Real-time observation of Brownian motion and cluster movement of ferro- and non-magnetic particles in magnetic fluids

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Abstract

Cluster movements of ferro- and non-magnetic particles in magnetic fluids were investigated using optical microscope system and image processing system. Real-time visualizations of the Brownian motion of particles and the chain-like cluster movement of both types of particle were performed under a magnetic field. The principal objectives of this study were to clarify the applicability of the optical microscope system and image processing system, and to analyze the growth process of the cluster under magnetic field. The analysis of particle image was done using Particle Tracking Velocimetry (PTV). The results clarified that the real-time observation of Brownian motion and cluster movement of ferro- and non-magnetic particles in magnetic fluids can be carried out using the optical microscope system and the PTV image measurement. Independent continuous measurements with changing positions and velocity of the minute particle were made possible. The study concluded that the system can obtain satisfactory results on growth process measurement of cluster under a magnetic field.

Keywords: Magnetic fluids; Nano-particles; Real-time observation; Cluster-formation; Cluster-movement

1. Introduction

With the progress of nanotechnology in the flow field, the flow measurement and control in micro- or nano-channel using nano-particles become essential. By using ferromagnetic particle in magnetic fluids as a nano-particle, it is considered that applying a magnetic field enables the flow field control. Magnetic fluids are suspensions of Fe₃O₄ ultra fine (5–15 nm) particles coated with a molecular layer of dispersant in a liquid carrier such as water or kerosene. The ferromagnetic nano-particles in magnetic fluids remain suspended because of thermal agitation and the resulting random walk and random rotation, i.e. Brownian motion.

The dispersant coating prevents particles from sticking to each other. However, considering the pair correlations between the particles under the magnetic field, fine ferromagnetic particles tend to form chains, parallel to the external field direction. This is referred as cluster formation of the ferromagnetic nano-particles in magnetic fluids.

Many experimental and theoretical studies have suggested that when a magnetic field is applied to magnetic fluids, some of the ferromagnetic nano-particles will form chain-like clusters [1]. However, a few contradictions still remain between the results derived from the theoretical model and the experimental results. These contradictions may be caused by disregarding the effects of agglomeration of colloidal particles. Non-magnetic particle behaviour in the magnetic fluids is also very interesting, considering the flow control. Fujita and Mamiya [2] investigated interaction forces between non-magnetic particles in the magnetic fluids theoretically and experimentally. Furthermore, very few attempts have been made at simultaneously observing cluster formation of non-magnetic and ferromagnetic particles in magnetic fluids. Therefore, it is necessary to investigate these nano-particles on the Brownian motion and cluster formation in magnetic fields. Hence, the development of measurement technique for real-time observation becomes essential.
In this paper, using an optical method of a light scattering system and image processing system, we study cluster formation of ferromagnetic and non-magnetic nano-particles in magnetic fluids. The analysis of particle image was done using Particle Tracking Velocimetry (PTV). So, in this study the PTV measurement of Brownian motion of non-magnetic particles mixed in kerosene-based magnetic fluid and nano-particles of water-based magnetic fluid and PTV measurement of the cluster movement in cluster formation process under a magnetic field are the main measurement items.

2. Experiments

Fig. 1 shows the schematic diagram of experimental apparatus. Water-based magnetic fluids W-40 and kerosene-based magnetic fluids HC-50, produced by Taiho Co. Ltd., Japan, were used as sample liquids. Water-based magnetic fluids were diluted with water to increase their optical strength. Since the diameter of the ferromagnetic particles was smaller than the wavelength of light, we observed the light scattered by the particles, called the Rayleigh-scattering using the cardioid condenser lens system [3]. Experiments were carried out using an optical microscope system with a cardioid condenser lens. The structure of an oil noctovision view cardioid condenser system is shown in Fig. 2. The sample was sandwiched between thin glass plates and was placed on a microscope stage made of aluminum. The light passing through the oil noctovision view cardioid condenser lens illuminated the sample with an intense cone shape. The cone-shaped light condensed at the sample from the side such that the apex was in the field of view. Thus, we could only observe light scattered by the ferromagnetic particles or the reflector particles in the sample liquid. The reason to use an oil noctovision view condenser lens was that the diameter of particles was far shorter than the wavelength of visible light. Moreover, the space between condenser lens and slide glass was filled with matching oil, having the same refractive index as the glass. The optical precision was enhanced. The microscope magnifications were \( \times 1000 \) and \( \times 400 \) and images were detected by a digital high-speed CCD camera (NEPTUNE-100) mounted on the microscope. The images of ferro- and non-magnetic particles were recorded on the memory in the digital high-speed camera which had a maximum framing rate of 1000 fps. Digital images recorded on the memory of the camera were taken into the personal computer at 512×320 pixels definition (bitmap format). Present optical system reveals the presence of ultra small sizes particles of less than 1000 nm diameter, and allows the observations of the particle motions in real-time.

The analysis of particle image was done using PTV. The PTV is one analytical technique of the image treatment way velocity meters and is used for the measurement of Brownian motion of the minute particles. Non-magnetic minute particle that had different diameter from that of magnetic nano-particle was mixed into the original liquid (50% weight concentration) of kerosene-based magnetic fluid, and the movements of those particles were measured. The diameter of particles added into kerosene-based magnetic fluid was 900 nm. The non-magnetic particles used in this case were spherical SiO\(_2\) particles called Micro Spherical Feather (MSF; Liquidgas Co. Ltd.). These particles have been developed as the hollow seeding-particles for laser Doppler velocimetry measurements. They have uniform diameter, light loose weight, high refractive index and high melting temperature. The microscope magnification was \( \times 1000 \) for Brownian motion measurement.

A non-uniform magnetic field was applied by an electromagnet with parallel direction to the sample. The applied magnetic field intensity was controlled by changing the DC current up to 5 A which allowed a magnetic field of 133 mT. In the measurement of cluster movement, a water-based magnetic fluid was diluted by pure water. The microscope magnification was \( \times 400 \) for the cluster movement.
movement measurement. Digitized pictures (512×320 pixels with 256 gray levels) were processed on the personal computer. At the magnification of ×400 and ×1000, one pixel was equivalent to 190 nm and 75 nm, respectively. Consequently, it is difficult to unambiguously identify isolated particles, but the large field of view allows us to observe large clusters containing many particles.

3. Results and discussion

Fig. 3 shows a result of the image measurement of the Brownian motion about magnetic nano-particles in water-based magnetic fluid and the non-magnetic particles in kerosene-based magnetic fluid using the PTV method. These figures are examples of the velocity vector obtained from the movement of magnetic particle between each image frame. The movement of magnetic particles had larger moving area than that of non-magnetic particles. The difference is caused by the difference of viscosity of the base fluid and difference of particle size. The probability density function of the velocity vector based on these vector data is shown in Fig. 4. The mean velocity of ferromagnetic particles is 15.86 μm/s and the mean velocity of non-magnetic particles is 2.83 μm/s. If the viscous difference were considered, the square-root of the particle diameter ratio becomes equal to the reciprocal of the velocity ratio with a formula of Einstein [4]. Because the size of primary cluster in the water-based magnetic fluids is about 200 nm as estimated by Nakatani et al. [2], the result of this measurement agrees well with the following equation:

\[
\sqrt{\frac{x^2}{\Delta t}} = \frac{2kT}{3\pi\mu d_p} \Delta t \quad \text{with} \quad d_p = \frac{2kT}{3\pi\mu V^2} \Delta t
\]

where, \(d_p\) is diameter of particles, \(k\) Boltzmann constant, \(V\) velocity of particles, \(\Delta t\) frame rate of video camera.

An example of the photography image on cluster formation of the ferromagnetic nano-particles under a magnetic field is shown in Fig. 5. Fig. 5(a) shows the vector of the cluster movement immediately after applying a magnetic field. Fig. 5(b) shows the vector of the cluster movement taken at 5 s delay after applying a magnetic field. Fig. 5(c) shows the vector of the cluster movement taken at a 15 s delay after applying a magnetic field. In these images, the applied magnetic field strength (\(B\)) was 135 mT. When an external magnetic field is applied in parallel to the sample cell, chain-like clusters are formed in the direction of the magnetic field. Since primary cluster of the magnetic nanoparticles in the water-based magnetic fluids is large in comparison with the magnetic nano-particle in the kerosene-based magnetic fluids [5], chain-like cluster in applying a magnetic field can be confirmed clearly as

![Fig. 3. Velocity vectors of Brownian motion of ferro- and non-magnetic particle; (a) Ferro-magnetic particles in water-based magnetic fluid, (b) Non-magnetic particles in kerosene-based magnetic fluid (HC-50 + MSF-10M, 50 wt%, \(B = 133\) mT, 25 °C, \(dp = 900\) nm).](image)

![Fig. 4. Probability density function on particle velocity of Brownian motion; (a) Magnetic particles in water-based magnetic fluid, (b) Non-magnetic particles in kerosene-based magnetic fluid.](image)
It is understood from Fig. 5 that the cluster grows larger with the advancement of time and the cluster movement decreases with the cluster growth. Fig. 5 implies that the chain-like cluster of the magnetic nano-particles moved larger to the horizontal direction rather than to the vertical direction. This difference was caused by there are more larger forces heading to the direction of magnetic field is acted on the magnetic particle during the cluster formation process.

Fig. 6 shows the measurement results of mean cluster length and magnetic nano-particles velocity in water-based magnetic fluids taken at 5 s delay after applying a magnetic field. In this experiment, growth process of the cluster is observed in 3 kinds of magnetic flux density (46.5, 91.5, 133.0 mT). It can be understood from this figure that mean cluster length increase with the increase of the magnetic flux density. The cluster growth rate is influenced by magnetic field strength as also clarified by the studies of Jeyadevan et al. [6] and Sawada et al. [7]. In addition, the cluster velocity decreases by increasing the cluster length. It shall be emphasized here that although the results agree well with that of Jeyadevan et al. [6] and Sawada et al. [7] on the tendency, however, it is the first time that the simultaneous measurement of the cluster growth and cluster velocity was ever attempted using the PTV method. From the measurement results, it is deduced that the effect of Brownian motion still remained even after applying a magnetic field in the cluster.

4. Conclusions

Velocity vectors of the Brownian motion of the ferro- and non-magnetic particles in magnetic fluids were investigated using an optical microscope system and PTV method. In addition, the cluster growth and velocity of magnetic nano-particles in the water-based magnetic fluids were also investigated using an optical microscope system, PTV method and electromagnet. In the measurement of Brownian motion, the ferromagnetic particles in water-based magnetic fluid and non-magnetic particles in kerosene-based magnetic fluid were used. Since we obtain the result that square root of the particle size ratio becomes equal to velocity ratio, it was clarified that particle size
measurement of the magnetic nano-particles was applicable for this measurement technique. It is possible to measure the movement of the particle with good accuracy, because this measurement technique continuously tracks every single particle.

As for the cluster measurement, the ferromagnetic nano-particles cluster cannot be observed in the case of kerosene-based magnetic fluids, when non-magnetic particles were mixed. However, the clusters of the magnetic nano-particles in the water-based magnetic fluids were sufficiently measurable, and the measurement of cluster length and velocity was carried out. It was found that the mean length of the chain-like cluster increased with magnetic field strength and elapsed time. In addition, it was also proven that the velocity in which the cluster moves lowered with the growth of the cluster.

The results clearly clarify that the measurement of Brownian motion of nano-particles and clusters can be carried out using an optical microscope system and PTV image measurement. It is also confirmed that this measurement system can obtain effective results for the measurement of growth process of the cluster by applying magnetic field.

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