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Simulation of Magnetic Fluid to Develop the Magnetic Chromatography for Magnetic Particle Separation

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A magnetic chromatography is a very useful system for an ion and/or fine magnetic particle separation. Recently, its performance has been enhanced using a superconducting magnet. The superconducting magnet can generate a high magnetic field and its strong magnetic field gradients in a very small flow channel. We have developed the magnetic chromatography system to separate the fine particles. However, its numerical simulation is difficult, since the scale of the fine magnetic particles in fluid is much different from the scale of the superconducting magnet generating the strong magnetic field. In order to accurately simulate the magnetic separation, it is necessary to develop the simulation code dealing with the multi-scale. The performance of the developed magnetic chromatography is evaluated by the developed simulation tool and it is clarified that it is unsuitable for magnetic particle separation. Therefore, a magnetic chromatography is newly designed and its performance is evaluated by the developed simulation tool.

Index Terms—**Ferrohydrodynamics, magnetic chromatography, magnetic separation, numerical simulation.**

I. INTRODUCTION

MANY MAGNETIC SEPARATION SYSTEMS with a superconducting magnet have been developed [1]–[3]. The superconducting magnet can generate a high magnetic field, and ferromagnets magnetized in the high magnetic field create strong magnetic field gradients. The strong magnetic field gradients attract magnetic particles in fluid to the ferromagnets. The magnetic separation technique using the magnetic field gradients is, however, unsuitable for separating magnetic particles with a very small radius (below 100 nm). The reason is that the magnetic force on the particles is relatively smaller than their diffusion force. On the other hand, the magnetic chromatography system is a very useful device. It utilizes the strong magnetic field gradients to separate the fine magnetic particles with different magnetic susceptibilities in a colloidal mixture [4]–[6].

We have developed a magnetic chromatography system to separate the fine magnetic particles [7]–[9]. In the developed magnetic chromatography, very thin ferromagnetic wires generating magnetic field gradients and force are located on the wall of the flow channel [8]. Therefore, the magnetic particles with a large magnetic susceptibility are extracted in the radial direction of the flow channel and concentrated on the ferromagnetic wires. The flow velocity around the ferromagnetic wires is drastically decreased to almost zero. However, the magnetic particles with a small magnetic susceptibility can go through the channel with weak attracting force.

In the developed magnetic chromatography, the ferromagnetic wires with width of 200 μm on magnetic column walls generate the strong magnetic field gradients. We had expected that the particles with a large magnetic susceptibility were extracted in the radial direction of the flow channel and concentrated around the channel wall, and the particles with a small magnetic susceptibility could go through the channel with weak attraction to the channel wall. In order to confirm the magnetic force attracting for the wall and the flow of the fine magnetic particles, we have developed the simulation code coupling the fluid dynamics and the electromagnetics. Previously, the simulation methods to deal with the fluid dynamics and the electromagnetics were already proposed [10]. However, in this paper, the magnetic moment method is employed, because it is suitable to simulate the magnetic field generated by the superconducting magnet whose size is much different from that of the magnetic chromatography. The magnetic field gradients generated by the developed magnetic chromatography are evaluated by the simulation.

II. MAGNETIC FLUID SIMULATION METHOD

A. Magnetic Field Simulation

On this study, the magnetic field simulation is solved by the magnetic moment method [11], [12], because the scale of the magnetic column is much different from that of the superconducting magnet. The magnetic moment method is more accurate than the domain method, such as the finite element method.

The governing equation of the magnetic field is as follows

$$-\frac{1}{4\pi}\int_V \left(\nabla'\cdot\boldsymbol{M}(\boldsymbol{r}')\right)\frac{\boldsymbol{r}-\boldsymbol{r}'}{\left|\boldsymbol{r}-\boldsymbol{r}'\right|^3}\mathrm{d}V' + \frac{1}{4\pi}\int_S\left(\boldsymbol{M}(\boldsymbol{r}')\cdot\boldsymbol{n}\right) \times\frac{\boldsymbol{r}-\boldsymbol{r}'}{\left|\boldsymbol{r}-\boldsymbol{r}'\right|^3}\mathrm{d}S' - \frac{1}{\chi_{\mathrm{m}}(\boldsymbol{r})}\boldsymbol{M}(\boldsymbol{r}) = -\boldsymbol{B}_{\mathrm{F}}(\boldsymbol{r}), \tag{1}$$

where ***r*** and ***r'*** are the position vector, χ_{m} is the susceptibility, and $\boldsymbol{B}_{\mathrm{F}}$ is the magnetic field generated by the superconducting magnet. The magnetic field strength $\boldsymbol{H}$ is obtained from

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$$\boldsymbol{H}(\boldsymbol{r}) = \frac{1}{\mu_0}\boldsymbol{B}_{\mathrm{F}}(\boldsymbol{r}) - \frac{1}{4\pi\mu_0}\int_V \left(\nabla'\cdot\boldsymbol{M}(\boldsymbol{r}')\right)\frac{\boldsymbol{r}-\boldsymbol{r}'}{\left|\boldsymbol{r}-\boldsymbol{r}'\right|^3}\mathrm{d}V' + \frac{1}{4\pi\mu_0}\int_S \left(\boldsymbol{M}(\boldsymbol{r}')\cdot\boldsymbol{n}\right)\frac{\boldsymbol{r}-\boldsymbol{r}'}{\left|\boldsymbol{r}-\boldsymbol{r}'\right|^3}\mathrm{d}S' - \frac{1}{\mu_0}\boldsymbol{M}(\boldsymbol{r}), \tag{2}$$

where μ_0 is the permeability in free space.

The magnetization of the fine magnetic particles in fluid is represented by [13]

$$\boldsymbol{M} = \phi M_{\mathrm{S}} L\left(\frac{\mu_0 m\left|\boldsymbol{H}\right|}{kT}\right)\frac{\boldsymbol{H}}{\left|\boldsymbol{H}\right|}, \tag{3}$$

where ϕ is the concentration of the magnetic particles, M_{S} is the saturation magnetization, L is the Langevin function, k is the Boltzmann constant, T is the absolute temperature, and $m=V_{\mathrm{P}}M_{\mathrm{S}}$. V_{P} is the volume of one magnetic particle. In this simulation, it is supposed that the magnetization is parallel to the magnetic field strength, so the internal angular momentum of the particles can be ignored. The magnetic susceptibility depends on the volume of magnetic particle. In this research, however, the applied magnetic field is so strong that the Langevin function L is almost 1.0. Consequently, the magnetization of the magnetic fluid is proportional to the concentration of the magnetic particles.

The magnetic force on fine magnetic particles is obtained by [12], [13]

$$\boldsymbol{F}_{\mathrm{mag}} = \mu_0\left(\boldsymbol{M}\cdot\nabla\right)\boldsymbol{H}. \tag{4}$$

where $\boldsymbol{F}_{\mathrm{mag}}$ is the magnetic force, and $\boldsymbol{M}$ and $\boldsymbol{H}$ are obtained from solving (1), (2) and (3).

B. Navier-Stokes Simulation

To compute the fluid velocity $\boldsymbol{v}$ in the narrow flow channel, the following Navier-Stokes equation is solved.

$$\rho\frac{\partial\boldsymbol{v}}{\partial t} + \rho\boldsymbol{v}\cdot\nabla\boldsymbol{v} = -\nabla p^{*} + \mu_0\left(\boldsymbol{M}\cdot\nabla\right)\boldsymbol{H} + \eta\nabla^2\boldsymbol{v}, \tag{5}$$

where ρ, p^* and η are the fluid density, the composite pressure and the coefficient of viscosity, respectively. The internal angular momentum of the particles is also ignored in (5). The Navier-Stoles equation is solved by the stabilized finite element method, i.e. the streamline upwind/Petrov-Galerkin and Pressure stabilizing/Petrov-Glerkin method [14].

C. Control Volume Simulation

The governing equation on the control volume is given by

$$\frac{\partial}{\partial t}\left(\rho\phi\right) + \nabla\cdot\left(\rho\boldsymbol{v}\phi\right) = \nabla\cdot\left(\Gamma\nabla\phi\right) + S, \tag{6}$$

where Γ and S are the scalar diffusion constant and the scalar source term, respectively. The fluid velocity $\boldsymbol{v}$ is obtained from solving (5). The concentration ϕ of the magnetic particles is obtained from solving (6). The concentration ϕ is fed back to compute the magnetization of the magnetic particle of (3). The ordinary finite element method is employed.

D. Magnetic Fluid Flow Simulation

For the flow simulation of the magnetic fluid in the narrow flow channel, the magnetic field, the Navier-Stokes and the control volume equations are solved sequentially. The common tetrahedral mesh is employed in the simulations. Fig. 1 shows the flowchart of the magnetic fluid flow simulation.

FIG. 1 HERE

The magnetization of the fine magnetic particles is computed from (1), (2) and (3), and then the fluid velocity is obtained from substituting the computed magnetization into (5). The concentration of the magnetic particles is computed from (6) with the computed fluid velocity. A series of simulations are repeated till the analysis time ends.

III. PREVIOUS MAGNETIC COLUMN

Fig. 2 shows the previously developed magnetic column, which was proposed and experimented in [6]–[9]. The height and width of the flow channel are 0.17 mm and 10 mm, respectively. The thin ferromagnetic wires of 0.2 mm in width are alternately located on the upper and lower walls of the flow channel. The superconducting magnet applies the magnetic field of 2.0 T to the magnetic column.

FIG. 2 HERE

Employing the developed magnetic column, it was difficult to separate the magnetic particles. To investigate the reason, the magnetic fluid flow is simulated by the developed simulation code mentioned above. As the result, it was observed that the magnetic fluid meanderingly flows with weak magnetic force for the ferromagnetic wires on the walls. Fig. 3 shows an example of the meandering fluid flow. The magnetic particle concentration distribution and the flow on the longitudinal cross-section are represented in Fig. 3.

FIG. 3 HERE

The magnetic force $\boldsymbol{F}_{\mathrm{mag}}$ given by (4) in the magnetic column is the cause of the meandering flow. Here, the magnetic field gradient $\nabla\boldsymbol{H}$ is generated by the thin ferromagnetic wires, and investigated to evaluate the performance of the magnetic column. Fig. 4 shows the distribution of the magnetic field gradients $\partial H_y/\partial y$ in the magnetic column, since the y component of magnetization is dominant due to applying the magnetic field in the y direction. As seen in Fig. 4, the direction of the magnetic field gradients alternately changes against the fluid flow. As the results, the previously developed magnetic chromatography has the low performance to separate the magnetic particles.

FIG. 4 HERE

IV. NEWLY DESIGNED MAGNETIC COLUMN

A. *Structure of the New Magnetic Column*

The previous magnetic column cannot generate the effective magnetic field gradients. Fig. 5 shows the newly designed magnetic column with ferromagnetic nano-wires. The wires are mode of nickel, the average diameter and length are 30 nm and 1.2 μm, respectively. The wires are located in right-triangular geometry configuration with distance of approximately 100 nm. The saturation magnetization of the ferromagnetic nano-wires was approximately 1.715 T in experiment when the over 1.0 T magnetic field parallel to the wires was applied.

FIG. 5 HERE

B. *Evaluation of Magnetic Field Gradients*

Fig. 6 shows the *y* component of the magnetic field gradient, since the *y* component of the magnetization of the magnetic particles is dominant. Fig. 6(a) and (b) show the color contour mapping with linear scale and the contour lines with exponential, respectively. The maximum value of the magnetic field gradient is approximately 1.13×10^{11} A/m^2, it is high enough to capture the magnetic particles.

FIG. 6 HERE

Before manufacturing the newly designed magnetic column, it is necessary to evaluate the distribution of the magnetic field gradients. As seen in Fig. 6(b), on the flow channel far from the walls, the positive value of the magnetic field gradients is observed in the upper part. On the other hand, the negative value is observed in the lower part. It is achieved that the magnetic particles attract for the upper or lower walls. However, near the walls, the magnetic field gradients changes alternately. On the surface of ferromagnetic nano-wire the attractive force works for the magnetic particles, but the repulsive force on the other surface of the walls. Fig. 7 shows the conceptual magnetic fluid flow and the magnetic forces. As the result, due to the low magnetic field gradients it is difficult to separate the magnetic particles by the newly designed magnetic column. However, if the distance between the ferromagnetic nano-wires shortened, the area of the magnetic repulsive forces could be decreased.

FIG. 7 HERE

By developing the magnetic fluid simulation code, it is possible to evaluate the performance to separate the magnetic particles before manufacturing a new magnetic column.

V. CONCLUSION

We have manufactured the magnetic column to separate the magnetic particles. However, the performance of the manufactured magnetic column is not high. Therefore, we have developed a new simulation code taking into account the magnetic field, the Navier-Sotkes and the control volume equations. By the simulation, the meandering flow of the magnetic fluid with weak magnetic force was observed in the manufactured magnetic column.

Accordingly, we have newly designed a magnetic column with ferromagnetic nano-wire to generate effective magnetic field gradients, and investigated the distribution of the magnetic field gradients. The magnetic forces directed to the walls are generated far from the walls, however, the magnetic forces alternately change near the surface of the wall. It is difficult to capture the magnetic particles on the walls. To enhance the performance, the distance of the ferromagnetic nano-wires should be investigated. In addition, it is necessary to investigate the performance of the newly designed magnetic column in experiments.

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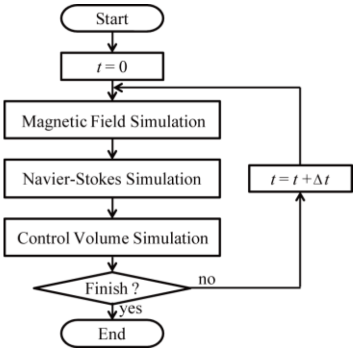
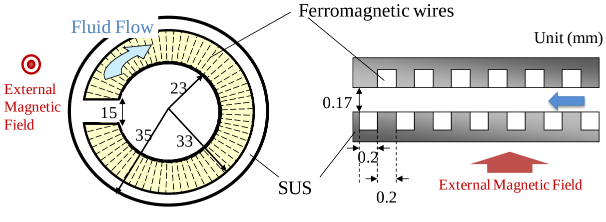


Fig. 1. Flowchart of the developed magnetic fluid flow simulation. The magnetic field, the Navier-Stokes and the control volume equations are solved in each time-step.



Top View

Cross Sectional View

Fig. 2. Schematic view of the previously developed magnetic column. The height and width of the flow channel is 0.17 mm and 10 mm, respectively. The thin ferromagnetic wires of 0.2 mm in width are vertically and alternately located against the flow direction with 0.2 mm apart.

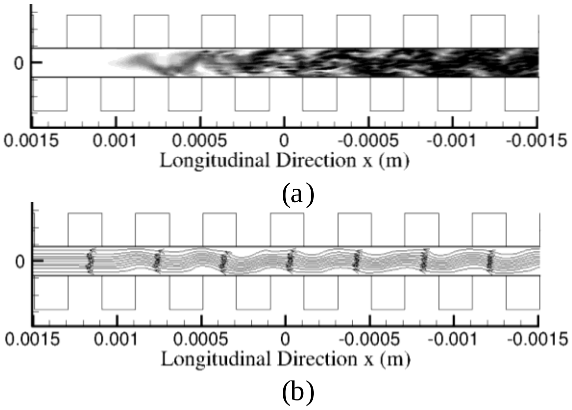


Fig. 3. The simulation results of the magnetic fluid flow by the developed simulation code. (a) the concentration distribution of the magnetic particles and (b) the meandering magnetic fluid flow.

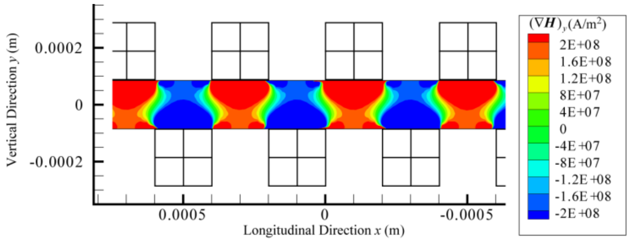


Fig. 4. The distribution of the magnetic field gradients in the flow channel of the previous magnetic column.

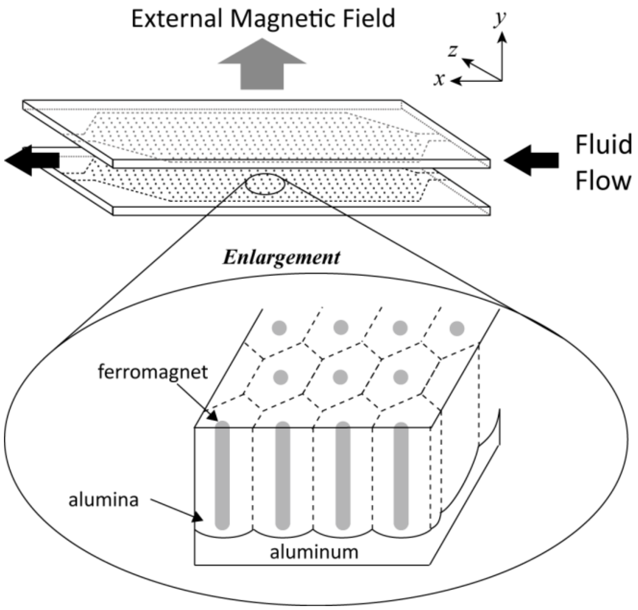


Fig. 5. The schematic view of the newly designed magnetic column. The ferromagnetic nano-wires are located in right-triangular geometry configuration, their distance is approximately 100 nm.

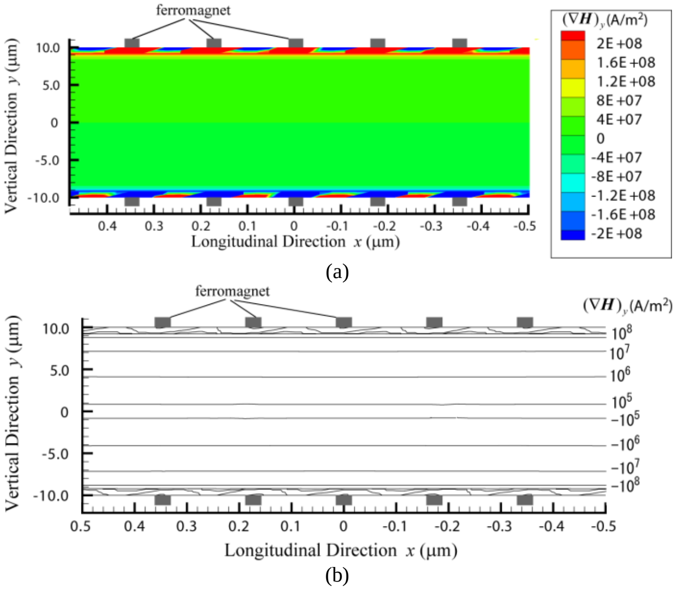


Fig. 6. The distribution of the magnetic field gradients in the flow channel of the newly designed magnetic column. (a) the color contour mapping with linear scale, and (b) the contour lines with exponential.

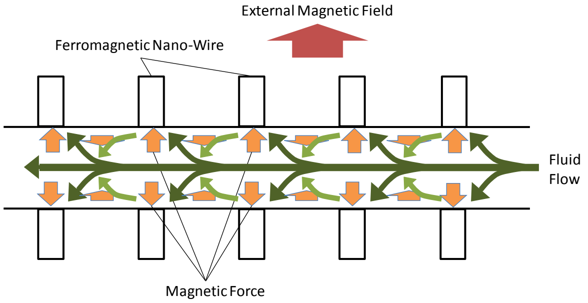


Fig. 7. The concept view of the magnetic force and the fluid flow in the flow channel of the newly designed magnetic column.