Journal of Magnetism and Magnetic Materials xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Viscous properties of ferrofluids containing both micrometer-size magnetic particles and fine needle-like particles

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ARTICLE INFO

Keywords:
Ferrofluid
Magnetic fluid
Magnetorheological fluid
Viscosity
Needle-like particle
Percolation

ABSTRACT

Ferrofluids containing both micrometer-size spherical magnetic particles and nanometer-size needle-like nonmagnetic hematite particles were newly produced. Average length of long axis of the needle-like nonmagnetic particles was 194 nm and the aspect ratio was 8.3. Shear stress and viscosity were measured using the rheometer with the additional equipment for viscosity measurements in the presence of magnetic field. When the total volume fraction of particles in the fluid is constant (0.30), there is the specific mixing ratio of the particles to increase viscosity of the fluid drastically in the absence of magnetic field due to the percolation phenomenon. The fluid of the specific mixing ratio shows solid-like behavior even in the absence of magnetic field. Mixing the needle-like nonmagnetic particles causes strong yield stress and strong viscous force in the presence of magnetic field.

1. Introduction

A magnetic functional fluid is a mixture of fine magnetic particles and a carrier liquid. Ferrofluids and magnetorheological fluids are examples of the magnetic functional fluids. Ferrofluids are stable suspensions of fine magnetic particles whose average diameter is about 10 nm [1,2], while magnetorheological fluids are mixtures of micrometer-size magnetic particles and a mother liquid. These fluids have some interesting characteristics such as magneto-viscous effect in the presence of magnetic field. One of the typical applications using magneto-viscous effect is a damper [3,4]. When the magnetic functional fluid is used as a working fluid in the oil damper, the damping force is controlled changing the intensity of applied magnetic field, thus, the damping force variable damper is obtained without any mechanical moving parts. Experimental and theoretical investigations on the viscous properties of ferrofluids [5–10] and magnetorheological fluids [11–18] have been reported by many researchers. Ido et al. have shown that the damping force of the damper using the magnetorheological fluid containing irregular shape magnetic particles is stronger than that of the damper using magnetorheological fluid containing only spherical magnetic particles [17]. This experimental result indicates that using non-spherical particles in the magnetic functional fluids is effective for increasing damping force, i.e., increasing viscosity. Yokoyama et al. also reported that using needle-like nonmagnetic particles instead of part of spherical magnetic particles in a magnetorheological fluid is also effective for increasing damping force [18].

In the present study, we prepared new magnetic functional fluids which were ferrofluids containing both micrometer-size spherical magnetic particles and submicron needle-like nonmagnetic particles. In the new magnetic functional fluids, there were three different types of particles, i.e., micrometer-size spherical magnetic particles, submicron needle-like nonmagnetic particles and nanometer-size spherical magnetic particles. Viscous properties of the fluids were investigated experimentally using a rheometer with a special equipment for measuring viscosity in the presence of magnetic field. Shear stress and viscosity were measured. Damping force of the prototype damper using the test fluids were also examined experimentally.

2. Experiments

For our experiments, we prepared two types of particles, i.e., micrometer-size spherical magnetic particles (BASF, HQ) whose average diameter was 1.1 μm and needle-like hematite particles whose length of the long axis was 194 nm and the aspect ratio was 8.3 (DOWA Electronics, HP-1). Fig. 1 shows the SEM photograph of the particles. The base fluids were mixtures of polyalphaorefin (Ferrotec, EXP.09045) and polyalphaorefin base ferrofluid (Ferrotec, APG-314). Total volume fraction of the particles in the test fluids was constant

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http://dx.doi.org/10.1016/j.jmmm.2016.10.015
Received 1 July 2016; Received in revised form 29 September 2016; Accepted 1 October 2016
Available online xxxx
0304-8853/

Please cite this article as: IDO, Y., Journal of Magnetism and Magnetic Materials (2016), http://dx.doi.org/10.1016/j.jmmm.2016.10.015

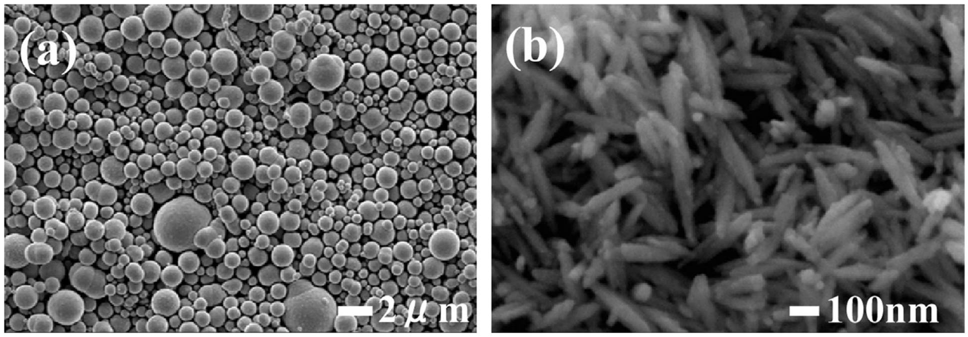


Fig. 1. SEM photographs of (a) micrometer-size magnetic particles (HQ) and (b) needle-like hematite particles (HP-1).

Table 1
Volume fraction of components of the test fluids.

Fluid	Particles			Base liquid	Density [g/ml]
	μm-size	Needle-like	nm size		
A	0.26	0.04	0	0.7	2.76
B	0.26	0.03	0.01	0.7	2.78
C	0.26	0.02	0.02	0.7	2.79
D	0.26	0.01	0.03	0.7	2.81
E	0.26	0	004	0.7	2.82

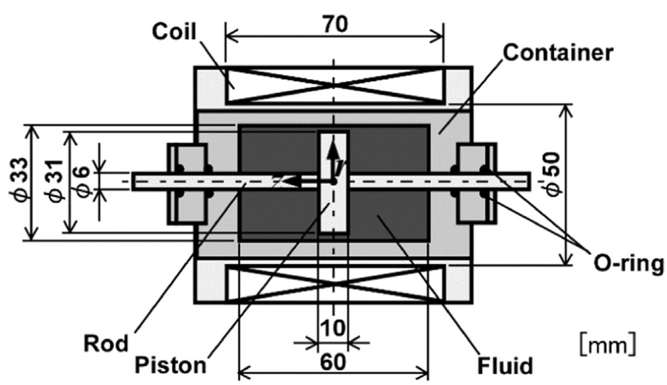
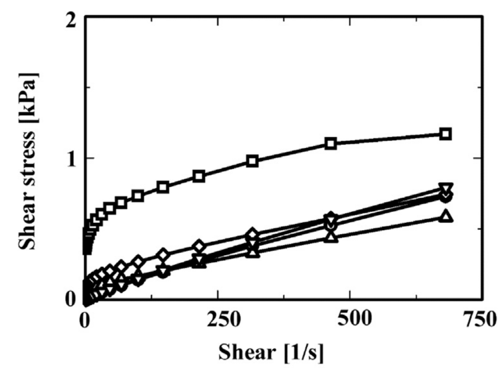
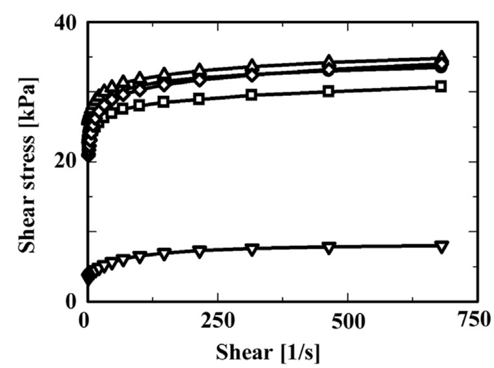


Fig. 2. Schematic of the double-rod type damper.



(a)



(b)

Fig. 3. Shear stress of the test fluids in the absence of magnetic field. Open inverted triangles: Fluid A (26:0:4), open circles: Fluid B (26:1:3), open triangles: Fluid C (26:2:2), open squares: Fluid D (26:3:1) and open diamonds: Fluid E (26:4:0). The applied magnetic flux densities are (a) 0 mT and (b) 500 mT.

(0.30) and the volume fraction of micrometer-size spherical magnetic particles was also constant (0.26). Five types of test fluids were prepared. Components of the test fluids are shown in Table 1. Small amount of smectite (Co-op Chemical, SAN-316) were added to the base fluid as a viscosity improver to avoid sedimentation of the particles. The volume fraction of the smectite was 0.022. As shown in Table 1, nanometer-size magnetic particles were included in the base ferrofluid, thus, the test fluid A did not include any ferrofluid.

In the present study, two types of experiment were performed, i.e., viscosity measurements and damping force measurements.

Viscous properties such as the shear stress and the viscosity were investigated using the rheometer (Anton-paar, MCR302). We cannot obtain the viscous properties precisely under applied magnetic field using a simple rheometer without any shield, because applied magnetic field influences the measurement results of viscous properties. Therefore the additional equipment (Anton-paar, MRD) was used for measurements in the presence of magnetic field. The shear stress and the viscosity were measured using rotating viscometer and magnetic field was applied perpendicular to the shear flow. The intensities of applied magnetic flux density were 0 mT and 500 mT. The shear rates were in the range from 1 to 700 (1/s).

Damping force of a prototype damper was also investigated experimentally. Fig. 2 shows the schematic of the double-rod type prototype damper which was used in our experiments. The container of the damper, rods and piston were made of aluminum and two O-rings were arranged at the exits of the container to avoid escape of the fluid. A coil was wired around the container to apply magnetic field which was parallel to the axial direction of the rod. The axis of the rod of the damper was arranged in the vertical direction. Rotational motion of the motor (Oriental motor, BX6400S) was transformed to reciprocating straight motion using the piston-crank mechanism. The damping force was measured using the load cell and the strain amplifier (Kyowa, LUX-a-2kN and DPM-750A), while the displacement of the piston was measured using the laser displacement sensor and the amplifier unit (Keyence, LB-040 and LB-1000). The measurements were performed at 50 plus or minus 5 °C on the surface of the damper. The piston was forced to vibrate with constant frequency and with constant stroke. The stroke was 8 mm and applied electric currents to the coil were 0, 1, 2, 3, 4, 5 and 6 A. The maximum magnetic flux density was about 82 mT on the central line of the orifice area when the applied electric current to the coil was 6 A.