Basic Study for the Controlling of the Dispersion and the Agglomeration of Magnetic Particles

H Nakamura, S Hashi and K Ishiyama
Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba 980-8577, Japan

ishiyama@riece.tohoku.ac.jp

Abstract. The effective way of controlling the dispersion and the agglomeration of the magnetic particles is desired for the medical treatment such as magnetic hyperthermia and drug delivery system using magnetic particles. In this study, we propose the principle of a new method of controlling them. If we use the magnetic particles with magnetic anisotropy, the particles can be rotated by the magnetic torque generated by the rotational magnetic field. When the rotating agglomerated particles are subjected to the fluid pressure, the agglomeration is parted into pieces and dispersed due to the increase of the drug force from the fluid. We found that it is important to control the Coulomb force between the particles by surface coating. As a basic study using the two magnetic particles, we confirmed the condition that the aggregated two small magnets get isolated experimentally with changing the thickness of the coating layer and the rotational frequency.

1. Introduction

Recently magnetic particles have been applied for medical field [1], [2]. They are expected to apply for magnetic hyperthermia treatment, drug delivery, magnetic markers, contrast enhancement for magnetic resonance imaging (MRI) and so on [3]. Magnetic particles that are applied for the human body need to be controlled their agglomeration and dispersion. For example, we need to agglomerate them at the affected area in drug delivery system not to diffuse medical agent, and after the treatment we also need to disperse them to prevent the magnetic particles from blocking the blood flow. In the previous works with isotropic magnetic particles such as magnetite and hematite, many surfactants and surface processing were proposed to prevent against the agglomeration. However magnetic particles cannot be dispersed finely because the manipulation using the magnetic gradient makes no force to separate the agglomerated particles. Therefore more effective way of dispersing magnetic particles is needed.

In this paper, we proposed a new method for the dispersion by using magnetic particles with magnetic anisotropy. In this case the particles can be rotated by the magnetic torque generated from the rotational magnetic field. Because the rotating agglomerated particles are subjected to the fluid pressure, the agglomeration is parted into pieces and dispersed due to the increase of the drug force. Moreover this way is positive because they are manipulated by external magnetic field. To confirm the dispersion of magnetic particles by the proposed way, as a basic study, we considered the isolation of two magnetic particles experimentally. We confirmed the condition that the aggregated two small
magnets get isolated experimentally with changing the thickness of the coating layer and the rotational frequency.

2. New method for dispersion

We proposed a new way of dispersing magnetic particles by using magnetic particles with magnetic anisotropy. In this case we can rotate each particle by magnetic torque generated by the rotational magnetic field. With increasing fluid resistance on the particle surface by increasing rotation velocity, the agglomerated particles are expected to be parted into pieces and dispersed finely by rotating each particle as shown in Fig. 1.

![Diagram of magnetic particles rotating in rotational magnetic field.](image1)

**Figure 1** Schematic of magnetic particles rotating in rotational magnetic field.

![Diagram of the force acting on magnetic particles when they rotate.](image2)

**Figure 2** Schematic of the force acting on magnetic particles when they rotate.

There are two important elements in dispersing two magnetic particles. One is to increase the fluid resistance by increasing rotation velocity as described above; the other is to control Coulomb’s force between two particles. In this study we attempted to control the Coulomb’s force by the thickness of the surface coating on the particles.

The principle of the isolation of the agglomerated particles is given as follows. The forces acting on particles in rotating are shown in Fig. 2. Coulomb’s force $F$ is acting between two particles and fluid resistance $F_L$ is acting in opposite direction from rotational direction. Because fluid resistance and Coulomb’s force are acting perpendicular to each other, we need to consider another force acting in opposite direction of fluid resistance. Therefore we assumed this force as static friction force $F_S$ on contacting surface between two particles. In the case that the fluid resistance $F_L$ becomes larger than the static friction force $F_S$, the agglomerated particles can be isolated because shearing force acts on particles’ contact surface and each particle rotates independently as a single magnetic material.

3. Experimental study

3.1. Experimental procedure

The Reynolds number $Re$, which is important element on fluid dynamics, is as follows.

$$Re = \frac{LU}{v}$$

(1)

where $L$ is characteristic linear a dimension of the body, $U$ is a representative velocity and $v$ is kinematic viscosity. Based on the Reynolds analogy rule, when Reynolds numbers are the same, the flow field distribution is qualitatively same. According to this theory, the motion of micrometer- or nanometer-sized magnetic particles can be estimated with the millimeter-sized magnets moved in high viscous fluid.
In this study, we used two small magnets whose diameters were 1.2 mm and high viscous silicone oil with a kinematic viscosity of $1 \times 10^5$ mm$^2$/s to simulate the micrometer-sized particles. Under these conditions, the Reynolds number is calculated as $4.7 \times 10^{-4}$, which is almost same as that for 1μm particle moving in the water. The 1.2mmφ NdFeB magnet was coated by 0.1mmφ zirconia balls in various thickness to control the Coulomb’s force between the magnets as shown in Fig.3. We put the magnets in silicone oil and applied rotational magnetic field of 16.0 kA/m by two-axis coils. We observed the motion of the aggregated two magnets with changing the thickness of coating layer $\delta$ and the rotational field frequency $f$. In addition, we use two kinds of magnet having different residual magnetization (Mr) to change the magnetic torque. Measured Mr by VSM was 0.66 T and 0.96 T. The Mr was controlled by changing the magnetizing field for the magnets.

3.2. Experimental results

The motions of the magnets were observed with changing $\delta$ and $f$. At the certain conditions, the two magnets were isolated and each magnet rotated independently. The conditions that the two magnets were isolated were shown by bars in Figs. 4 and 5. According to this figures, it was found that we could isolate two magnets by applying the rotational magnetic field. On the figure, two calculated lines were also shown. These lines were drawn under the conditions below [4].

1) The magnetic torque for aggregated two magnets is larger than the drag force, and the magnets can rotate in sync with the rotational field.

2) The fluid resistance $F_l$ (drag force from the fluid) is larger than the static friction force $F_s$.

In the Figs. 4 and 5, the area between two lines agrees with the condition. It was found that the experimental results fit for the condition; therefore the isolation of the particles in this experiment was done under the principles we proposed. Figure 6 shows the photo of the isolation of the magnets.

![Figure 3 Coated magnets](image)

**Figure 3** Coated magnets

![Figure 4 Motion of magnets and conditions for isolation in changing f and δ. Mr of the magnet was 0.66 T.](image)

**Figure 4** Motion of magnets and conditions for isolation in changing $f$ and $\delta$. Mr of the magnet was 0.66 T.

![Figure 5 Motion of magnets and conditions for isolation in changing f and δ. Mr of the magnet was 0.96 T.](image)

**Figure 5** Motion of magnets and conditions for isolation in changing $f$ and $\delta$. Mr of the magnet was 0.96 T.
5. Conclusion

We proposed a new way of dispersing magnetic particles and considered the isolation of two particles as a basic study. In the experiment with two small magnets, we confirmed that two magnetic particles were possible to be isolated and the isolation condition agreed well with the theoretical results. These results show that the proposed way is applicable to disperse magnetic particles. Furthermore, fabricating fine particles based on the condition shown in this paper, the dispersion of magnetic particles with rotational magnetic field is expected.

6. Reference

[1] Honda H 2001 *J. Magn. Soc. Jpn.* 25 1301
[2] Abe M and Handa H 2004 *J. Magn. Soc. Jpn.* 28 841
[3] Handa H, Abe M and Noda H 2006 *Biomedical and Environmental Applications of Functionalized Magnetic Beads* Tokyo CMC Publishing 85
[4] Nakamura H, Hashi S and Ishiyama K 2009 *J. Magn. Soc. Jpn.* 33 (to be published)