Dynamic Behavior of Two Ag Nanowires Dispersed in Magnetic Fluid

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Nanofluids have attracted much attention in the field of heat transfer because of their exceptional heat transfer ability. The authors have proposed a silver nanowire-dispersed magnetic nanofluid. Interestingly, its thermal conductivity is tunable by the direction of the applied magnetic field, because the dispersed Ag nanowires orient to the field direction. But the dynamic behavior of Ag nanowires is not well understood. In the present study, the translation process of the neighboring two Ag nanowires was theoretically analyzed. When the Ag nanowires are dispersed in the magnetic fluid and exposed to the magnetic field, the Ag nanowires apparently behave as a diamagnetic material because the surface of the Ag nanowires is magnetically charged. With assuming that single magnetic moment places at the center of Ag nanowires, the magnetic dipole interaction force, which is the attraction force, acts on the Ag nanowires, and the wires contact each other with taking a long time.

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1. Introduction

Magnetic fluids are a magnetic suspension in which 10 nm-sized magnetic nanoparticles stably disperse in a proper carrier liquid such as water, hydrocarbon oils, ester oils and so on[1]. The Magnetic fluids are a highly sensitive fluid to magnetic fields. When a magnetic field is applied to the magnetic fluid, the magnetic moments of the particles orient to the field direction and this lead the particles aligning with the field, and forming chain-like structures (clusters) [2].

One of the most interesting features of magnetic fluid is an anisotropic thermal conductivity in the presence of a magnetic field. In general, the inherent thermal conductivity of the magnetic particles is higher than that of the carrier liquids [3,4]. When a magnetic field is applied, the clusters formed along the field facilitate the heat conduction, resulting in that the thermal conductivity in this direction is enhanced. The thermal conductivity of the magnetic fluid is known to be anisotropy in the presence of magnetic field, which is associated with the formed clusters along the magnetic field. There are many contributions to investigate the anisotropic thermal conductivity of the magnetic fluids [5-12]. For example, Li et al. [7] investigated the thermal conductivity of aqueous magnetic dispersions 0.0 – 5.0 vol. % of 26 nm diameter Fe nanoparticles. They revealed that the thermal conductivity is enhanced when the magnetic field is applied parallel to the temperature gradient, on the other hand, the perpendicular field has no influence on the thermal conductivity. Although the thermal conductivity is enhanced when the parallel magnetic field is applied, the enhancement is not significant, approximately 10 % order enhancement.

To realize the further thermal conductivity enhancement, the authors focus on the dynamic behavior of non-magnetic materials dispersed in a magnetic fluid, called inverse magnetic fluid. When the non-magnetic materials are dispersed in a magnetic fluid and exposed to an external magnetic field, it is known that the non-magnetic materials behave like a magnetic material [13]. Interestingly, the non-magnetic materials align with the applied magnetic field and form clusters likewise the magnetic nanoparticles [14]. This unique phenomenon is associated with the magnetic surface charge due to the magnetized magnetic nanoparticles. When the non-magnetic particles are placed in the magnetized magnetic fluid, the surface of the non-magnetic materials is magnetically charged, resulting in that the non-magnetic materials apparently behave as a diamagnetic material. Consequently, the Coulomb force or the magnetic dipole interaction forces act on the materials and they interact with each other [13]. If the non-magnetic materials have high thermal conductivity such as silver and copper, exceptional thermal conductivity enhancement is expected because the high thermal conductivity materials form the clusters and facilitate the heat conduction.

When metal nanowires form cross-linked structures in a carrier liquid, it has been known that the thermal conductivity is significantly enhanced up to 1,350 % [15]. The authors [16] has proposed an Ag nanowire-dispersed magnetic fluid (Ag NWD-MF), in which Ag nanowires are stably dispersed in the magnetic fluid. The authors found that the Ag nanowires orients to the applied magnetic field direction, and the thermal conductivity is enhanced [16]. This phenomenon may be associated with the apparent magnetization of non-magnetic materials.

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2. Theoretical Approach to Dynamic Behavior of Ag Nanowires Dispersed in Magnetic Fluid

2.1 Magnetic behavior of non-magnetic materials dispersed in magnetized magnetic fluid

Owing to the fact that the magnetic nanoparticles are ultrafine particles with the diameter of approximately 10 nm, the particles have single magnetic domain and moment, resulting in the superparamagnetism\[1\]. When a non-magnetic material is dispersed in the magnetized magnetic fluid as depicted in Fig.1, the surface of the non-magnetic material is magnetically charged, because of the magnetized magnetic nanoparticles of which magnetic moment orients to the applied magnetic field. Consequently, the non-magnetic material is apparently magnetized to be a diamagnetic material [13]. The apparent magnetic moment of the non-magnetic material is induced instantaneously because, for the magnetic nanoparticles, their relaxation time to orient the magnetic moment toward the external magnetic field is significantly fast of \(10^{-7}\) s order [1]. The apparent magnetic moment orients opposite direction against those of the magnetic nanoparticles. If the non-magnetic material has magnetic shape anisotropy and the axis of easy magnetization orient to the different direction of the apparent magnetic moment, the torque associated with magnetic shape anisotropy act on the non-magnetic material [17]. Consequently, the non-magnetic material starts rotating and finally orients to the applied magnetic field direction. Actually, this rotational behavior has been observed in our previous experimental observation using a dark field microscopy [16].

If two non-magnetic materials are dispersed in the magnetized magnetic fluid, these materials magnetically interact with each other and show the mobility. Fujita and Mamiya [13] proposed two models to describe the interaction forces acting on such non-magnetic materials. One of them is the magnetic charge model, and another is the magnetic dipole model. In the magnetic dipole model, the magnetic moment is assumed to be single and place at the center of the non-magnetic particles. This model was employed in the present study as described in the following section 2.2.

2.2 Dynamic behaviors of Ag nanowires dispersed in magnetized magnetic fluid

Although the Ag nanowires display extremally low diamagnetization under a strong magnetic field, the Ag nanowires are assumed to be non-magnetic material in this paper, because the magnetic field strength dealt in this paper is extremally low of \(\sim 80\) mT. When Ag nanowires are dispersed in a magnetic fluid and are exposed to an external magnetic field, the Ag nanowires are apparently magnetized as a diamagnetic material. Because the nanowires have a shape anisotropy, their dynamic behavior may consist of (a) a rotation process – orientation to the magnetic field, and (b) a translation process – contact between nanowires as sketched in Fig. 2. In the present study, we focus on (b) the translation process to understand the dynamic behavior of Ag nanowires dispersed in the magnetized magnetic fluid.

To simplify the discussion on the translation process, in this study, the contact time between two Ag nanowires, which have completely oriented to the magnetic field, and placed on the same line. In general, the value of the magnetic permeability of the magnetic fluid is 1.1~2.0.

(a) Rotation and orientation of Ag nanowires to the magnetic field direction. Left and right sides figures illustrate the morphology before and after applying a magnetic field, respectively.

(b) Translation of Ag nanowires. Left and right sides figures illustrate the morphology before and after the wires contact, respectively.

Fig.1 Schematic illustration to describe the apparent magnetization and the rotation of non-magnetic materials dispersed in the magnetized magnetic fluid.

Fig.2 Schematic illustration of the dynamic behaviors of Ag nanowires immersed into the magnetized magnetic fluid.
Because there is a significant difference in magnetic permeability between a non-magnetic material and a magnetic fluid, the magnetic permeability of non-magnetic materials relatively become low comparing with the one of the magnetic fluid. With considering the magnetic permeability of the magnetic fluid as a reference, the non-magnetic materials apparently behave as a diamagnetic material. In this state, the magnetic field inside the non-magnetic materials $H'$ is given by

$$H' = H - \frac{N}{\mu_f} M$$

(1)

Where $H$ is the external magnetic field, $N$ is the demagnetizing factor, and $\mu_f$ is the magnetic permeability of magnetic fluid. $M$ is the apparent magnetization of the non-magnetic material which is induced by the difference of the magnetic permeability between the magnetic fluid and the non-magnetic material, given by

$$M = (\mu_a - \mu_f)H'$$

(2)

where, $\mu_a$ is the magnetic permeability of the non-magnetic material. From Eqs. (1) and (2), the apparent magnetization $M$ is derived as

$$M = \frac{\mu_f (\mu_a - \mu_f)}{(1 - N) \mu_f + N \mu_a} H$$

(3)

And the magnetic moment $m$ is

$$m = \frac{\mu_f (\mu_a - \mu_f)}{(1 - N) \mu_f + N \mu_a} H \cdot V$$

(4)

, where $V$ is the volume of the non-magnetic material. When two non-magnetic materials have the apparent magnetic moments of $m_1$ and $m_2$, respectively, the magnetic potential between these two non-magnetic materials $U$ are given by

$$U = -\frac{m^2}{2 \pi \mu_f r^3}$$

(6)

The magnetic dipole interaction force $f_{Mag}$ is the gradient of the magnetic potential $U$, and given by,

$$f_{Mag} = \frac{\partial U}{\partial r'} = \frac{3 m^2}{2 \pi \mu_f r'^3}$$

(7)

Substituting Eq. (4) to Eq. (7), the magnetic dipole interaction force acting on Ag nanowires is given as the following equation with taking their demagnetizing factor into account.

$$f_{Mag} = \frac{3}{2 \pi (s+b)^3} H^2 \frac{\mu_f (\mu_f - \mu_a)^2}{(1 - N) \mu_f + N \mu_a} V^2$$

(8)

Where $s$ is the distance between edges of two nanowires as sketched in Fig. 3, and $b$ is the length of the nanowire. The demagnetizing factor $N$ of Ag nanowire is given by the following equation with the assumption that the shape of the nanowire is a cylinder [18].

$\log_{10} N = -0.13398 - 1.36759 \log_{10} p$

$$0.42801 \sqrt{p - 0.05588 \sqrt{p + 0.00060}}$$

(9)

Where $P$ is the aspect ratio ($b/a$) and $a$ is the diameter of Ag nanowire.

When the nanowires move in a viscous fluid, the viscous drag force $f_{Drag}$ acts on the nanowires, which is given by the following equation [19, 20].

$$f_{Drag} = \frac{2 \pi \eta u}{\ln (2b/a) + \gamma}$$

(10)

Fig. 3 Schematic illustration to describe the distance between Ag nanowires $s$. 

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130 (130)
Where $\eta$ is the fluid viscosity, $\nu$ is the moving viscosity of Ag nanowire, $\gamma$ is the constant depending on the aspect ratio $p$.

The equation of motion for Ag nanowires with taking the magnetic dipole interaction force $f_{Mag}$ and the viscous drag force $f_{Drag}$ into account is

$$\frac{d\nu}{dt} = f_{Mag} - f_{Drag}$$

(11)

Where $\xi$ is the mass of the Ag nanowire. With discretizing Eq.(11) and solving it numerically, the translation process, in particular – the contact process between two Ag nanowires, could be theoretically analyzed.

3. Results and Discussion

3.1 Dynamic behavior of two Cu spherical particles dispersed in magnetized magnetic fluid

To verify the theoretical results with the introduced equation of motion (Eq.(11)), the contact time between two Cu spherical particles dispersed in the magnetized magnetic fluid was analyzed. It should be noted that the Ag nanowires, which were employed in our previous work [16], are incredibly tiny with the diameter of about 70 nm. Because of the small diameter, it is impossible to visualize and observe the dynamic behavior of Ag nanowires using a microscope. Therefore, the dynamic behavior, in particular – the contact process of two Cu spherical particles with the diameter of 20 µm, were visualized using the darkfield microscopy with customizing to apply a homogeneous magnetic field. The details of the customized microscope are described in Ref.[16]. In the analysis of their dynamic behavior, the equation of motion, Eq.(11), was solved with the demagnetizing factor $N = 1/3$, and the viscous drag force $f_{Drag} = 3\pi \eta d u$, where $d$ is the diameter of the particle. Other calculation conditions were set as the fluid viscosity $\eta = 150 \times 10^{-3}$ Pa·s, the magnetic field $H = 31$ mT, the magnetic permeability of magnetic fluid $\mu_f = 1.2 \mu_0$ H/m, the magnetic permeability of Cu particle $\mu_n = 0.99 \mu_0$ H/m, the density of copper $8.94 \times 10^3$ kg/m$^3$.

Fig. 4 shows the darkfield microscope images of the Copper µm-sized particle in the magnetic fluid (a) immediately after and (b) after 3.97 seconds from applying the magnetic field. When the magnetic field is applied, the Cu particles are apparently magnetized because the surfaces of the Cu particles are magnetically charged due to the magnetized magnetic nanoparticles. Consequently, the magnetic dipole interaction force act on the particles. Initially, the two Cu particles were placed to make their distance 30 µm as shown in Fig. 4(a). After applying the magnetic field, the mobilities of the particles were observed due to the effect of the magnetic dipole interaction force, and finally, these particles contacted with each other after 3.97 seconds from applying the magnetic field. The theoretical result for the contact time was 3.80 seconds. The theoretical result showed a good agreement with the experimental observation. The introduced equation (Eq. (11)) was found to be able to demonstrate well the translation process of the nonmagnetic materials dispersed in the magnetized magnetic fluid.

3.2 Dynamic behavior of Ag nanowires dispersed in magnetized magnetic fluid

To realize the dynamic behavior of Ag nanowires dispersed in the magnetized magnetic fluid, the translation process, in particular – the contact process between two Ag nanowires which align with the magnetic field and place on the same line, was theoretically analyzed. When the Ag nanowires are dispersed in the magnetized magnetic fluid, the magnetic dipole interaction force $f_{Mag}$ and the viscous drag force $f_{Drag}$ act on the Ag nanowires.

Fig. 5 shows the theoretical results relating to the viscous drag force $f_{Drag}$ with respect to the aspect ratio of Ag nanowires. The plots represent the theoretical result with the experimental conditions, which were conducted in our previous work (Ref.[16]) at the magnetic field of...
80 mT. In the previous work, three type of Ag nanowires with their diameter of 70 nm and various aspect ratios of 29, 70, and 162 were prepared, and the effect of aspect ratio on the anisotropic thermal conductivity was investigated. As shown in Fig. 5, the viscous drag force $f_{\text{Drag}}$ dramatically increases, and then slightly increase with the aspect ratio. In a range of our previous study, the aspect ratio of 29~162, it is found that the aspect ratio does not influence the viscous drag force $f_{\text{Drag}}$ so much.

Fig. 6 shows the theoretical results relating to the magnetic dipole interaction force $f_{\text{Mag}}$ with respect to the distance between two Ag nanowires at the aspect ratio of 29, 70 and 162. As shown in Fig. 6, different trends of the magnetic dipole interaction force $f_{\text{Mag}}$ depending on the aspect ratio are observed. When the distance $s$ is less than 5 μm, the magnetic dipole interaction force $f_{\text{Mag}}$ increases with the aspect ratio decreasing. On the other hand, when $s > 5 \mu$m, the magnetic dipole interaction force $f_{\text{Mag}}$ increases with the aspect ratio increasing. This is because, shown in Eq. (10), in a range of $s < 5 \mu$m, the length of Ag nanowire mainly influences the magnetic dipole interaction force $f_{\text{Mag}}$, on the other hand, in a range of $s > 5 \mu$m, the volume of Ag nanowire mainly influences the force.

Fig. 7 shows the theoretical results for the contact time between the two Ag nanowires placed at various initial distance $s$. As shown in Fig. 7, owing to the fact that the magnetic dipole interaction force depends on the aspect ratio and the distance $s$, the contact time also has two different trends depending on the aspect ratio. That is, when the initial distance $s$ is less than 10 μm, the contact time become longer with increasing the aspect ratio. In this range, the magnetic dipole interaction force $f_{\text{Mag}}$ is enhanced with the aspect ratio decreasing. Therefore, the nanowire with shorter aspect ratio contact earlier. On the other hand, the contact time become faster when the aspect ratio increasing. This is because the magnetic dipole interaction force $f_{\text{Mag}}$ is enhanced with the aspect ratio increasing due to the volume of Ag nanowire. In our previous work in Ref [16], the volume fraction of Ag nanowires dispersed in the magnetic fluid was 0.029 ~ 0.110 vol.%. With taking the volume fraction into account, the minimum initial distance $s$ should be 16 μm, which could be calculated by the following equation.

$$s = \sqrt{\frac{25 \pi b^3}{\sigma}} - b$$ (12)

Where $\sigma$ is the volume fraction of Ag nanowire. When $s > 16 \mu$m, the contact time is faster with the aspect ratio increasing. That is, in our previous study, the Ag nanowires with the aspect ratio of 162 contact with each other and form clusters earlier than other conditions. But it is should be noted that the contact time is $10^5$ order minutes, which means that the contact of Ag nanowires does not influence on the field-induced anisotropic thermal conductivity of the Ag NWD-MFs. The rotation of Ag nanowires, orientation to the field direction, mainly affect the anisotropic thermal conductivity.
From the obtained theoretical results, from the view point of the translation of Ag nanowires, it was found that the Ag nanowires with shorter length and larger volume are suitable to enhance the thermal conductivity in the Ag NWD-MFs.

4. Conclusions

To optimize the thermal conductivity enhancement in Ag NWD-MFs, it is essential to understand the dynamic behavior of the Ag nanowires dispersed in the magnetized magnetic fluid. In the present study, the dynamic behavior, in particular – the translation process of Ag nanowires, was theoretically investigated. The equation of motion taking the magnetic dipole interaction force and the viscous drag force into account can well describe the dynamic behavior of the Ag nanowires. The contact time of two Ag nanowires depends on the volume fraction of Ag nanowires and their aspect ratio. In a range of the aspect ratio of 29 ~ 162, which were the conditions in our previous work in Ref [16], the contact time is found to be significant long. This result means that the translation process of Ag nanowire does not influence the thermal conductivity enhancement. The enhancement is mainly induced by the rotation of the Ag nanowire to the magnetic field direction. The present analysis showed that the suitable Ag nanowire to induce the thermal conductivity enhancement is the shorter length and large volume.

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