Investigation on Novel Magnetic Chromatography with Ferromagnetic Nano-Wires for Ion Separation

So Noguchi and SeokBeom Kim

Abstract—**Magnetic chromatography is a very useful system for ion and/or fine magnetic particle separation due to strong magnetic field gradients in a very small flow channel. We have developed the magnetic chromatography system to separate the ions and fine particles. It is, however, difficult to separate the ions or the magnetic particles using the developed magnetic chromatography. It makes the strong magnetic field gradients in the flow channel, but the alternate direction of the gradient is not suitable for magnetic separation. Therefore, we have newly designed a novel magnetic column with ferromagnetic nano-wires. In this paper, the new magnetic column is presented, and the magnetic field and its gradients in the flow channel are investigated.**

Index Terms—**Ferrohydorodynamics, magnetic separation, magnetic chromatography.**

I. INTRODUCTION

MAGNETIC magnetic separation is a very useful system for ion and/or fine magnetic particle separation due to strong magnetic field gradients in a very small flow channel. Therefore, various magnetic separation systems have been developed and presented. The high gradient magnetic separation techniques, using superconducting magnets to apply the high magnetic field, were proposed [1]–[4]. However, the high gradient magnetic separation techniques are not useful in separating the ions or the magnetic particles with very small radius (below 100 nm). The reason is that the magnetic force of the particles is relatively smaller than their diffusion force. On the other hand, the magnetic chromatography system is a very useful device that uses the strong magnetic field gradients for separating ions or magnetic particles with different magnetic susceptibilities in a colloidal mixture [5]–[7].

We have developed a magnetic chromatography system to separate the ions and fine magnetic particles [8]–[10]. In the developed magnetic chromatography system, ferromagnetic wires with width of 200 μm, that generate the magnetic field gradients, are located at the upper and lower walls [9]. Therefore, we have 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. Thus, the distribution of concentration in the radial direction would be different and the exhaustion time different as well. In order to confirm the magnetic force attracting for the wall and the flow of the ions and magnetic particles, we have developed the simulation code coupling the fluid dynamics and the electromagnetics [10], [11]. As the result, the meandering fluid flow with weak magnetic force attracting for the wall was observed.

In this paper, at first, the magnetic field gradients generated by the old magnetic chromatography, that was presented in the papers [8]–[10], were evaluated. Moreover, a new magnetic chromatography system is proposed, there are many nano-wires on the walls to generate the magnetic field gradients. In addition, the height of the flow channel is also investigated.

II. MAGNETIC FORCE

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

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

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 [12], [13]. The magnetic force is represented by the last term on the right hand in (1).

In this paper, the magnetic field $\boldsymbol{H}$ is obtained using the magnetic moment method [10], [11], 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 $\boldsymbol{F}_{mag}$ is evaluated, that is, the gradient of the magnetic field $\nabla \boldsymbol{H}$ is the most important factor.

III. PREVIOUS MAGNETIC CHROMATOGRAPHY

The magnetic chromatography system was previously proposed and tested [7]–[10]. The magnetic column is shown in Fig. 1, and a strong magnetic field was applied to it by a superconducting magnet. The height and width of the flow

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channel are 0.17 mm and 10 mm, respectively. The ferromagnetic wires of 0.2 mm in width are vertically and alternately located on the upper and lower walls with 0.2 mm apart. However, it was difficult to stably separate ions or magnetic particles. Therefore, the simulation code considering fluid dynamics and electromagnetics has been developed in order to investigate the fluid flow [10], [11]. As the result, it was observed that the magnetic fluid meanderingly flows with weak magnetic force onto the walls. An example of the meandering fluid flow obtained by the simulation is shown in Fig. 2 [11].

The magnetic force $\boldsymbol{F}_{mag}$ causing the meandering is given by [12], [13]

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

Here, the magnetization $\boldsymbol{M}$ of the magnetic particle or the ion is excited by the superconducting magnet. On the other hand, the magnetic field gradient $\nabla \boldsymbol{H}$ is generated by the ferromagnetic wires on the walls. Therefore, the magnetic field gradient $\nabla \boldsymbol{H}$ is investigated to evaluate the performance of the previously proposed magnetic chromatography system. The y component of magnetic field gradient is shown in Fig. 3, since the y component of magnetization is dominant due to applying the magnetic field in y direction by the superconducting magnet. As seen in Fig. 3, the direction of the magnetic field gradient alternatively changes against the flow. The magnetic force also alternatively changes as shown in Fig. 4. As a result, it is difficult to attract the ions and magnetic particles onto the walls. The previously proposed magnetic column is unsuitable for the magnetic separation.

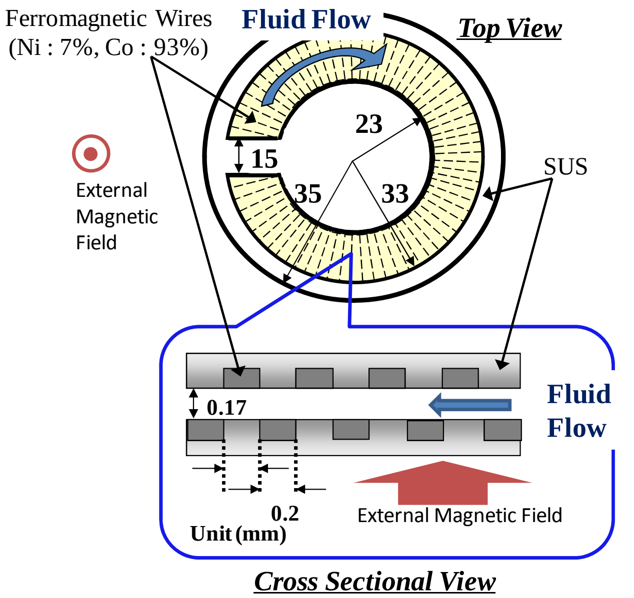

Fig. 1. The schematic view of the magnetic column and the flow channel of 0.17 mm in height and 10 mm in width. The fine ferromagnetic wires of 0.2 mm in width are vertically and alternately arranged against the flow direction with 0.2 mm apart.

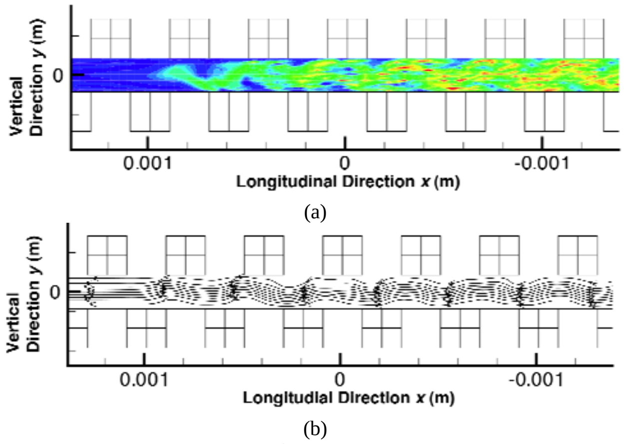

Fig. 2. (a) the concentration of the magnetic particles on the vertical cross-section of the flow channel and (b) fluid flow. The largely meandering flow is observed.

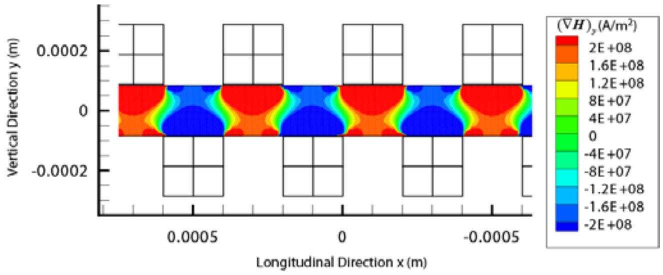

Fig. 3. The vertical y component of magnetic field gradient.

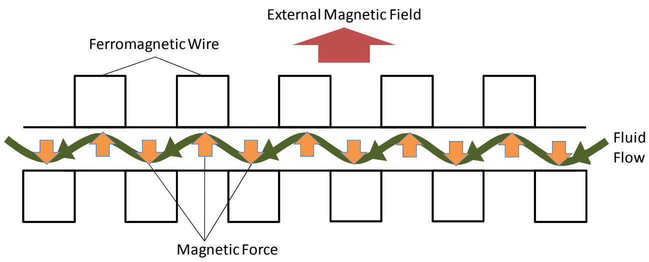

Fig. 4. The concept view of the magnetic force and the fluid flow.

IV. New Magnetic Chromatography

A. *Design of Magnetic Chromatography*

The previously proposed magnetic chromatography [8]–[10] can't generate the effective magnetic field gradients. Therefore, we have newly designed a magnetic chromatography with ferromagnetic nano-wires, as shown in Fig. 5. The wires are made of nickel, the average diameter and length are 30 nm and 1.2 μm, respectively. The wires are arranged in right-triangular geometry configuration, their distance is approximately 100 nm. The saturated magnetization of the wire was approximately 1.715 T in experiment when the over 0.1 T magnetic field parallel to the wire was applied.

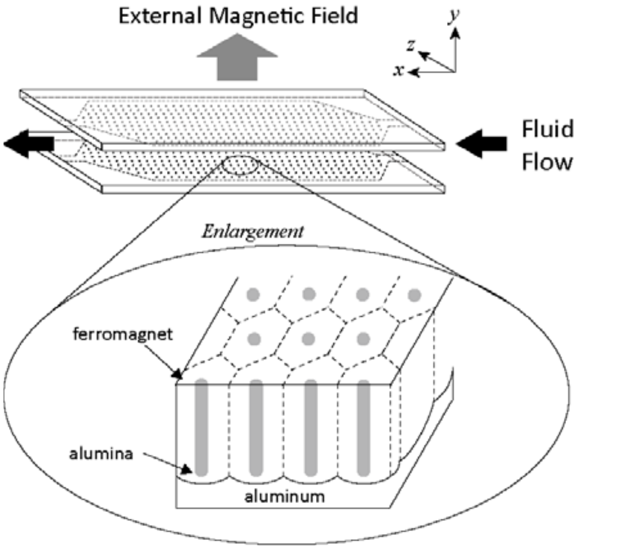

Fig. 5. The schematic view of the newly developed magnetic column. The ferromagnetic wires are arranged in right-triangular geometry configuration, its distance is approximately 100 nm.

B. *Magnetic Field Evaluation*

The magnetic field in the flow channel of the new magnetic column mentioned above is computed on condition that the 2 T external magnetic field is applied by the superconducting magnet. The computed distribution of the magnetic field is shown in Fig. 6, where the height of the flow channel is 20 μm. Fig. 6(a) shows the magnetic field on the top wall of the flow channel, Fig. 6(b) on the transverse cross-section of the flow channel.

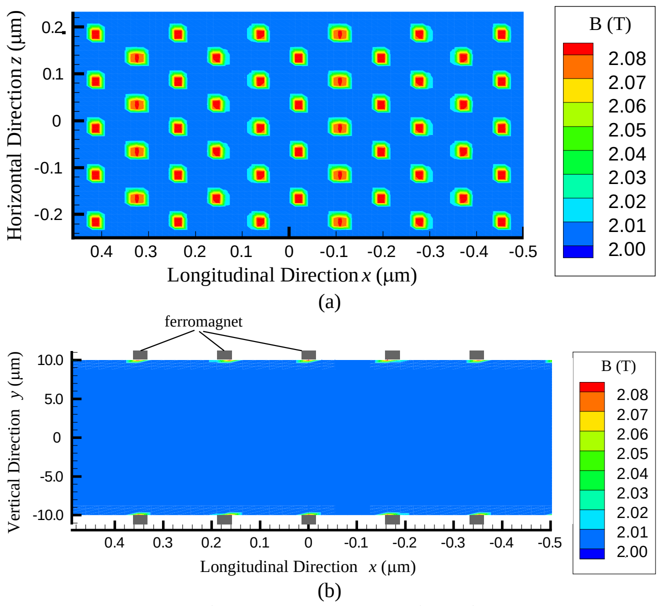

Fig. 6. The magnetic field on the top wall of the flow channel and the transverse cross-section of the flow channel.

The *y* component of magnetic field gradient is shown in Fig. 7, since the *y* component of magnetization of the ion is dominant. Figs. 7(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 1.13×10^{11} A/m^2, it is high enough to capture the ions or magnetic particles. However, the area with high magnetic field gradient is too narrow, as compared with the previous magnetic chromatography. As seen in Fig. 7(b), the magnetic field gradient becomes exponentially high near the upper and lower walls. Therefore, it is expected that the fluid flows for the walls, as shown in Fig. 8. However, the magnetic field gradients and the magnetic forces around the center of the flow channel are relatively small, that is, the suitably long flow channel of the newly proposed magnetic chromatography is needed.

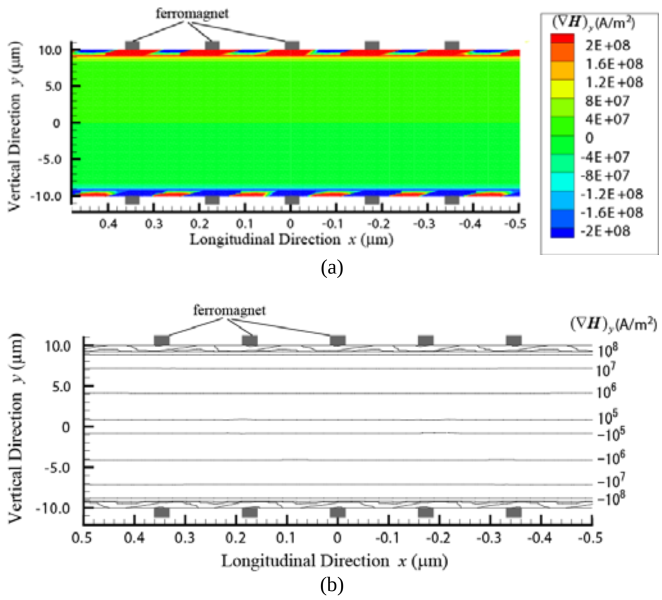

Fig. 7. The *y* component of the magnetic field gradient. (a) the color contour mapping with linear scale, and (b) the contour lines with exponential.

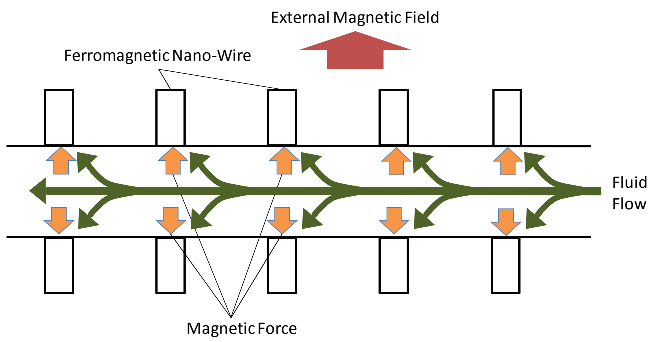

Fig. 8. The concept view of the magnetic force and the fluid flow in the flow channel of the newly proposed magnetic chromatography system.

C. *Height of the Flow Channel*

The performance of the magnetic chromatography is strongly dependent on the height of the flow channel. Of course, the lower it is, the stronger the magnetic force attracting for the walls is. So the magnetic field gradients are investigated on the different heights of flow channel. In this paper, the evaluation functions *f*(*e*) is defined as

$$f(e) = 1 - \frac{l_e}{L}, \qquad (3)$$

where L is the height of the flow channel and l_e is the distance between $\nabla \boldsymbol{H} = \pm 10^e$ A/m^2, as shown in Fig. 9. Fig. 10 shows the plots of the evaluation function $f(e)$ when e = 5, 6, 7 and 8. From Fig. 10, when the height of the flow channel is over 100 μm, the area of the high magnetic field gradient is too narrow. On the other hand, it becomes drastically wide when the height is below 20 μm. However, it is difficult to manufacture the magnetic chromatography with the extremely low flow channel. Therefore, when the flow channel is relatively high, the long flow channel is required.

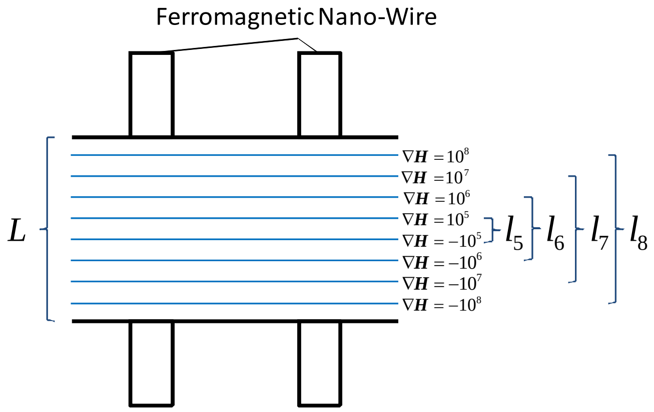

Fig. 9. The evaluation function of the magnetic field gradients.

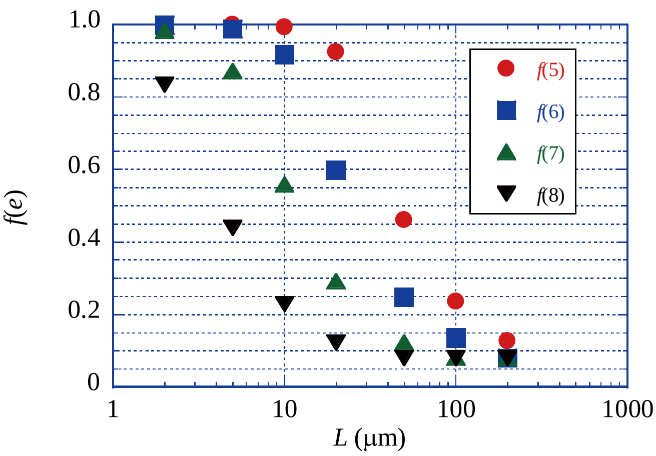

Fig. 10. The evaluation function value with the different height of the flow channel.

V. Conclusion

We have previously developed the simulation code coupling the fluid dynamics and the electromagnetics [10], [11] to investigate the behavior of the magnetic fluid inside the flow channel of the magnetic column. However, the performance of the magnetic column previously proposed in [8]–[10] was unexpected for use of the magnetic chromatography. Therefore, in this paper, the magnetic field gradient inside the flow channel was investigated. As the result, it was confirmed that it alternatively changed against the flow and the magnetic fluid meanderingly flowed with weak magnetic force onto the walls of the flow channel.

The previously proposed magnetic chromatography [8]–[10] couldn't generate the effective magnetic field gradients. Therefore, we have newly designed the magnetic chromatography with ferromagnetic nano-wires. It can generate the effective magnetic field gradients by which the ions attract onto the wall of the flow channel. Moreover, the relation between the flow channel height and the magnetic field gradient was clarified. If the flow channel is too high, the magnetic field gradient around the center of the flow channel is small. In that case, the long flow channel is required.

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