Rheological properties of magnetoelectrorheological fluids with complex disperse phase

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Abstract. The results of experimental investigations of mechanical properties of magnetoelectrorheological fluids – adaptive media, which respond to both electric and magnetic fields – are presented. The influence of the concentration of components of complex disperse phase on the rheological sensitivity is investigated. All compositions have shown a synergetic effect.

1. Introduction

Dielectric fluid dispersed systems, having a capability to change their rheological properties under the influence of both electrical and magnetic fields have appeared for the first time in the paper of S. Gorodkin, W. Kordonsky et al., 1991, and were called magnetoeletrorheological fluids (MERFs) [1]. The formation of the structure in such dispersions, being a result of interactions of both ferromagnetic cores of particles and surface charges, gives a strengthening, synergetic effect. Theoretical discussion of this effect was reported in papers [2, 3]. E. Postrekhin and L. Zhou [2] have suggested a formula to evaluate the effect of both fields: \(\tau = 0.5(a_\varepsilon \varepsilon_0 E^2 + a_\mu \mu_0 H^2)\), where \(a_\varepsilon, a_\mu\) – are the functions of the dielectric constant and magnetic permeability respectively.

Despite of perspective flexible use of two channels of controlling hydromechanical characteristics of MERF, not more than twenty publications, dedicated to this problem, have appeared for the last 15 years [2 – 12]. Apparently, it is due to the complicity of the studied phenomena both from experimental and theoretical points of view. MERF (or lately they have been also called electromagnetic rheological fluids [2, 3, 7]) – are multi component systems, having a structure dependent both on complex peculiarities of physical-chemical phenomena at phase interfaces and on peculiarities of polarization and magnetization of the filler material. Therefore, the main problems of effective MERF development are associated with initial problems of search and creation of the dispersed filler, which should be structurally sensitive to the simultaneous impact of two fields.

In the present time, the creation of commercially valuable compositions, that have a good response in each of the fields, give a total substantial increase of shear stresses in two fields, and also provide a noticeable above summary effect, has not been yet finished, and the best of the compositions still need the application of high-cost and labor consuming technologies of obtaining.

We have set a goal to develop an effective MERF on the basis of accessible materials without complex preliminary preparation stages.
2. Materials and methods

In the present paper we report on the results of the experimental investigation of rheological characteristics of three compositions of magnetoeletrorheological fluids based on the complex dispersed phase, composed of two fillers. All fluids had a strong magnetic filler ($C_1$) – carbonyl iron (CI). The particles of carbonyl iron are a complex formation in the form of onion-like structures from elementary Fe and its compounds with carbon, nitrogen and oxygen in the quantity not more than 3%, distributed in the form of concentric sublayers. We have used carbonyl iron of the brand BASF EW in as received condition, the particles of which had the size of 2 – 8 µm and had a double dielectric coating of SiO$_2$ and were characterized by electric resistance $> 10^{10}$ Ohm·cm. The second filler ($C_2$) in each composition was a powder in as received condition of $\alpha$-Fe$_3$O$_4$, or iron oxide $\gamma$-Fe$_2$O$_3$, known after a certain treatment as filler for MERF [1]; or SiO$_2$ in the form of aerosil, activated by amine, also known as active filler for electrorheological fluids. The transformer oil served as dispersion medium.

By preparation of MERF, we have mechanically mixed two powders of dispersed phases, then we have added a dispersion medium. In experiments the fluids with the total volume concentration of dispersed phase 10% were used. The compositions of MERF with the following composition of two phases were studied: $C_1=0\%$, $C_2=10\%$; $C_1=2.5\%$, $C_2=7.5\%$; $C_1=5\%$, $C_2=5\%$; $C_1=7.5\%$, $C_2=2.5\%$. To investigate the role of carbonyl iron the results were compared to the data of analogous measurements with the content of only $C_2=5\%$ in MERF.

The rheological experiments were performed on a special coaxial-cylindrical viscometric bell-type cell serving as an attachment to the torque meter of the viscometer RV-12 manufactured by HAAKE. The cell is similar to that described in [8]. The force lines of the magnetic and electric fields are parallel one to another and normal to the shear.

The measurements of shear stress $\tau$ have been carried out at varying: magnetic field intensity $H = (0 – 100)$ kA/m, electric field strength $E = (0 – 1.8)$ kV/mm, shear rate $\gamma = (2 – 575)$ s$^{-1}$.

3. Main Results

Magnetoeletrorheological fluids behave similarly in linear viscoplastic medium with a small yield stress in the absence of fields. The essential shear stress enhancement occurs under action of the electric and magnetic fields. The dependencies of shear stress on the electric field strength without and with magnetic field of maximum intensity for MERF with $C_1=0\%$ and $C_2=5\%$ for $\alpha$-Fe$_3$O$_4$ (n1), SiO$_2$ (n2), $\gamma$-Fe$_2$O$_3$ (n3) and with $C_1=5\%$ and $C_2=0$ (n4) are displayed in Figure 1. It is seen that for the first and third compositions the electrorheological effect is insufficient in comparison with the bigger increase of $\tau$ in electric field for the fluid sample n2. In magnetic field, however, the sample n2 is not sensitive, while the filler $\gamma$-Fe$_2$O$_3$ (n3) in two fields gives the noticeable increase $\Delta \tau = \tau – \tau_0$, which is due to both magnetorheological and electrorheological responses in almost equal share. Here $\tau_0$ is the shear stress at $E = 0$ and $H = 0$. At $E = 0$ in magnetic field with intensity 100 kA/m, $\Delta \tau = 85$ Pa, and at additional impact of the electric field of $E = 1$ kV/mm, we get $\Delta \tau = 150$ Pa.

By the presence of carbonyl iron in the composition of MERF, the response on the magnetic field and the impact of both fields is noticeably increased. The dependencies of $\tau$ for MERF-1, containing carbonyl iron at volume concentration 5% and 5% of $\alpha$-Fe$_3$O$_4$ vs. intensity of magnetic field are shown in Figure 2. It is seen, that the magnetic field influence is more essential for this MERF than that of the electric field, because of significant magnetic sensitivity of carbonyl iron. MERF-2 with the same concentration of aerosil gives larger increment of shear stress in the electric field than ones with $\alpha$-Fe$_3$O$_4$, since aerosil has a higher electrorheological activity (Figure 3). The MERF-3 with $\gamma$-Fe$_2$O$_3$ of the same concentration has bigger values of shear stress in the absence of the external fields because of a needle like shape of $\gamma$-Fe$_2$O$_3$ particles (Figure 4). Under influence of the electric and magnetic fields $\tau$ for MERF-1, MERF-2 are the biggest.

The proportion between components concentrations of the disperse phase does not exert essentially on the relative shear stress increment under the electric field. The carbonyl iron concentration increase caused enlargement of the relative shear stress under the magnetic field influence and under combined
**Figure 1.** Shear stress of MERFs vs the electric field intensity \((\dot{\gamma} = 2.2 \, s^{-1})\). 1, 2 – n1; 3 – n2; 4, 5 – n3; 6 – n4. 1, 3, 4 – \(H = 0\); 2, 5, 6 – \(H = 100 \, kA/m\).

**Figure 2.** Shear stress of MERF-1 vs the magnetic field intensity \((\dot{\gamma} = 2.2 \, s^{-1})\). 1 – \(E = 0\); 2 – \(E = 0.9 \, kV/mm\); 3 – \(E = 1.36 \, kV/mm\); 4 – \(E = 1.8 \, kV/mm\).

action of the both fields.

The concentration dependencies of relative shear stress increment of MERF on the basis of carbonyl iron and \(\alpha\)-Fe\(_{2}\)O\(_{3}\) are shown in Figure 5. Analogous dependencies occurred for MERFs on the base of \(\gamma\)-Fe\(_{2}\)O\(_{3}\) and aerosil. Only for fluids on the basis of \(\gamma\)-Fe\(_{2}\)O\(_{3}\) the relative shear stress increased practically linear with the growth of carbonyl iron concentration in the magnetic field and under combined action of the fields, while for fluids on the basis of \(\alpha\)-Fe\(_{2}\)O\(_{3}\) and aerosil this increase is more significant for the carbonyl iron concentration range up to 0.025 (Figure 5).

For every MERF with two types of disperse particles the synergistic effect is revealed in the most of shear rate range. The dependence of its index \(\xi = \frac{\Delta \tau_{EH}}{\Delta \tau_{E} + \Delta \tau_{H}}\) on the shear rate for MERF-3 on the basis of carbonyl iron and \(\gamma\)-Fe\(_{2}\)O\(_{3}\) \((C_1 = C_2 = 5 \, \text{vol. \%})\) is shown in Figure 6. As seen from the Figure, the synergistic effect is more significant for the low shear rate.

**Figure 3.** Shear stress of MERF-2 vs. the magnetic field intensity \((\dot{\gamma} = 2.2 \, s^{-1})\). Notations are the same as in Figure 2.

**Figure 4.** Shear stress of MERF-3 vs. the magnetic field intensity \((\dot{\gamma} = 2.2 \, s^{-1})\). Notations are the same as in Figure 2.
Figure 5. The dependence of relative shear stress increment of MERF with α-Fe₂O₃ and CI on the CI concentration. γ = 36 s⁻¹. 1 – E=1.36 kV/mm; 2 – H=100 kA/m; 3 – E=1.36 kV/mm; H=100 kA/m.

4. Conclusions
The results of the experimental investigations of rheological properties of MERF on the basis of carbonyl iron, iron oxides and aerosil are presented. Optimum compositions of MERFs with a two-component solid phase are obtained, one of the components (CI) having magnetorheological and the other one – electrorheological properties. The investigated fluids show a high increase of the absolute value of the shear stress under action of the electric and magnetic fields due to the presence of carbonyl iron as filler. Minimal content of CI in MERF with the filler α-Fe₂O₃, giving the maximal effect, is 2.5 vol. %. All the compositions have shown the synergetic effect. Its value depended on the ratio of concentrations of the filler and shear regimes, and also on the material of the solid phase. The possibility of the effective control of the properties using two independent physical channels will allow us to apply these materials to many devices and technologies (hydraulic systems, heat exchangers, vibroprotector devices, etc.).

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