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Current Perspectives

A comprehensive viscosity model for micro magnetic particle dispersed in silicone oil

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ABSTRACT

Magnetorheological behavior of micro magnetic particle dispersed in silicone oil has been characterized by a multiplied form of phenomenological models taking the effect of shear rate, powder volume fraction, temperature and magnetic flux density. Magnetorheological fluid samples with seven different particle volume fraction were prepared by adding ferrite particles in silicone base oil and their shear viscosity of fluid samples were measured under three different temperatures (40 °C, 70 °C, and 110 °C) and ten different magnetic flux density (0–100 mT). The fluid had an upper limit to the increase of viscosity under the effect of external magnetic field and the saturation values were dependent on the operating temperature, shear rate and volume fraction of magnetic powder. The rheological behaviors have been characterized by our developed model which can be very useful for the precise control of the magnetorheological fluid.

1. Introduction

Magnetorheological fluids (MR fluids) are liquids whose flow properties are conveniently controlled by externally given magnetic field. The viscosity of MR fluids changes in the order of magnitude by magnetic field, which is useful for the mechanical systems requiring rapid vibration controls or torque transmissions [1,2]. There have been many applications such as shock absorbers, seismic vibration dampers, brakes, clutches, artificial joints and actuators [3–5]. They have also biomedical applications, thermal energy transfer and chemical sensing applications [6,7].

MR fluids consist of three components: base fluid, metal particles and stabilizing additives [8]. The base fluid functions as a carrier which has lubricating and damping properties. Hydrocarbon oils, mineral oils or Silicon oils are commonly used as base fluid. They behave as Newtonian fluids, where their viscosities are not varied by shear rates. For metal parties, high magnetic properties are required to response actively to the magnetic field. Particle iron, carbonyl iron and iron cobalt alloys are commonly used as metal particles and their size ranges from 1 μm to 9 μm [9,10]. Since metal particles have high density, stabilizing additives are also necessary to prevent the sedimentation. Ferrous oleate and lithium stearate are often used as these additives.

The main feature of MR fluids is the change of viscosity under the effect of externally applied magnetic field. The magnetic field induces chain-like assemblies of metal particles in base fluid, which increase the viscosity of base fluid according to the magnitude of the magnetic field. Once magnetic chains are formed in base fluids, they become non-Newtonian fluid, whose viscosity is changed by shear rates [11]. These behavior of MR fluids are known to follow the characteristics of Bingham fluid for the presence of yield stress, which is regulated by external magnetic field [12]. MR fluids are also known to be subject to shear thinning fluid, whereby the viscosity decreases with shear rate [13].

To describe this non-Newtonian behavior of MR fluids, Hershel–Bulkley model is generally used by employing yield stress concept, which is a function of magnetic flux density [14]. This model can explain well the shear thinning behavior and viscosity change with magnetic field together. However, in the real applications of MR fluids, not only the shear rate and magnetic field but also the operating temperature, one of the tricky factor to control, affects to the viscosity change [15]. For a base fluid such as silicone oil, the temperature effect is critical for its high thermal conductivity. In addition, the initial input particle volume fraction also highly affects to the rheological behavior of MR fluids, which can be characterized by suspension models such as Einstein model, Roscoe model, Mooney model, or Krieger & Dougherty model [16–19].

While each viscosity models for each effects are actively studied for suspensions and composite polymers, there were only a few attempts to consider all the effects together within a viscosity model for MR fluids. Moreover, we found a saturation phenomenon of viscosity at high magnetic field, which cannot be simply characterized by the conventional Hershel–Bulkley model. This

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viscosity saturation phenomenon was also reported by several other researches on ferrofluids [20–23], while they were not characterized as viscosity models.

In this study, we have investigated the effect of operating conditions on micro magnetic particle dispersed silicone oil and developed a phenomenological viscosity model representing the effects of temperature, shear rate, particle volume fraction, and magnetic flux density.

2. Experimental

2.1. Materials

A ferrite magnetic powder was used in this study as a micro magnetic particle. The powder has the average particle size of 2.14 μm and its morphology is shown in Fig. 1. To investigate the effect of relative particle volume fraction on the rheological behavior of MR fluids, the ferrite powder was mixed with silicone oil with different relative particle volume fraction such as 0%, 10%, 20%, 30%, 40%, 50% and 60%. While commercial MR fluids barely have more than particle volume 10%, these various test regime is to find and characterize the general tendency of viscosity change with the different amount of particles.

2.2. Experimental

To investigate steady shear rheology, a plate–plate type rotational rheometer was employed in this study. A schematic diagram of the rotational rheometer is shown in the Fig. 2. An electromagnetic coil was placed under the sample holding plate and DC power supply was linked to allow current in the coil, generating magnetic field penetrating vertically and uniformly through the MR fluid samples. To measure the generated magnetic flux density, a thin transverse type probe is placed between the thin lower shear plate and the electromagnetic coil set. Both of upper shearing plate and lower fixed plate are made of non-magnetic material to exclude the effects from the interaction between the plates and generated magnetic field. A hot plate was also embedded in the rheometer to change the temperature of fluids. With this rheometer system, the shear viscosity of seven different samples was measured at three different temperatures of 40 °C, 70 °C and 110 °C under eleven different magnetic flux density of 0–100 mT, and shear rate in the regime of 5–500 1/s. While obtaining data, at high shear rates, wall slip is present, thus proper correction has to be made to account the effects of wall slip. Rabinowitch correction was applied to the experimental data.

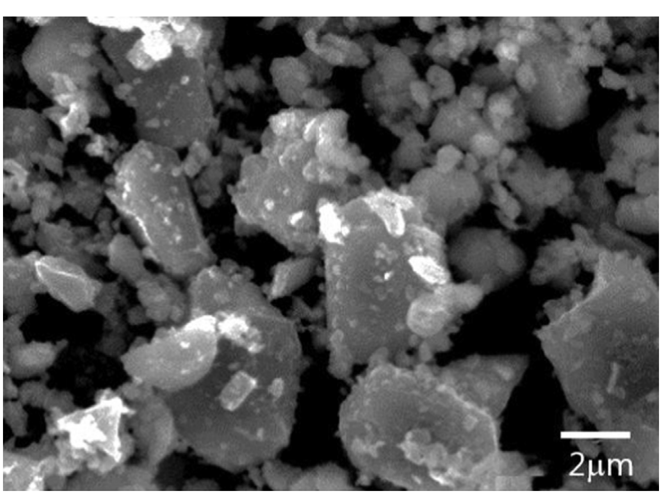

Fig. 1. SEM image of ferrite magnetic particle.

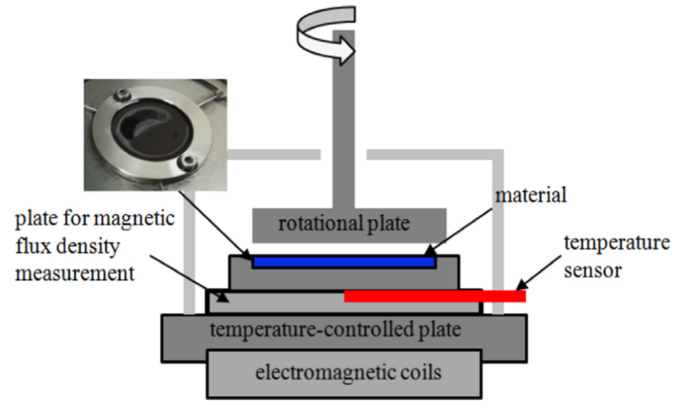

Fig. 2. Schematic diagram of rotational rheometer.

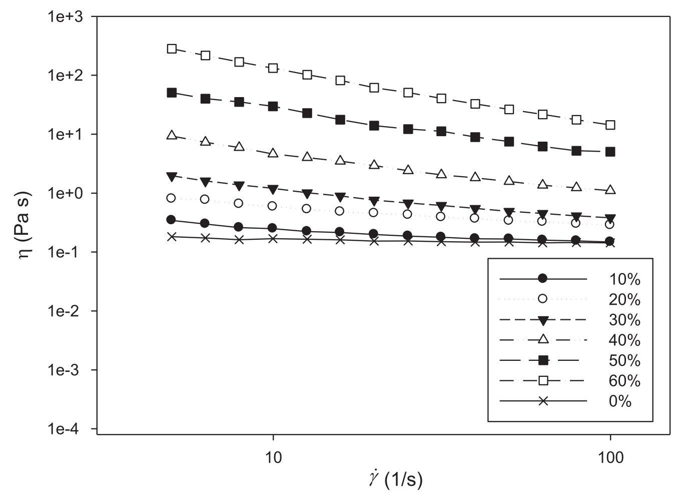

Fig. 3. Particle volume fraction effect on the shear viscosity of MR fluids under 0 T at 40 °C.

3. Results and discussion

Fig. 3 shows the shear viscosity with seven samples with different powder volume fraction. The base fluid with 0% of metal particle had Newtonian fluid-like behavior with no significant viscosity changes under different shear rates. However, once metal particles were added to the base fluid, it had non-Newtonian fluid-like behavior. For samples with 10%, 20%, 30%, 40%, 50%, and 60%, the shear thinning behaviors have been observed. As the particle volume fraction increased, the shear viscosity also increased in the order of magnitude. The presence of particles disturb the shear flow of MR fluid, thus increasing the shear viscosity. Therefore, more volume of particles in the based fluid led to higher shear viscosity. As shown in Fig. 4, for high concentrated samples, their viscosity differences were visible by comparing the stirred surface for the samples with 30%, 40%, 50%, and 60% powders. Few seconds after stirring sample fluids, the surface of higher particle volume fraction were less flattened by gravity and surface tension force.

The shear rate dependency (S) can be well described with the power law model [16]

$$S = \dot{\gamma}^{n-1} \quad (1)$$

where n indicates the flow behavior. When n is equal to unity, the fluid can be regarded as Newtonian fluid, without any shear rate