Study on magnetic separation of nanosized ferromagnetic particles

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Abstract. In recent researches in medicine and the pharmaceutical sciences, the magnetic separation technology using nanosized ferromagnetic particle is essential. For example, in the field of cell engineering, magnetic separation of nanosized ferromagnetic particles is necessary, but separation technology of nanosized particle using magnetic force has not been established. One of the reasons is that magnetic force acting on the object particles decreases as particle diameter becomes small, and makes magnetic separation difficult. In this study, magnetic force acting on the separation object was enlarged by the combination of superconducting magnet and the filter which consists of ferromagnetic particle. As a result of particle trajectory calculation and magnetic separation experiment, it was confirmed that the ferromagnetic particles of 15nm in diameter can be trapped in the magnetic filter under an external magnetic field of 0.5T. The ferromagnetic particles of 6nm in diameter which could not be separated under the same condition could also be trapped under 2.0T of external magnetic field.

1. Introduction

In recent researches in medicine and the pharmaceutical sciences, magnetic separation technology using nanosized ferromagnetic particle has gained importance [1]. In the field of cell engineering, nanosized ferromagnetic particles of several nanometers to 20nm in diameter is required, and magnetic separation technology of nanosized particle using magnetic force must be established [2−5]. However, magnetic force acting on the object ferromagnetic particle decreases as particle diameter becomes small, and makes magnetic separation difficult [6].

In this study, to enlarge magnetic force acting on the object ferromagnetic particles, we tried to design a magnetic filter consisting of densely packed ferromagnetic particles of 0.3mm in diameter in the glass tube of 4mm in inner diameter. First, two dimensional finite element model of the magnetic filter was constructed, and the magnetic field analysis and the fluid analysis were performed. Based on these results, the particle trajectory of the ferromagnetic particles of φ=6nm and φ=15nm in the vicinity of the magnetic filter were calculated by solving the dynamic equation of the object ferromagnetic particle in order to examine the possibility of magnetic separation. Next, to verify the
result of simulation, magnetic separation experiment of ferromagnetic particles of $\phi=6\text{nm}$ (FePt) [7] and $\phi=15\text{nm}$ (Fe$_3$O$_4$) using the developed filter was conducted, and possibility of separation in the actual system was studied.

2. Experiment

2.1. The magnetic field analysis and the fluid analysis of the magnetic filter

The distribution of magnetic field intensity and flow velocity distribution in the model calculated by using ANSYS® Ver.10.0 (ANSYS, Inc.) is shown in Figure 1. As shown in Figure 2, two dimensional finite element model was constructed based on maximum distance between two particles in three dimensional close-packed structure of spherical particle. Experimental conditions are shown below.

The maximum magnetic flux density at the center of coil were set to 0.5T and 2.0T, the particle diameter of the object ferromagnetic particles was set to 6nm and 15nm, the fluid was set to water (viscosity=1cP), and inflow velocity was set to 0.01m/s. The filter consisted of uniformly arranged ferromagnetic particles of 0.3mm in diameter (Figure 1).

![Figure 1. A schematic view of magnetic separation system.](image)

![Figure 2. The method of making two dimension model.](image)
2.2. Calculation of the particle trajectory of the ferromagnetic particles in the vicinity of magnetic filter

Magnetic force and drag force acting on the object particles were calculated based on the parameters obtained from the numerical analysis in each node using the magnetic field analysis and the fluid analysis using ANSYS. Motion equations of the object particles in the node using those forces were solved, the acceleration was calculated, and the next node was searched. The particle trajectory of the ferromagnetic particles in the vicinity of magnetic filter was calculated by repeating this operation.

2.3. Synthetic procedure of nanoparticles

FePt and Fe$_3$O$_4$ were supplied by Hitachi Maxell, Ltd.. The FePt nanoparticles were synthesized by reduction of platinum acetylacetonate and decomposition of iron pentacarbonyl in the presence of oleic acid and oleyl amine. The Fe$_3$O$_4$ nanoparticles were synthesized by the pyrolysis of iron carboxylate salts.

2.4. Magnetic separation experiment of nanosized ferromagnetic particles

To verify the result of simulation under 0.5T and 2.0T of external magnetic field in the experiments 2.1 and 2.2, magnetic separation experiment with actual the ferromagnetic particle was conducted. The developed magnetic filter was put under 0.5T and 2.0T of external magnetic field. Magnetic separation was performed by passing the fluid containing FePt (φ=6nm), Fe$_3$O$_4$ (φ=15nm) (Table 1) through the magnetic filter. The ferromagnetic particles were dispersed in n-hexane or toluene because nanosized particles are difficult to disperse uniformly in water. To measure the density of the ferromagnetic particles dispersed in organic solvent before and after the separation, the ferromagnetic particles were dissolved in 50% HCl after evaporating organic solvent, and measured by inductively-coupled plasma atomic emission spectrometry. The separation efficiency was estimated from change in the density of ferromagnetic particles.

| Materials | Particle diameter(nm) | Saturation magnetization(T) | Fluid(Viscosity) | Density(mg/ml) |
|-----------|-----------------------|-----------------------------|-----------------|---------------|
| Fe$_3$O$_4$ | 15                    | 0.408                       | toluene(0.6 mPa·s) | 0.1           |
| FePt      | 6                     | 1.144                       | n-hexane(0.3 mPa·s) | 0.15          |

3. Results and discussion

3.1. The magnetic field analysis and the fluid analysis of the magnetic filter

As a result of the magnetic field analysis, the magnetic flux density and the magnetic gradient are higher in oblique direction between particles compared with horizontal direction between particles under both 0.5T and 2.0T of external magnetic field. Moreover, the magnetic flux density increased towards outside of the glass tube (Figure 3a). From the result of the fluid analysis, fluid speed near the top of the particles is slowest, and that at the center between the particles in horizontal direction is fastest (Figure 3b).

These results predict that the accumulation rate of the object particles on the magnetic filter is the highest in the vicinity of obliquely upward area of the magnetic filter towards the direction of the flow.
3.2. Calculation of the particle trajectory of the ferromagnetic particles in the vicinity of magnetic filter

The particle trajectory of the ferromagnetic particles of $\phi=6\text{nm}$ and $\phi=15\text{nm}$ showed that the ferromagnetic particles of $\phi=15\text{nm}$ could be trapped in the magnetic filter under 0.5T of external magnetic field (Figure 4a). In contrast, the ferromagnetic particles of $\phi=6\text{nm}$ could not be trapped in the magnetic filter under 0.5T of external magnetic field (Figure 4b). However, when external magnetic field was set to 2.0T, the ferromagnetic particles of $\phi=6\text{nm}$ also could also be trapped in the magnetic filter (Figure 4c).

3.3. Magnetic separation experiment of nanosized ferromagnetic particles

To verify the result of simulation discussed above, magnetic separation experiment under 0.5T and 2.0T of external magnetic field using FePt ($\phi=6\text{nm}$) and Fe$_3$O$_4$ ($\phi=15\text{nm}$) which are dispersed in n-hexane or toluene was conducted. Fe$_3$O$_4$ ($\phi=15\text{nm}$) could be trapped in the magnetic filter under 0.5T of external magnetic field (Figure 5a). On the other hand, FePt ($\phi=6\text{nm}$) could not be trapped in the magnetic filter under 0.5T of external magnetic field (Figure 5b), but it could be trapped in the magnetic filter under 2.0T of external magnetic field (Figure 5c).
4. Conclusion
The possibility of the magnetic separation using nanosized ferromagnetic particles was considered by calculation of the particle trajectory of nanosized ferromagnetic particles examined and the magnetic separation experiments of ferromagnetic particles.

As a result of particle trajectory calculation and magnetic separation experiment, it was confirmed that the ferromagnetic particles ($\phi=15$nm) can be trapped in the magnetic filter consisting of densely packed ferromagnetic particles of 0.3mm in diameter in the glass tube of 4mm in inner diameter under 0.5T of external magnetic field. The ferromagnetic particles ($\phi=6$nm) which could not be separated under the same condition could also be trapped under 2.0T of external magnetic field.

In this study, it was confirmed that the ferromagnetic particles which could not be trapped under external magnetic field using permanent magnet become possible to separate by increasing external magnetic field using superconducting magnet.

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