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POLAR-MOLECULE-DOMINATED ELECTRORHEOLOGICAL (PM-ER) FLUIDS: THE PROPERTIES AND EVALUATIONS*

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In recent years, a new type ER fluids named as polar-molecule-dominated electrorheological (PM-ER) fluids have been developed, of which the yield stress can reach more than 100 kPa and behaves a linear dependence on the electric field. A brief description on the composition and synthesizing method for the materials is given. The main merits of PM-ER fluid are as follows: high yield stress, the shear stress increasing with shear rate up to more than 10^3 s^{-1}, low current density, rapid electric response and anti-sedimentation. Some perspectives on PM-ER fluid and its applications are presented.

1. Introduction

Since the first discovery of Winslow on ER fluid, much effort has been paid to the study of the physical mechanism and the materials. The ER effect arising from the interaction of the polarized particles, which form chains and columns along the direction of the external electric field, has been well understood.[1–4] Typical character of this traditional dielectric ER fluid are that the yield stress is low (usually less than 10 kPa) and showed a quadratic dependence on the field strength. The low yield stresses of the available traditional dielectric ER fluid cannot meet the requirements for practical applications.

In recent years a serial of giant ER fluids have been developed,[5–12] the yield stress of which can reach more than 100 kPa and behaves a linear dependence on the electric field. These ER fluids are now termed as the polar-molecule dominated electrorheological (PM-ER) fluids based on a new mechanism. The polar molecules adsorbed on the particles are aligned by significantly enhanced local electric field in the gap between neighboring particles. The interaction from the aligned polar

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molecules is much larger than that of the polarized particles in traditional ER effect. A detail description on the mechanism has been given in our previous publications.[13–15]

In this paper we are going to present the properties and perspectives of those PM-ER fluids studied in our group.

2. Materials of PM-ER Fluids

Several PM-ER fluids with high yield stress are manufactured. The solid particles based on Ti–O,[7] Ca–Ti–O,[8] Sr–Ti–O,[9] La–Ti–O[16] were prepared with wet chemical technique. The dielectric constant of the particles should be high enough and the conductivity should be low. There must be polar molecules (O–H, C–O, C=O, N–H *et al.*) adsorbed on the particles from the particle preparing procedure which are crucial factor for PM-ER effect differing from the traditional ER one. If the particles are heated to high temperature (about 500°C) and then all the adsorbed polar groups are released, the ER fluids consisted of the sintered particles lose their character of high yield stress showing a traditional ER effect.[15]

The size of the particles is in the range of 50–10^3 nm with the density of 2.2–3.5 g/cm^3 which depends on the species and size of the particle. For instance, the density of Ca–Ti–O particles with the size of 50–100 nm is about 2.35 g/cm^3. The small size and the low density of the particles are benefit against sedimentation of the suspensions. Silicone oil, mineral oil, lubricating oil or hydraulic oil can be selected as dispersion liquid.

3. Characters of PM-ER Fluids

The yield stress τ_y of PM-ER fluid can be as high as 100, 200 kPa and even higher depending on the composition and concentration of the fluids. It should be emphasized that in measuring the shear stress by a conventional rheometer it is found that ER fluid slides along the electrodes and the measured values of shear stress deflect to lower side of the linear dependence on electric field when the shear stress is higher than about 100 kPa. Consequently the nominal value measured with a flat electrode is much lower than the intrinsic value of the fluid. This sliding at electrode originates in that the boundary condition at the interface of fluid-electrode is not as the same as inside of ER fluid.[15,17] Therefore, the electrodes for measuring PM-ER fluid must be treated to be rough enough. Even though the measured shear stress still is less than the intrinsic value for the PM-ER fluids with extra large yield stress. By using a cut-shearing method the measured yield stress can be close to the real value,[15,18] although the measured values are not very accurate (with an error of 10 percent approximately).

As an example, Fig. 1 shows a measured yield stress versus electric field for Ca–Ti–O based PM-ER fluid, which is consisted of Ca–Ti–O particles suspending in hydraulic oil with a volume fraction of 55%. It can be seen that the yield stress of this sample can reach about 400 kPa at a filed of 5 kV/mm. Obviously, the values

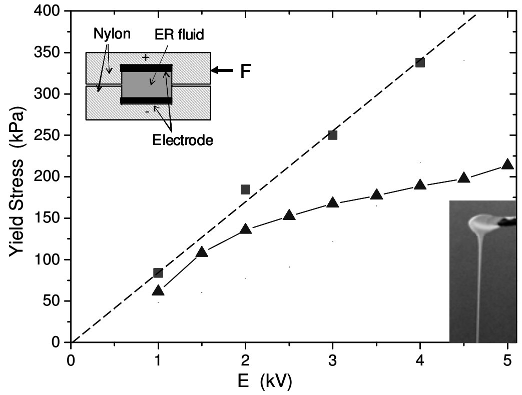

Fig. 1. The yield stress versus electric field of Ca–Ti–O particles based PM-ER fluid. The triangle symbols indicate the measured results by using parallel plate rheometer with rough electrodes. Square symbols represent the measured values with cut-shearing method as plotted in inset. Dashed line shows the ideal values of yield stress. The image at lower right shows the flowability of this ER fluid.

of yield stress measured by parallel plate rheometer with rough electrodes is only about half of that measured with cut-shearing method in high τ_y region. Distinct slide on the electrodes can be observed in the measurement by using conventional rheometer.

Changing the volume fraction ϕ of the suspensions the yield stress can be adjusted. For this Ca–Ti–O based PM-ER fluid the yield stress τ_y is about 50, 100, 200 kPa at 5 kV/mm in the case of $\phi = 33\%$, 44%, 50%, respectively. Also ϕ is one of the factors to influence the viscosity at zero field. In general, at a field of $E = 5$ kV/mm, the ratio of $\tau_y/\tau_y(E = 0)$ can reach more than 10^4 for a fluid with $\tau_y \approx 50$ kPa while the ratio is less than 5×10^2 when $\tau_y \approx 200$ kPa.

The apparent shear stress $\tau_E(\dot{\gamma})$ versus shear rate $\dot{\gamma}$ can be obtained with a clutch like apparatus by measuring the torque. Figure 2 shows a typical torque-shear

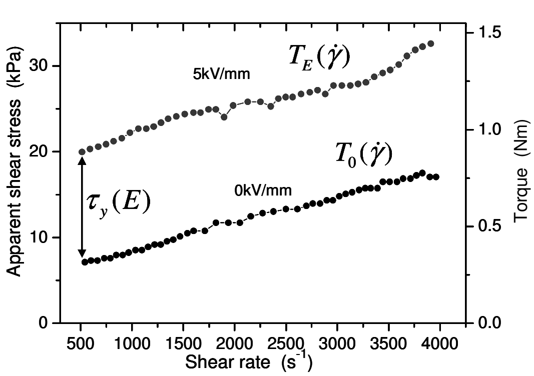

Fig. 2. Relation of torque versus shear rate for a Ca–Ti–O based dilute PM-ER fluid. The rater high torque at zero field is mainly form the sealing friction of clutch.

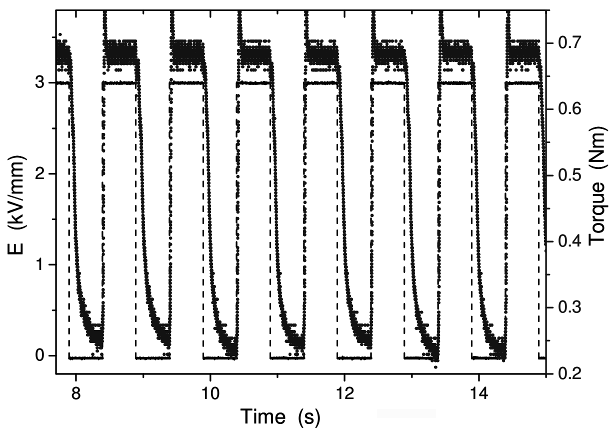

Fig. 3. The torque responses under $0-3$ kV/mm square field at $\dot{\gamma} = 50$ s^{-1}. Dashed line indicates the electric field and the dots are torque values.

rate relation for a Ca–Ti–O based dilute PM-ER fluid in which the torque $T_E(\dot{\gamma})$ increases with shear rate up to more than 4×10^3 s^{-1}. The measurement at higher shear rate is baffled by the heating effect especially for the PM-ER fluids possessing high yield stress.[17] Obviously, although $T_E(\dot{\gamma}) - T_0(\dot{\gamma})$ or $\tau_E(\dot{\gamma}) - \tau_0(\dot{\gamma})$ almost keeps unchanged in all region of shear rate, the ratio $T_E(\dot{\gamma})/T_0(\dot{\gamma}) = \tau_E(\dot{\gamma})/\tau_0(\dot{\gamma}) \approx \tau_y(E)\alpha^{-1}\dot{\gamma}^{-1}$ (for $\alpha > 0$) decreases with shear rate increasing. Where α is the slope of torque increasing with shear rate, which depends on the rheological property of material and the design of clutch. The improvement in both aspects to reducing α is necessary for achieving better efficiency in the applications.

The electric response time is less than 1 ms measured with a rapid square wave field. However, practically, there usually are an electric RC decays appeared in the torque measurement with a clutch. Figure 3 shows the torque responses under $0 - 3$ kV/mm square field. The time delay of the torque value happens due to the electric charging and discharging when the field turns on and off, because the dielectric constant and the resistance of the material are rather large. The RC time constant measured is about tens of millisecond, which is consistent with the calculation based on the capacity and the resistance in the arrangement of clutch. Therefore it is necessary to apply fast enough electric circuits to meet the requirement in a rapid controlling system.

The electric current density of PM-ER fluids prepared in our group is normally in the range of 0.01–10 μA/cm^2. Also there is almost no sedimentation observed in our PM-ER fluid because of the low density and small size of the particles.

4. Merits and Issues of PM-ER Fluid for Applications

(1) The high yield stress of PM-ER fluid being able to attain hundreds of kPa is a big advantage in technical applications, of which the maximum value is several

times higher than MR fluids and hopefully to be further enhanced. To manufacture PM-ER fluids with even higher yield stress is potentially in the works. With high τ_y ER fluids smaller and more efficient devices are possibly to be fabricated by applying a relatively low electric field. Besides the flow mode and shear mode in the applications, the character of PM-ER fluids with extra high yield stress may result in a new field for applications i.e., as a smart structural material. The shear modulus of the sample shown in Fig. 1 is measured to be about 60 MPa at 5 kV/mm. This modulus tunable feature by adjusting electric field is attractive in technology, for instance, in making a sandwich structure combining with metallic or other conductive materials.

(2) Low current density of the ER fluids is benefit for making the devices with low energy dissipation. Typically, the power of less than 1W is enough for a small device, supplied by the batteries. The arbitrary shape of electrodes and high efficiency of the PM-ER fluid are favorable for designing compact or potable devices, which can be convenientlly controlled even in a multichannel operating system.

(3) There are some issues for PM-ER fluids should be further studied or improved. Firstly, the long term stability of the fluids in the applications has not been well tested. Several factors must be considered including the firmness of the polar molecules and the influence of the impurities falling out from the electrodes or other parts. Practical experiences for applications are still lacking. We also should pay attention to the surface treatment of the electrodes for the fluids with high shear stress. In respect of materials, to reduce the viscosity at zero electric field and to produce identical as well as duplicable ER fluids with high quality and a certain quantity are an ongoing process.

5. Conclusions

Several types of PM-ER fluids have been developed in our group, of which the excellent characters are described. The yield stress can be as high as 100, 200, 400 kPa, respectively, by adjusting the composition and concentration of the materials. The shear stress increasing with shear rate up to more than $10^3\ s^{-1}$. The current density of the fluids is lower than 10 $\mu m/cm^2$ and even less than 1 $\mu m/cm^2$ at a field of 5 kV/mm. Moreover, almost no sedimentation of the particles in the fluids can be observed. Some perspectives and related technical issues on PM-ER are discussed. Efforts are concentrated to improve the viscosity at low zero field, long term stability and quantity production of PM-ER fluid for its practical applications.

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