FLOW VISUALIZATION OF FERROMAGNETIC NANO-PARTICLES ON MICROCHANNEL FLOW USING DARK FIELD MICROSCOPY

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Abstract

This paper reports the experimental research on the growth and dispersion processes of cluster formation in a water-based magnetic fluid in micro capillary flow. The magnetic fluids are suspensions of ultra fine particles coated with a molecular layer of dispersant in a liquid carrier, such as water or kerosene. The ultra fine particles are coated with single- or double-layer surfactants to attain stable dispersion. However, numerous experimental studies have indicated the existence of primary cluster of ferromagnetic nano-particles in a water-based magnetic fluid. The purpose of this research is to observe the characteristics of primary clusters in micro capillary flow. The thermal behaviour of ferromagnetic nano-particles in micro capillary flow was observed through micro-visualization using the optical dark-field microscope system and particle tracking velocimetry (PTV) data processing system. Real-time visualization of the Brownian motion of primary clusters in a water-based magnetic fluid in micro capillary flow was carried out. Furthermore, the effect of magnetic field on the growth process and dispersion process of cluster formation in micro capillary flow was investigated.

1 Introduction

With the current state-of-the-art of nanotechnology, significant progress has been made in the researches on micro-fluidic device flow or micro-channel flow. In this respect, the interests in the application of the magnetic fluids to control the micro-channel flow have been increasing. This has been one of the prominent topics in the field of magnetic fluid. A magnetic fluid is composed of solid, magnetic, single-domain particles coated with molecular layer of dispersant in a liquid carrier such as water or kerosene. To attain stable dispersion in non-polar or polar solvent, the particles are coated with single- or double-layer surfactants. However, many experimental studies have suggested that when a magnetic field is applied to a magnetic fluid, a fraction of the ferromagnetic particles would form clusters. Kamiyama and Satoh [1] investigated the effect of a magnetic field on apparent viscosity of a magnetic fluid caused by the clustering. They found that cluster formation is particularly noticeable in the case of water-based magnetic fluid. Nakatani [2] found that in the water-based magnetic fluid, a large numbers of agglomerated magnetic particles are observable even in zero external fields using a dark-field observation system. They pointed out that the water-based magnetic fluid shows significantly different rheological-properties and much higher apparent viscosity compared to a kerosene-based magnetic fluid. Nakatani [2] and Jeyadevan & Nakatani [3] found that in the water-based magnetic fluid, a large numbers of agglomerated magnetic particles are observable even in zero external fields using a dark-field observation system. They pointed out that the much higher apparent-viscosity in the water-based magnetic fluid is caused by this agglomerated magnetic particles. Nakatani [2] calls this agglomeration as primary cluster. When an external field is applied, the primary
cluster has a chain-like structure called the secondary-cluster stretched in the magnetic field. The cluster growth rate is influenced by external field strength as clarified by the studies of Jeyadevan & Nakatani [3] and Sawada et al [4]. It is indispensable to obtain the size of primary cluster for micro-channel control using magnetic fluid. Hence, Kikura et al [5] analyzed the primary cluster in a magnetic fluid using the optical microscope system and PTV. The analysis by Kikura [5] obtains the particle size distribution and evaluates the average particle size in the primary cluster in a magnetic fluid. However, until recently, there are only few studies that investigated the behavior of ferromagnetic nano-particle and cluster formation in a magnetic fluid.

In the present study, flow visualization of ferromagnetic particles and primary clusters in a water-based magnetic fluid was investigated using an optical microscope system. Real-time observation of the Brownian motion of ferromagnetic particles was effectively carried out using dark-field condenser lens system. The Brownian motion of ferromagnetic particles was analyzed by means of Particle Tracking Velocimetry (PTV) to obtain the velocity field. Using the velocity value of the particle motion and Einstein's equation for Brownian motion, the viscosity of fluid evaluation in the water-based magnetic fluid can be obtained. The influence of the concentration of magnetic particle in a magnetic fluid on particle size determination was also investigated. In addition, thermal behavior of ferromagnetic particles in micro capillary flow was observed through the micro visualization using the optical dark-field microscope system and PTV data processing system. The real-time observations of the motion of ferromagnetic particle in the water-based magnetic fluids in micro capillary flow were carried out. Furthermore, the effect of a magnetic field on the growth process and dispersion process of cluster formation in micro capillary flow was studied.

2 Experiment

Figure 1 shows a schematic diagram of the experimental apparatus. Water-based magnetic fluid W-40 produced by Taiho Co. Ltd., is used as sample liquid. In the experiment to evaluate the viscosity of the water-based magnetic fluid, the non-magnetic particle with different diameter from the magnetic nano-particle was blended to the water-based magnetic fluid. Afterward, the movement of those particles was measured. Then, the water-based magnetic fluid was diluted by water to increase its optical strength. Considering that optical microscopes have diffraction-limited resolutions approaching 500nm in the lateral directions, the light scattered by nano-size particles were observed using the dark-field microscope system with oil immersion dark-field condenser lens made by Olympus U-DCW as shown in Fig. 2. In order to perform reliable observation, a high quality microscope designed with high numerical aperture, low field curvature, low distortion, and
corrected for spherical and chromatic aberrations is required. For this purpose, the universal plan Apochromat oil-immersion objective lens (Olympus UPLAPO 40XOI3PH) was selected for the microscope system (Olympus BX50) using 12V/100W halogen illumination source. In PTV measurement of a micro capillary flow, a 70μm micro capillary and a 20μm x 200μm x 50mm glass rectangular microchannel, fabricated by Wale apparatus Co. Inc, was mounted to a microscope slide as shown in Fig. 3. The rectangular microchannel was glued to a circular capillary tube. Plastic tubing connects the capillary tube to the syringe pump (KDS-100). The microchannel was then placed on microscope stage. The object plane was placed at approximately 10μm from the bottom of the 20μm thick micro-channel. A syringe pump was used to produce a 3.4μl/h and 5.1μl/h flows through the microchannel. The light passing through the dark-field condenser lens illuminates the sample with a high intensity cone shape. The cone-shaped light condenses at the sample from the side, such that the apex is in the field of view. Thus, the only scattered light on ferromagnetic nano-particles using the dark-field condenser lens gathers in the image. Moreover, the space between condenser lens and microchannel was filled with matching oil, which was the same refractive index as glass. The optical precision was enhanced. The microscope magnification of 400 or 1000 times images were detected by a CCD camera (NEPTUNE-100) installed on the microscope. The scattered speck images from ferro- and non-magnetic particles were recorded on the memory. Digital images recorded on the memory of the camera were taken into a personal computer at 640×480 pixels definition (bitmap format). The analysis of particle image was done using Particle Tracking Velocimetry (PTV). The PTV is one analytical technique of the image treatment way velocity meters and is used for the measurement of the micro-capillary flow. It is a well-established technique utilized to measure fluid/particle velocity fields [6]. The technique is based on the measurement of small particles displacement agitated by the Brownian motion. The non-magnetic particle with different diameter from the magnetic nanoparticle was mixed with the 5% weight concentration of water-based magnetic fluid. Then, the movement of those particles in micro-capillary flow was measured. Diameters of particles added in a water-based magnetic fluid were 500nm (Duke Scientific Co.). A non-uniform magnetic field was applied in a span-wise direction to the micro-capillary flow using electromagnet. The applied magnetic field intensity was controlled by changing the DC current up to 5A that allowed a magnetic field of 133mT.

3 Results and Discussions

Using the dark-field microscope system, a high-intensity scattering-light could be observed in the water-based magnetic fluid. Twinkling and randomly moving specks were also observable. These specks represented primary clusters as pointed out by Nakatani [3], since the dark-field observation could not allow the ferromagnetic nano-particle with a diameter smaller than 10nm. Figure 4 shows the vector field of non-magnetic particles with 10 frames with a rate of 30 fps, analyzed by the PTV in the water-based magnetic fluid with 5% weight concentration of ferromagnetic nano-particles. The optical system was adjusted accordingly in order to catch the light scattered by only the non-magnetic particle. Velocity measurements were performed by recording two images of the
particles in a motion-field separated by a specified time delay. In Fig. 4, it is shown that each analyzed frame is resulted from two frames of particle motion. Although the numbers of particles were limited by the influence of the image’s contrast, the analysis results clarified that all the particles were satisfactorily observed in the image area. However, Fig.4 also shows that the random walk of each particles were observable in order to analyze the Brownian motion.

From the results of PTV analysis, velocity distribution of standard particle in a water-based magnetic fluid was obtained. Figure 5 shows the velocity distributions of the particles analyzed by the PTV. Figure 5 shows that the higher concentration results in lower velocity compared with the one at low concentration. The difference is caused by the difference of viscosity of the water-based magnetic fluid. Fig. 5 (a) shows the mean velocity of 3.98μm/sec, and Fig. 5 (b) shows the mean velocity of 11.59μm/sec. From this fact, it was confirmed that the Brownian motion in a magnetic fluid depends upon the concentration of ferromagnetic nano-particles.

The Brownian motion is one of the important aspects when utilizing a sub-micron particle to trace fluid field for velocity field measurement. The random mean square particle displacement \( s^2 \) associated with Brownian motion for frame interval \( t \) of the digital video camera is expressed as

\[
\langle s^2 \rangle = 2D\Delta t
\]  

where the Brownian diffusion coefficient \( D \), first derived by Einstein [7], is given as

\[ D = \frac{kT}{3\pi \mu l_p} \]  

(2)

Here, \( d_p \) is diameter of particles, \( k \) Boltzmann constant, \( T \) absolute temperature of the fluid, and \( \mu \) the viscosity of the fluid. Using equations (1) and (2), it is possible to evaluate the viscosity from measured velocity of the particle \( V \left(\frac{\langle s^2 \rangle}{\Delta t^2}\right) \), which calculated by PTV applying the following equation,

\[
\mu = \frac{2kT}{3\pi d_p V^2 \Delta t}
\]  

(3)

To verify the current viscosity of fluid evaluation using the equation (3), experiments were performed using the viscometer (Sibata Scientific Technology Ltd.). The Brownian motion intensified with the decrease in fluid’s viscosity. From the PTV result, the following...
Fig. 6. Relation between the PTV result and measured values in a water-based magnetic fluid (W-40+350nm)

figures are plotted based on the results of mean viscosity of fluid. Figure 6 shows the relation between the mean viscosity of fluid from equation (3) and the values of viscometer in a water-based magnetic fluid. In Fig.6, the measurement errors of this evaluation agreed with Eq. (3) within +/- 15%.

In the following experiment, real-time visualization of the ferromagnetic particle in the water-based magnetic fluid with 1% weight concentration in micro circular capillary was carried out. Firstly, in micro capillary flow using the capillary, an external magnetic field was applied in perpendicular to the micro capillary flow. Figure 7 shows the dispersion process of cluster formation in a water-based magnetic fluid in micro capillary flow after 120 seconds with applying a magnetic field. The time deviation between each dark-field image was t = 133 ms. The applied magnetic field strength was B = 75.5 mT. As the zero external magnetic field was applied, a chain-like cluster dispersed along the flow. From this visualization image, the instantaneous axial velocity distribution is calculated as shown in the Figure 8. The horizontal axis indicates span-wise position, and the vertical axis indicates instantaneous axial velocity. The black and white dots represent instantaneous axial velocity at t = 1/5 seconds and t = 4/5 seconds after releasing of the magnetic field, respectively. In addition, the triangle symbols represent instantaneous axial velocity right releasing of the magnetic field.

Secondary, in micro capillary flow using the rectangular micro channel, an external magnetic field was applied in perpendicular to the micro capillary flow. In this experiment, the growth processes of the cluster formation were observed in 3 kinds of magnetic flux density (46.5, 91.5, 133.0 mT). And the flow rate was set at 5.1 μl/h. Figure 9 shows the effect of a magnetic field on cluster formation in a water-based magnetic fluid in micro capillary flow after 60 seconds with applying a magnetic field. The stronger the magnetic field, the more the mean cluster length increased. Relation between mean cluster length and magnetic field in a water-based magnetic fluid in micro capillary flow is shown in Figure 10. From the Fig. 10, we can compare the mean cluster length with the flow rate of 3.4 μl/h and 5.1 μl/h. From this figure, it is found that the mean cluster length is slightly shorter, as increasing of the flow rate.

Thirdly, in micro capillary flow using the rectangular micro channel, an external magnetic field was applied in perpendicular unilateral direction to the micro capillary flow. The chain-like clusters moved to the side of the imposed magnetic field. About 2 minutes later, the
Fig. 8. Velocity profiles of micro capillary flow in a water-based magnetic fluid (W-40, 1w%, 75mT)

Fig. 9. Effect of a magnetic field on cluster formation in a water-based magnetic fluid in micro capillary flow (W-40, 1w%)

Fig. 10. Relation between the measured cluster length and the magnetic field in a water-based magnetic fluid in micro capillary flow (W-40, 1w%)

Fig. 11. Cluster formation in a water-based magnetic fluid in micro capillary flow applying unilateral magnetic field (W-40, 5w%+500nm)
cluster formation flowed at a certain position. Figure 11 shows that the cluster formation in the water-based magnetic fluid in micro capillary flows after about 180 seconds by applying the unilateral magnetic field. In this experiment, the standard particle was mixed with the water-based magnetic fluid with 5% weight concentration in order to increase the scattered light intensity from the particles. The flow rate was set at 3.4μm/h, and the applied magnetic field strength was B=133mT. From this result, the mean-axial velocity distribution of the rectangle microchannel flow was calculated as shown in the Figure 12. The black and white dots represent mean axial velocity without magnetic field and particle velocity distribution with applying magnetic field. In addition, the triangle symbols represent not only the mean axial velocity of cluster formation, but also the mean position and the mean cluster length by applying the magnetic field. By applying the magnetic field to the flow, the mean particle velocity decreased at the range of existing the cluster formation. Furthermore, at the particle velocity distribution was strongly affected by the cluster existence. In addition, the particle velocity distribution at the range of existing the cluster formation was higher than the cluster velocity. That is why the distance between the clusters was comparatively wide. As a result, the particle velocity distribution includes the higher particle velocity among the clusters.

4 Conclusions

Thermal behavior and fluid viscosity evaluation in a water-based magnetic fluid were investigated using an optical dark-field microscope system and PTV data processing system. Using the Einstein’s equation for Brownian motion, the mean viscosity of fluid compared with the values of viscometer in a water-based magnetic fluid. And then, the measurement errors of this evaluation agreed with equation within +/- 15%. In addition, the thermal behavior of ferromagnetic particles in micro capillary flow was observed though the micro visualization using an optical dark-field microscope system and PTV data processing system. The real-time observations of the motion of ferromagnetic particle in water-based magnetic fluids in micro capillary flow were carried out. Furthermore, the effect of a magnetic field on growth process and dispersion process of cluster formation in micro capillary flow was investigated.

References