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Electro-Rheological Properties of Transformer Oil-Based Magnetic Fluids

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The aim of this work was to study rheological behavior of nanofluids affected by electric field and temperature. We used transformer oil-based magnetic fluids, the suspensions of permanently magnetized colloidal particles (Fe_3O_4) coated by a stabilizing surfactant and immersed in transformer oil. The rheological characterization of transformer oil-based magnetic fluid was performed using the rotational rheometer MCR 502 in the shear rate from 10 to 1000 s^{-1}.The strength of electric field was changed in the interval 0–6 kV cm^{-1}. The flow curves and viscosity functions detected at three different temperatures 25, 50, and 75 °C disclose rheological characteristics of samples, first of all the viscosity growth under increasing strength of electric field.

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1. Introduction

When an electric field is externally applied to a suspension obtained by dispersing dielectric solid particles into an electrically insulating liquid, the viscosity of that sample changes according to the degree of the applied voltage. In this phenomenon, known as the Winslow or an electrorheological (ER) effect, the viscosity and shear stress of the dispersion as a whole apparently increase because solid particles are internally polarized and statically aggregated with each other by the action of the electric field. The fluid which produces this ER effect is called an ER fluid. On the other hand, a solution comprising an insulating liquid and having dispersed therein magnetic particles has been known as a magnetic fluid (MF). MFs are characterized by mutual attraction of magnetic particles under application of an external magnetic field and, as a result, the viscosity of the fluid apparently increases. Since both MF and ER are excellent in response and controllability to applied magnetic and electric fields, they can be used as working fluid for various machines and apparatus and that is the reason for continuous research to improve their characteristics [1–6].

Our interest in this paper is focused on the suspensions of permanently magnetized colloidal particles (Fe_3O_4) coated by a stabilizing surfactant and immersed in transformer oil (TOMF). For their exquisite and thermal properties they have a potential to become an alternative to conventional transformer oils used in the transformer, the most significant and essential part in the modern power grid system for transmission and distribution of electric power. It is assumed that the electric field induced viscosity change can play a key role in the streamer initiation and affect in this way the breakdown field strength of TOMF. Our recent study on TOMF showed that the interfacial relaxation processes contribute to the total dielectric response of TOMF. Moreover, by means of dielectric spectroscopy on thin TOMF layers with applied DC bias voltage, we found strong indications that the external electric field induces aggregation of the magnetic nanoparticles. We have clearly demonstrated visually observable pattern formation in TOMF exposed to a DC electric field [7]. These results motivate us to undertake further comprehensive research on electrorheological properties of TOMF.

2. Experimental

In the present work, TOMFs based on Mogul oil as a carrier liquid was used. The TOMF was prepared by the chemical precipitation method of ferrous and ferric salts in alkali medium. To stabilize the suspensions, oleic acid was selected as a surfactant to cover the nanoparticles in order to prevent particle agglomeration. The amount of activator was calculated with weight percentage of the suspensions of magnetic (Fe_3O_4) nanoparticles and oil. From the magnetization curve obtained by using the vibrating sample magnetometer (VSM) method, the volume concentration of magnetite particles of the prepared TOMF was determined as 6.6% and the particle diameter as about 10 nm. The samples with different particle volume fractions φ_v (1 and 3.1%) were obtained by diluting the original TOMF.

The basic properties of the three types of selected TOMFs are summarized in Table I. Experimental investigation of the rheological properties of TOMF was carried out using the electrorheological cell of the Physica MCR 502 rheometer of Anton Paar Company (Austria) with continuous strain in the shear rate range 10–1000 s^{-1} and electric field strength from 0 to 6 kV cm^{-1} at the

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temperatures of 25, 50, 75 °C. The measuring cell of the device represents a system of coaxial cylinders consisting of the outer fixed cylinder with a cylindrical rotor immersed into it. The studied sample was placed in the annular gap between the cylinders and it was tempered with the aid of the Peltier system.

3. Results and discussion

The saturation magnetization at room temperature of individual samples increases with increasing amount of magnetic particles in TOMFs as it can be seen in Table I.

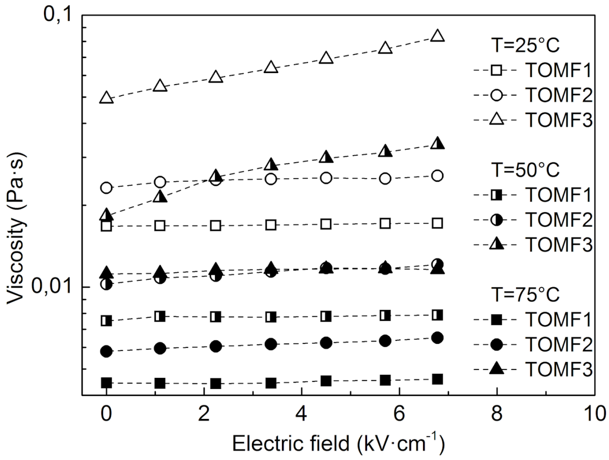

Fig. 1. The viscosity versus increasing electric field at different temperatures (full, half, empty symbols $T = 75\,°C$, $T = 50\,°C$, $T = 25\,°C$, respectively) for TOMF1 (□), TOMF2 (○) and TOMF3 (Δ) in Mogul oil as the carrier liquid. TOMF 1, 2, 3 correspond to volume concentrations 1, 3.1, and 6.6%, respectively.

The viscosity of TOMFs was measured at three different temperatures: 25, 50, and 75 °C. Moreover, every experiment was carried out under absence and in the present electric field in the range from 0 to 6 kV cm^{-1}. The shear rate was changed in the interval from 10 to 1000 s^{-1}. We can see (Fig. 1) the TOMFs value of viscosity as a function of the electric field at shear rate 400 s^{-1} where the samples behave as Newtonian fluids, since their viscosities do not depend on the shear rate (Fig. 2).

TABLE I

The basic parameters of the investigated MF samples: χ_{DC} — estimated DC magnetic susceptibility, M_S — saturation magnetization, ρ — density, φ_v — magnetic volume fraction.

Sample	M_s $[\frac{\mathrm{Am}^2}{\mathrm{kg}}]$	φ_v [%]	χ_{DC}	ρ $[\frac{\mathrm{g}}{\mathrm{cm}^3}]$
TOMF1	4.968	1	0.1402	0.91567
TOMF2	13.197	3.1	0.4147	1.04383
TOMF3	23.15	6.6	0.765	1.28

Figure 1 confirms the expected behavior of TOMFs at which the viscosity increases with increasing electric field. It is observed for all TOMFs. The highest

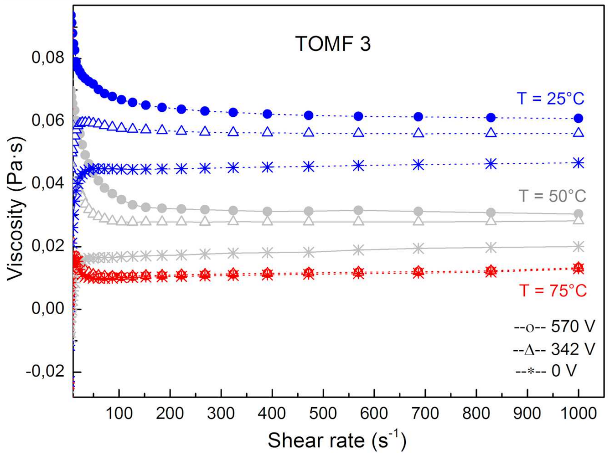

Fig. 2. Viscosity versus shear rate for TOMF3 at temperature 25 °C (blue), 50 °C (grey), and 75 °C (red). Every of these temperature was measured in the absence of electric field (stars) and in the presence of electric fields 3 kV cm^{-1} (342 V) and 5 kV cm^{-1} (570 V). We show only two values of the electric field for greater clarity.

growth of viscosities (34% and 45%) were measured for TOMF3, the magnetic fluid with maximum volume concentration of magnetic particles, at temperatures 25 °C and 50 °C, respectively. It was observed when the electric field changed from 0 to 6 kV cm^{-1}. On the other hand, the minimum viscosity growth (3%) was measured for TOMF1 at 25 °C. In general, we can say that the smaller amount of magnetic particles and the higher the temperature is, the less value of viscosity is observed. Moreover, at the same time, the viscosity of TOMFs increases in response to the rising strength of the external electric field (Fig. 2). The viscosity versus temperature of TOMF3 is partially shown in Fig. 2, from which it can be seen that the viscosity of TOMF3 decreases with the increase of the temperature. The influence on viscosity is coming from changing the viscosity of pure oil with temperature and from Brownian motion of nanoparticles [8]. With the increasing temperature the Brownian motion of the particles in the TOMF was strengthened, which reduced the speed difference between the carrier liquid and the magnetic particles. The flow curves with controlled shear rate mode measured at different experimental conditions (various temperature and strength of the electric field) are very complicated mostly at low shear rate in the range (10, 100) s^{-1}, as one can see in Fig. 3. The minimum influence of the electric field on the viscosity of TOMF3 is seen for the measured data at 75 °C and the maximum is at the 50 °C, where the shear rate is 10 s^{-1} for both the temperatures. The shear thinning behavior of TOMF3 was observed when the viscosity decreased with the increasing shear rate, on the contrary to the shear thickening behavior when the measured viscosity increases together with the increasing shear rate (Fig. 3). These different behaviors of the sample with changed experimental conditions can be explained by different mechanisms of the behavior of magnetic particles covered by surfactant immersed in transformer oil. In general, the ER effect is due to the dielectric constant contrast between the solid particles and the liquid in a colloid, when each solid particle would be polarized under an electrostatic field, with an effective dipole moment. The resulting (induced) dipole–dipole interaction means that the particles tend to aggregate and form columns along the applied field direction. The formation of columns is the reason why the high-field state of TOMFs exhibits increased viscosity able to sustain shear in the direction perpendicular to the applied electric field [9, 10].

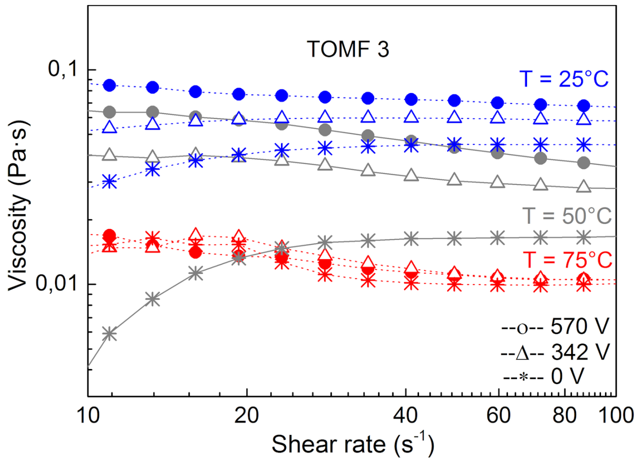

Fig. 3. Viscosity versus shear rate for TOMF3 at temperatures 25 °C (blue), 50 °C (grey) and 75 °C (red). Every of these temperatures was measured in the absence of electric field (stars) and in the presence of electric fields 3 kV cm^{-1} (342 V) and 5 kV cm^{-1} (570 V). We show only two values of electric field for more clarity.

4. Conclusions

Experimental study of the rheological properties of TOMFs has been performed under different electric field strengths at the temperatures and shear rate range of 25, 50, and 75 °C, and 10–1000 s^{-1}, respectively. The flow curve and the viscosity function disclose a shear thickening in the presence of electric field. The experimental results show, on one hand, the expected behavior of TOMFs when the increase of the TOMFs viscosity values under the electric field is observed, but, on the other hand, below the shear rate 100 s^{-1} the suspension is affected by the shear rate much more. Due to this fact the shear viscosity functions have non-monotonic variations, as we could expect in connection with the applied changes of temperature, the electric field strength and shear rate. This can be explained by a competition between the particle–particle electrostatic interactions due to polarization and the Brownian thermal forces. It would be very helpful to study rheological characteristics of TOMFs at shear rates below 10 s^{-1}. Attempts to explain the found interesting observations will be the matter of our future research in this area.

Acknowledgments

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