure formation, specifying the distinctive features of the rheological ERF response.

Under the conditions of flow realized in hydrosystems when the shear and electric forces counteract, these times must undoubtedly vary.

In the present article, the ERF rheokinetics was studied on two flow models. In one of them, the fluid flowed along fixed coaxial electrodes; in the other, shear flow was realized in a rotary cylindrical-electrodes-equipped system. The above materials, with a weight content varying up to 20-60%, served as the fluid components.

Experiments were made on a modified constant-shear-stress viscosimeter manufactured at INKhS of the USSR Academy of Sciences [12], on laboratory hydraulic devices at HMTI of the Belarus Academy of Sciences, and at Sheffield University. In the rotary viscosimeter, a small gap Δr = 2.2 mm provided a uniform shear rate at large radial sizes of the electrodes R_{mean} = 50.2 mm. The ERF layer deformation was determined through the tape recording of the inner-cylinder displacement by the contactless optical method. To study transient regimes, rheological measurements were made when the shear load was applied at electric field cutoff. The measuring methods were detailed in [12]. First, slow time variation of deformation was observed and then an accelerated one which was more noticeable, the higher the shear stress and the

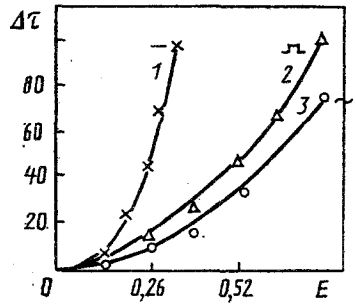

Fig. 3. Shear stress increment $\Delta\tau = \tau_E - \tau_0$ (Pa) of ERF (DM) vs electric field strength (kV/mm): 1) constant voltage; 2) variable sinusoidal voltage with a frequency of 50 Hz; 3) pulse positive-polarity voltage with a frequency of 50 Hz and a duration D = 0.5.

smaller the electric field (Fig. 2). It is seen that the characteristic system return time t^{**} to the initial structureless state is unity-ten seconds for the studied ERFs upon electric field cutoff over small shear load (tens of Pa) and electric field strength ($E \leq 1$ kV/mm) ranges. With increasing voltage, the time of the ERF response to the applied electric field proved to be smaller than the values measured by this viscosimeter ($t_0 \leq 0.01$ sec).

At constant shear rate, the standard rotary viscosimeter "Rheostat-2" was utilized to study the ERF response to a single and periodic electric signal over the frequency range 3-2000 Hz. However, the measurement of a small rotational moment on the soft dynamometer-provided devices can be inadequate for a real high-frequency response due to meter nonlinearity, as well as due to the time delay when a constant shear rate is assigned. The results in Fig. 3 are obtained for the most favorable conditions at a minimal deviation of the relation $\tau(\gamma)$ from the linear one. A sufficiently large value of the error (35%) enables one to speak only about the general tendencies in comparing the data on the effect of different types of field ($\tau \sim f(E)$) on the rheology of ERFs, not estimating them quantitatively. Also, it should be borne in mind that in each case considered, different energy is supplied to the electrodes per unit time: $W = U^2_0R$ is the constant voltage; $W = U^2_0/2R$ is the variable sinusoidal voltage; $W = U^2_0D/RT$ is the positive-polarity voltage pulses (D is the pulse duration, T is the period, U_0 is the amplitude value of the voltage).

For Poiseuille flow the time response was obtained on a valve mounted in the flow cylindrical channel and composed of five coaxial-cylindrical bushes placed with a 1-mm gap. The ERF was poured into a hydrosystem where a screw pump with a dc engine drive generated the circulation motion in the entire circuit. The fluid flow rate varied up to 500 cm^2/sec. The piezoelectric pressure transducer LKh-60 was mounted in front of the valve (Ø = 60 mm, L = 50 mm) and allowed variable pressures up to 10 kg/cm^2 over the frequency range up to 100 kHz to be measured. The amplifier US-29 was used as a coupling amplifier, and the memory oscilloscope S8-13 was used to record pressure pulses. To generate a pulse field, in one of the runs of experiments we designed a special high-voltage generator containing a high-voltage source, electronic switch, and paired pulse generator G5-26. The switch operation was controlled by the paired pulse generator, allowing two rectangular voltage pulses with an amplitude up to 50 V shifted relative to one another to be obtained. The duration of the obtained pulses was recorded over a sufficiently wide range from microseconds to seconds. In the experiments, the generator was used in the one-time regime; one of the pulses opened the switch and the high-voltage source was connected to the valve considered while the other pulse started the oscilloscope S8-13 with the assigned lead.

Upon electric pulse cutoff, the switch is turned off and the high-voltage source is disconnected from the valve. Over the duration range 10^{-4} to $5 \cdot 10^3$ sec the generator provides a practically rectangular pulse shape. With increasing duration the pulse shape somewhat distorts, approaching an exponential one relative to the trailing edge. In the experiments, the memory oscilloscope recorded step-by-step the high-voltage pulses supplied to the test channel as well as the pressure pulses corresponding to them.

Figure 4 shows pressure pulse characteristics obtained under the same electric action on the channel but at different ERF flow rates. As seen from this figure, increasing the flow rate and, hence, the flow velocity through the valve results in a decrease of the leading edge curvature and pressure pulse amplitude. The trailing edge curvature slightly changes

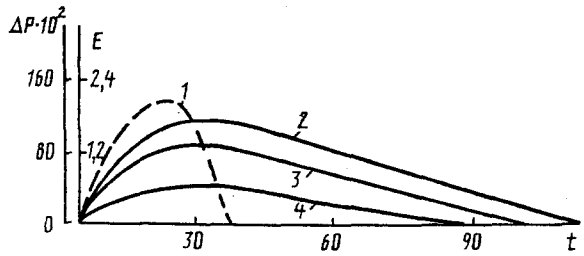

Fig. 4. Time variation of electric voltage (1) and pressure drop (kPa) on the valve for different ERF flow rates (DM concentration is 50%): 2) Q = 20 cm³/sec; 3) 30; 4) 38.

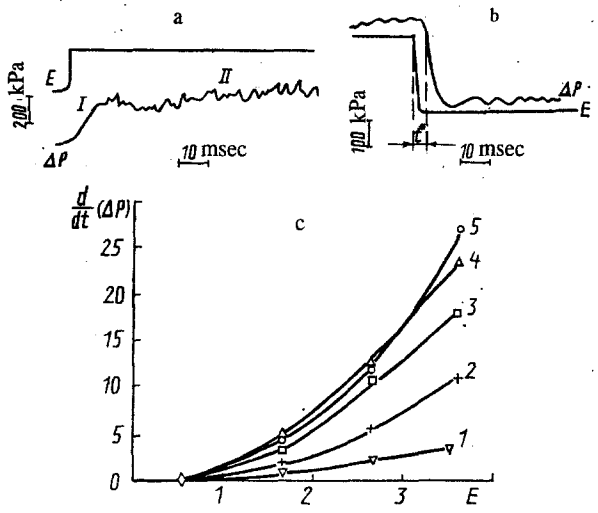

Fig. 5. Time variation of the valve pressure at electric voltage supply (a) and cutoff (b), E = 3.6 kV/mm for Q = 145 cm³/sec; c) rate of change of the pressure drop vs electric voltage at different ERF (PS) flow rates through the channel: 1) Q = 228 cm³/sec; 2) 145; 3) 63.4; 4) 32; 5) 15.

with flow rate increase. Moreover, at large flow rates the pressure pulse duration decreases and the pressure maximum is attained earlier. More exact time measurements of ΔP(t) in the stepwise regime of the field as well as for sinusoidal supply of positive-polarity voltage in addition to the constant steady high-voltage signal were made on the device described in [3]. No dielectrophoresis was supported by the identical response of the ERF at electrode polarity reversal. Piezotransducers with a natural frequency of 100 kHz were also used to record the pressure. The temperature was kept constant (T = 30 ± 0.5°C) to exclude any effect of fluid conduction variations. A valve composed of three coaxial cylinders, with a 0.5 mm gap between them, 100 mm long was used. The inner-cylinder diameter was 51 and 64 mm. The flow rate varied from 16 to 230 cm³/sec.

It is found that the pressure variation is inconsiderable over a small voltage range (E ≤ 2 kV/mm). When an electric field is applied, a step is observed in ΔP(t) (see section I, Fig. 5a), after which the course of the characteristics becomes quasilinear. The pressure variation is from 0.04 to 0.3 bar/sec at the minimal flow rate and an electric field strength of 0.6 and 1.8 kV/mm, respectively. With increases of flow rate by almost 4 times the pressure increases only as many as twice. Doubling the potential yields an 8-9-fold variation of the pressure.

In the general case, while turning on and cutting off the step voltage a short delay takes place before the pressure variation (Fig. 5a) has been fixed. The observed high-frequency pressure fluctuations are attributed to the specific features of the gear pump operation. At high electric strengths 0.2 ≤ E ≤ 4 kV/mm, after the step has become evident the pressure growth depends nonlinearly on the time. Under electric field cutoff (Fig. 5b) the pressure first sharply decreases

and then continues to decrease according to an almost linear law. The ERF response time is some microseconds when the voltage changes step-by-step.

Figure 5c shows the characteristic dependence of the rate of change of the pressure on the applied voltage over section II (Fig. 5a). Experiments were also made over the entire frequency range for the frequency variation of the electric field strength E = 3.6 kV/mm from 0.2 to 40 Hz. The corresponding harmonic pressure variation was observed. At higher frequencies, besides the pressure fluctuations, a slow increase in the absolute value of the valve pressure was recorded.

CONCLUSION

The stated experimental results on the time response of an ERF to an electric action have shown that different response over the time range 10^{-5}-10^{3} occurs, depending on the value and shape of the electric field and shear action. The specific features revealed, namely, primary delay of the pressure response with an ERF flowing in the channel and its behavior in each of two phases, rapid (step variation) and slow, require further detailed study and quantitative determination of the constants in the time relations $\Delta P(t, t_0, t^*, t^{**})$. The same also refers to the shear ERF layer response under Couette deformation.

The preliminary estimates made by G. Block and A. Inoue [14, 15] have shown that the intensity of the ERF rheological response depends on the rate of forming and changing the charge on the surface of the solid phase particles, i.e., it is specified by the nature of the material used and the electric situation at the phase interface. Although our experiments with two types of ERF (silica and polymer-base in different dispersing media) have revealed no essential differences in their time response to the electric pulse, the problem of the effect of the hydrocarrier receipe on its electrorheological response invites refinement and further study.

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