Magnetoviscosity and wettability of magnetic fluids containing magnetite nanocubes

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ABSTRACT
Magnetic fluids have been widely implemented in engineering and biomedical applications due to their tuneable rheology and magnetization. In this paper, magnetite (Fe₃O₄) dispersed in hexane are investigated. Synthesized by the reduction of ferric acetylacetonate, nanoparticles including nanocubes are obtained with the average size of 13.7 nm. Their dispersion only slightly modifies the wettability and viscosity of hexane. By contrast, the viscosity of the magnetic fluid is significantly increased from 0.284 to 0.339 cP when the U-tube viscometer was subjected to 142 Oe magnetic field from an electromagnet. This magnetoviscosity is attributed to the interaction between nanoparticles in response to the applied magnetic field. The adjustment of fluid flow by magnetic field can be utilized in nanolubrication and bearing.

1.0 INTRODUCTION
Magnetic fluid is a fascinating class of functional materials composed of magnetic particles dispersed in liquids (Odenbach, 2004). Whereas “magnetorheological fluids” is the term for colloidal suspensions of microscale particles, those containing nanoparticles are sometimes referred to as “ferrofluid”. By combining magnetic characteristics with fluid properties, these magnetic fluids have been implemented as shock absorbers, seals and lubricants (Huang et al., 2016; Ravaud et al., 2009). In the operations, the interactions between magnetized particles are sensitive to external magnetic fields. In addition to magnetic properties, their applications in bearing systems are governed by other characteristics including wettability and viscosity.

Whereas the wettability indicates how much liquids is in contact with and able to spread on solid surfaces, the viscosity is directly related to the flow ability of liquids. A variety of techniques...
can be used in the characterization of viscosity. Viscometers commonly used in industrial processes are classified based on their operation principles into Orifice viscometer, Rotational viscometer, Vibrational viscometer, falling piston viscometer, Falling ball viscometer, and Capillary viscometer. The Capillary viscometer, also known as U-tube viscometer, employs a U-shape glass tube with two bulbs. Since the time for liquid to travel from one side to the other in the tube is dependent on its viscosity, the comparison of liquid flows in this simple apparatus gives rise to the values of kinematic viscosity.

Recent advances in nanotechnology enable the synthesis of magnetic nanoparticles with various shapes and sizes (Sulaiman et al., 2017; Nadejde, C. et al., 2015). Nanoparticles exhibit superparamagnetism at the expense of ferromagnetism when they are reduced into the single-domain size range. Colloidal stability is achieved by the surface modification of nanoparticles. The applications of magnetic colloids in mechanical engineering as well as biomedicine can be extended (Nadejde, C. et al., 2015). In this paper, magnetite (Fe₃O₄) nanoparticles are synthesized and subsequently dispersed in hexane. The wettability of magnetic fluids is measured in terms of the contact angle and the variation of viscosity under the influence of magnetic field is investigated.

2.0 EXPERIMENTAL PROCEDURE

Magnetite nanoparticles were synthesized from the reduction of ferric acetylacetonate (Fe(acac)₃) under a nitrogen (N₂) atmosphere using Schlenk line. Oleic acid and oleylamine were added as surfactants to inhibit particle aggregations. Magnetic fluids were obtained by dispersing the as-synthesized nanoparticles in hexane. The procedure is summarized in Figure 1.

Figure 1: Synthetic procedure of magnetic fluids with surface-modified magnetite nanoparticles in hexane.
The average particle size was characterized by the Dynamic Light Scattering (DLS) technique. By dropping magnetic fluids on carbon-coated copper grids, the morphology of dried particles was inspected by the Transmission Electron Microscopy (TEM). Contact angles of magnetic fluids and hexane were measured by the drop shape analysis. Drops releasing from a needle onto a flat surface were repeated for six times and their static angle were evaluated from the contour of droplets.

A capillary viscometer was a U-shaped tube with a bulb on each side in Figure 2(a) obtained by the glassblowing. The viscosity was measured by filling the magnetic fluids in the right side of the U-tube. The time of the liquid flow recorded from the right to the left bulb was used in the determination of viscosity. To perform magnetoviscosity, the experiments were carried out with the U-tube installing between the pole faces of an electromagnet as shown in Figure 2(b). The flow duration under the magnetic field of 142 Oe was then compared to that measured without an applied magnetic field. Each experiment was repeated five times to reduce the random errors.

3.0 RESULTS AND DISCUSSION

As shown in Figure 3, the shape of nanoparticles is polygon and this TEM image suggests that some magnetite nanocubes are obtained. The particle size distribution curve obtained from the DLS (not shown here) has a single peak centered around 16 nm with an average diameter 13.7 nm. Compared to the oil-based colloids in previous reports (Huang et al., 2009; Trivedi et al., 2017), the size of magnetite nanoparticles from their co-precipitation syntheses are comparable to that in the current report but their shapes are nearly spherical. The difference confirms that a variety of morphology can be obtained from the variation in the synthesis.
Figure 3: TEM image of magnetite nanoparticles from magnetic colloids.

Table 1: Contact angle of hexane and magnetic fluid droplets averaged from six repeated measurements.

<table>
<thead>
<tr>
<th>Liquid sample</th>
<th>Contact angle (degree)</th>
</tr>
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<tbody>
<tr>
<td>Hexane</td>
<td>10.4±0.3</td>
</tr>
<tr>
<td>Hexane containing magnetite nanoparticles</td>
<td>10.8±0.4</td>
</tr>
</tbody>
</table>

Table 1 shows that the dispersion of magnetite nanoparticles do not substantially affect the wettability of hexane. This is possibly due to the small size of the nanoparticles and the small contact angle of the carrier liquid. The slight increase in contact angle from 10.4° (for hexane) to 10.8° (for magnetic colloid) suggests that the contribution in cohesive forces by magnetic nanoparticles is more pronounced than their disruption on those between hexane. Nevertheless, the effect of random disruption is evident in the increased standard deviation in repeated measurements.

Table 2: Time of liquid flow in the viscometer and resulting viscosity with and without magnetic fields averaged from five repeated measurements.

<table>
<thead>
<tr>
<th>Magnetic field (Oe)</th>
<th>Time of Flow (s)</th>
<th>Viscosity (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>41.6±0.9</td>
<td>0.284</td>
</tr>
<tr>
<td>142</td>
<td>50.2±7.6</td>
<td>0.339</td>
</tr>
</tbody>
</table>

The measured time of magnetic fluid flow in the viscometer \(t_{\text{colloid}}\) is used to determine the viscosity \(\eta_{\text{colloid}}\) according to the formula;

\[
\frac{\eta_{\text{colloid}}}{\eta_{\text{water}}} = \frac{\rho_{\text{colloid}}}{\rho_{\text{water}}} \frac{t_{\text{colloid}}}{t_{\text{water}}}
\]  

(1)

Where \(\rho_{\text{colloid}}\) and \(\rho_{\text{water}}\) are respectively the densities of the magnetic fluid and water. \(\eta_{\text{water}}\) is the referenced viscosity of water and \(t_{\text{colloid}}\) is the measured time of water flow in the same U-tube apparatus. Substituting other parameters, the viscosity of the magnetic fluid is computed as 0.284 cP, a comparable value to that of hexane.
Table 2 show that magnetic fluids take significantly longer time to travel in the U-tube under the application of magnetic field. The small transverse field of 142 Oe is sufficient to increase the viscosity from 0.284 to 0.339 cp. This result suggests that whereas the introduction of nanoparticles including nanocubes of 13.7 nm in average size only slightly affect the wettability and viscosity of hexane, the interactions between nanoparticles in response to external magnetic field are marked. The effect of magnetic field on the viscosity (Cunha et al., 2016) and tribological properties (Shahrivar et al., 2014) of ferrofluids and magnetorheological fluids were previously reported. Such manipulation can also be applied in the use of water-based ferrofluids.

4.0 CONCLUSION

In summary, magnetite nanoparticles were synthesized from the reduction of Fe(acac)$_3$ in N$_2$ atmosphere and then dispersed in hexane. According to the TEM image, a large number of magnetite nanoparticles in this magnetic fluid had polygon shape with the size around 15 nm. The presence of magnetite nanoparticles only slightly increased the contact angle of hexane from 10.4±0.3 to 10.8±0.4 degree. Magnetoviscosity of the magnetic colloids was demonstrated by tracking its flow in a glass U-tube installing between pole faces of an electromagnet. When the U-tube was subjected to 142 Oe magnetic field, the viscosity was increased to 0.339 cp compared to the value of 0.284 cp measured without applied magnetic field.

REFERENCES