Magnetic Field Gradients and Fluid Flow Computation for Design of Magnetic Chromatography to Separate Magnetic Particles

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Abstract — Magnetic chromatography is an effective system for fine magnetic particle separation due to strong magnetic field gradients. We have developed the magnetic chromatography system to separate the fine magnetic particles. To develop the system, we have also developed the simulation code taking into account the fluid dynamics and electromagnetics, and evaluated the performance of the developed magnetic chromatography. However, the developed magnetic chromatography has a low performance on the magnetic particle separation. Therefore, we have designed a new magnetic chromatography and it is evaluated using the developed simulation code.

I. INTRODUCTION

Magnetic separation is a useful system for separating fine magnetic particles due to strong magnetic field gradients in a very small flow channel. Therefore, various magnetic separation systems have been developed. We have also developed a magnetic chromatography system to separate the fine magnetic particles [1]-[2]. In the developed magnetic chromatography system, ferromagnetic wires with width of 200 μm, that generate the magnetic field gradients, are located on the upper and lower walls. 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 [2]. Consequently, the meandering fluid flow with weak magnetic force attracting for the wall was observed.

In this paper, the magnetic field gradients generated by the previous magnetic chromatography are evaluated by the developed simulation code. Moreover, a new magnetic chromatography system is designed, and there are many nano-wires on the walls to generate the magnetic field gradients. The magnetic field gradients of the newly designed magnetic chromatography are also investigated by the simulation.

II. MAGNETIC FORCE

The governing equation of the magnetic fluid flow is the Navier-Stokes equation

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\nabla p^* + \mu_0 \left(\boldsymbol{M} \cdot \nabla \right) \boldsymbol{H}, \qquad (1)$$

where $\boldsymbol{v}$, p^*, μ_0, $\boldsymbol{M}$ and $\boldsymbol{H}$ are the fluid velocity, the composite pressure, the permeability in free space, the magnetization of the fluid and the magnetic field strength, respectively. The magnetic force attracting for the magnetic particles is represented by the last term on the right hand in (1).

In this paper, the magnetic field is computed using the magnetic moment method, since the scale of the magnetic fluid is much different from that of the superconducting magnet. In order to investigate the performance of the magnetic chromatography, the magnetic force

$$\boldsymbol{F}_{mag} = \mu_0 \left(\boldsymbol{M} \cdot \nabla \right) \boldsymbol{H} \qquad (2)$$

is evaluated. Here, the magnetization of the magnetic particle is given by

$$\boldsymbol{M} = \phi M_S L \left(\frac{\mu_0 m |\boldsymbol{H}|}{kT} \right) \frac{\boldsymbol{H}}{|\boldsymbol{H}|}, \qquad (3)$$

where ϕ is the concentration of the magnetic particles, M_S the saturation magnetization, L the Langevin function, k the Blotzmann constant, T the absolute temperature, and $m=V_p M_S$, where V_p is the volume of a magnetic particle. The magnetic susceptibility is dependent on the size of magnetic particle, however, in the paper, the magnetic field is so strong that the Langevin function L becomes almost 1.0. That is, the magnetization of the magnetic fluid is proportional to the concentration of the magnetic particles.

Consequently, the magnetic force F_{mag} is strongly dependent on the gradients of the magnetic field and the concentration of the magnetic particles.

III. EVALUATION OF THE OLD MAGNETIC COLUMN

The magnetic field gradients of the previously developed magnetic column, as shown in Fig. 1, are investigated. A strong magnetic field (2 T) was applied to it by a superconducting magnet. Here, Fig. 2 shows the magnetic fluid flow obtained by the developed simulation code. However, it cannot capture the magnetic particles on the wall, since the magnetic fluid meanderingly flows with weak magnetic force onto the walls. Thus, Fig. 3 shows the distribution of the magnetic field gradients $\frac{\partial H_y}{\partial y}$ 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. 3, the direction of the magnetic field gradients alternatively changes against the flow. As the result, the magnetic force also alternatively changes, and it is difficult to attract the magnetic particles onto the walls. It was confirmed that the previously proposed magnetic column was unsuitable for the magnetic separation.

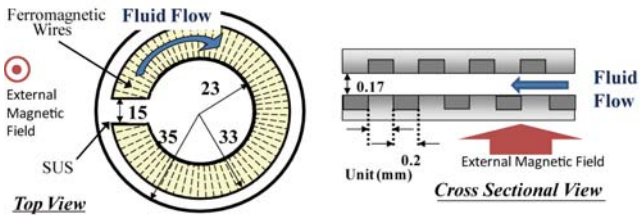

Fig. 1. Schematic view of the old magnetic column.

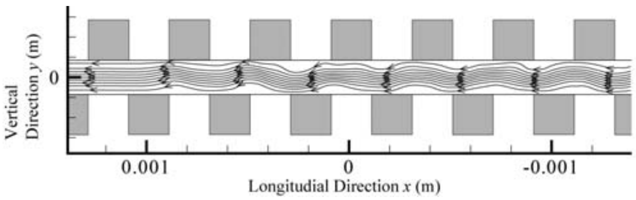

Fig. 2. Meandering Magnetic fluid flow simulated by the developed code.

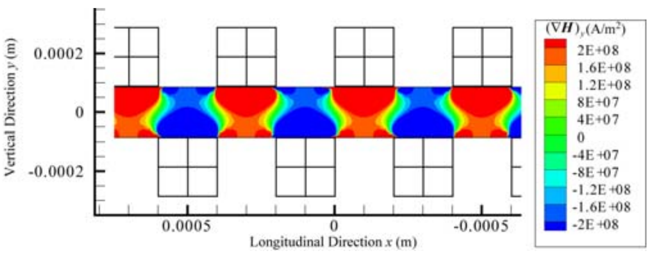

Fig. 3. Distribution of the magnetic field gradients.

IV. DESIGN OF A NEW MAGNETIC COLUMN

We have newly designed a magnetic column with many ferromagnetic nano-wires, as shown in Fig. 4. The wires are made of nickel, and the diameter and length are 30 nm and 1.2 mm, respectively. The wires are arranged in right-triangular geometry configuration, their distance is 100 nm. The saturated magnetization of the wire was approximately 1.715 T in experiment when the over 0.1 T magnetic field was applied in parallel to the wire.

The magnetic field gradients in the flow channel of the new magnetic column are computed on condition that the 2 T external magnetic field is applied. Fig. 5 shows the distributions of the magnetic field gradients $\frac{\partial H_y}{\partial y}$. Figs. 5 (a) and (b) show the color contour mapping with linear scale and the contour lines with exponential. The maximum value of the magnetic field gradient is $1.13{\times}10^{11}$ A/m^2, it is high enough to capture the magnetic particles. The magnetic field gradients become exponentially high near the upper and lower walls. As the result, it is expected that the fluid flows for the walls and the magnetic particles are effectively captured, as shown in Fig. 6.

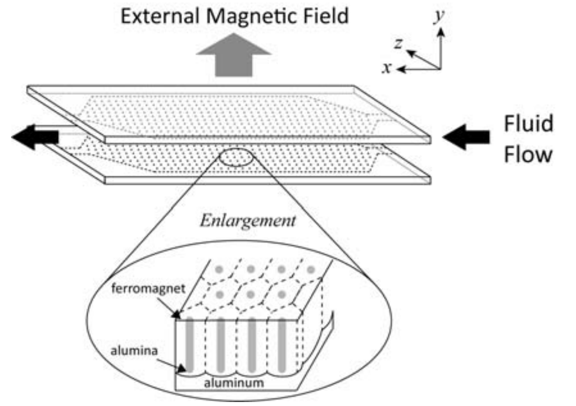

Fig. 4. Schematic view of the newly designed magnetic column.

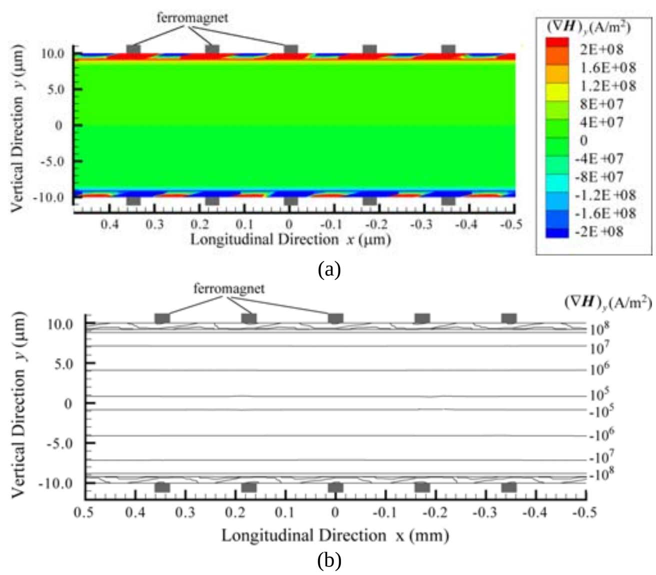

Fig. 5. Distributions of the magnetic field gradients. (a) the color contour mapping with linear scale (b) the contour lines with exponential scale.

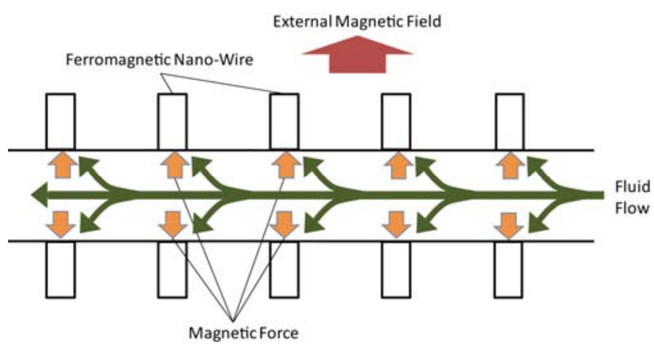

Fig. 6. Magnetic fluid flow in the newly designed magnetic column and the magnetic forces.

V. REFERENCES

[1] S. Noguchi, S. B. Kim, and K. Kataoka, “Development of Numerical Analysis Method for Magnetic Separation of Magnetic Particle and Ion with Magnetic Chromatography,” *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 961-964, Jun. 2010.

[2] S. Noguchi, and S. B. Kim, “Development of Numerical Simulation Method for Magnetic Separation of Magnetic Particles,” *Proc. 14th Bienn. IEEE Conf. on Electromagnetic Field Comp.*, Chicago, 2010.

[3] R. E. Rosenweig, *Ferrohydrodynamics*, Dover Publications, Inc., 1997.