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Research and development of new magnetic filter for high gradient magnetic separation

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Abstract

We have been developing a new magnetic filter so that small sized paramagnetic substances can be separated even in a low magnetic field (lower than 2T). The developed filter is a packed ferromagnetic filament with a triangular cross section. The filament has a diameter of 120 μm and a length of 3 mm, and is mechanically packed with a volume ratio of 17.6%. Using this filter, a magnetic separation experiment of hematite was carried out using a superconducting magnet at the field of 2T. Similarly, magnetic separation was performed using a conventional magnetic filter. It became clear that the separation efficiency of newly developed filter is high as that of conventional mesh filter. The smaller sized hematite (<3 μ m) could be separated though conventional mesh filter could not separate.

Keywords: magnetic filter, high gradient magnetic field, triangular cross sectional filament, hematite

1. INTRODUCTION

We have been developing a high gradient magnetic separation system (HGMS), and this method is expected to be applied in various fields because it is possible to separate suspended particles from the suspension medium at high speed and in large quantities with high efficiency. The magnetic separation for paramagnetic materials has been paid particular attention in the series of works. This is because it can be expected to be used in a wide range of applications, such as decontamination of soil [1-2], scale removal [3-4], wastewater treatment [5], abrasive recovery [6], and phosphorus recovery [7]. We are particularly interested in the magnetic separation of paramagnetic micro-particles with a diameter of several μm or less in relatively low magnetic fields (below 2 T). A magnetic filter that creates a high gradient magnetic field is thought to be an important factor for this realization, and the research and development on a magnetic filter for separation of paramagnetic substances has being conducted [8].

In the previous work, a magnetic filter with a triangular cross section was developed and reported that its separation performance was found to be better than the conventional one [8]. It was demonstrated the possibility of separating paramagnetic particles with a Halbach magnet (empirical magnetic field strength of 0.8T).

In this work, a more versatile magnetic filter with a triangular cross section was used and carried out magnetic separation experiments on hematite under 2 T using a superconducting magnet. As a result, it became clear that even small sized hematite particles can be separated magnetically and demonstrating the practicality of the magnetic filter developed.

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2. PRINCIPLE OF HGMS

A high-gradient magnetic separation method generally refers to a method of separating a suspended substance from a suspension using a magnetic force. The separation efficiency is determined by the magnitude relationship between the drag force from the suspension and the generated magnetic force.

A drag force is a that acting on particles as the particles flow, and usually acts to push suspended particles away. Therefore, the magnetic force must exceed the drag force for magnetic separation. The drag force is proportional to the radius of the particle and proportional to the velocity difference between the particle and the suspension as formula (1).

$$\mathbf{F}_D = 6\pi\eta r_p(\mathbf{v}_f - \mathbf{v}_p) \tag{1}$$

where $\mathbf{F}_d$ is the drag force, r_p is the radius of a spherical particle, η is the viscosity of the suspension medium, $\mathbf{v_f}$ and $\mathbf{v_p}$ are the velocity of the suspension medium and the particle velocity, respectively.

On the other hand, the magnetic force is determined by the product of the suspended particle volume and magnetization as well as the magnetic gradient as shown by formula (2).

$$\mathbf{F}_m = V(\mathbf{M} \cdot \nabla)\mathbf{H} \tag{2}$$

where $\mathbf{F}_m$ is the magnetic force, $\mathbf{M}$ is the magnetization, and $\mathbf{H}$ is the external magnetic field. All represented by vectors.

The larger the volume of the object, the stronger the magnetic force, also, the larger the magnetization of the suspended particles, the larger the magnetic force result in easy separation magnetically. In a given magnetic field, a ferromagnetic material has a large magnetization and a large magnetic force is induced. It can be seen that in a paramagnetic or a diamagnetic material, a large external magnetic field is needed to increase the magnetization. This is the reason why the high external magnetic field is needed when a paramagnetic material is targeted.

On the other hand, when considering practical use, there is a demand to keep the magnetic field strength low ($B < 2T$).

Therefore, it becomes important to control the magnetic field gradient, which is another element of the magnetic force. Equation (3) shows the x-direction component of equation (2), and it can be seen from this equation that the magnetic gradient is directly involved in the magnetic force.

$$F_x = V\left(m_x \frac{\partial H_x}{\partial x} + m_y \frac{\partial H_y}{\partial x} + m_z \frac{\partial H_z}{\partial x} \right) \tag{3}$$

It can be understood that it is necessary to create a large magnetic gradient in order to magnetically separate fine paramagnetic particles in a space with a low external magnetic field.

The high gradient magnetic field is created by arranging a ferromagnetic wire in the magnetic field space and realizing the high gradient field near the wire, which is called a magnetic filter. Different from ordinary mesh filters, particles can be separated by magnetic force even with large mesh size, and pressure loss can be reduced and high-speed, large-scale processing is possible.

In order to actually separate them, a magnetic force sufficiently larger than the drag force expressed by Equation (1) is required. Assuming a spherical object and comparing (1) and (2), the drag force is proportional to the radius of the particle and the magnetic force is proportional to the volume, that is the cube of the radius. This means that the magnetic force decreases rapidly compared to the drag force as the particle size decreases, indicating that high-speed processing of fine particles becomes difficult. A method of generating a magnetic force that can overcome the drag force is important.

In this study, we attempted to magnetically separate small sized paramagnetic particles in a low magnetic field by increasing the magnetic gradient.

3. MAGNETIC FILTER

A filter made of ferromagnetic wires placed in a magnetic field to create a high gradient magnetic field is called a magnetic filter. The thinner the wire diameter, the higher the magnetic gradient, but the narrower the range of the high magnetic gradient. A conventional magnetic filter uses a thin wire with a circular cross section that is woven into a mesh as shown in Fig. 1(a).

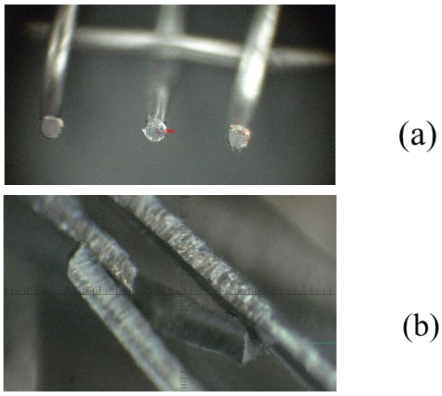


Fig. 1. Photos of filter filaments. (a) Conventional magnetic filter filament with circular cross section and, (b) Developed magnetic filter filament with triangular cross section.

In this study, it was focused on the fact that the magnetic gradient depends on the shape of the ferromagnetic material placed in the magnetic field, and a magnetic filter was developed with a triangular cross section that generates a high magnetic field gradient [8].

A conventional filter consists of circular cross-section wires. If the diameter is 100μm and the external magnetic field is 2T, the magnetic gradient becomes about 20,000T/m near the filter. On the other hand, in a triangular cross section, depending on the direction, an external magnetic field of 2 T generates 70,000 to 200,000 T/m (calculated by FEM), which is an order of magnitude higher. This is the reason why we employed the triangular cross section wire for the filter. A stainless steel fiber with a triangular cross section (SUS430, 120㎛×3mm) was used as shown in Fig. 1(b). The surface area of a triangular cross section filter is about twice as large as that of a circular cross section filter

4. EXPERIMENTALS

4.1. Hematite

Paramagnetic hematite (α-Fe_2O_3, supplied by Toda Kogyo Corp., volume magnetic susceptibility 2.0×10^{-4}) was used. The isoelectric point is between 6 and 7. The particle size distributions (cumulative frequencies) corresponding to 10% (D10), 50% (D50), and 90% (D90) are approximately 9.3, 23, and 32 μm, respectively at pH 7.

1L of a hematite suspension (at pH 6 slightly off the isoelectric point) with a concentration of 50 ppm was passed through at a flow rate of 3.2 mm/s by a liquid feeding pump (ELEYA RP2100). The suspension that passed through the magnetic filter was recovered and filtrated with membrane filter of which pore size is 0.45 μm and weighed. The separation efficiency was calculated by subtracting the passing hematite weight from the initial hematite weight. It means that the obtained separation efficiency is more accurately “the separation efficiency of the device”, not that of the filter. This is because the amount remaining in the system is also considered to have been

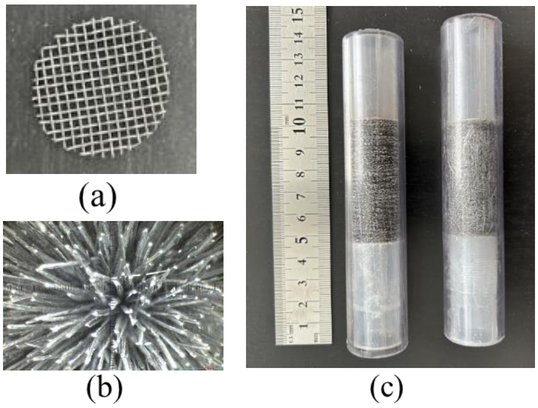


Fig. 2. Magnetic filter used in the experiment. (a) Mesh used in the conventional filter, (b) Triangular cross-section filament used in the new filter, (c) Right: New magnetic filter, Left: Conventional magnetic filter.

separated. Microscopic observations of the magnetically uncaptured hematite in passed suspension were also made.

4.2. Magnetic Filter

In this study, a magnetic filter is used to increase the magnetic gradient. As shown in Fig. 2(a), a conventional mesh-shaped magnetic filter (wire diameter Φ0.3 mm, 20 meshes) was prepared. A magnetic filter was fabricated by laminating 100 sheets of this mesh of which total weight was 22 g (Fig. 2(c) left). Also, a magnetic filter was fabricated using a filament with a triangular cross section (Fig. 2(b)), and its performance was compared with that of a conventional filter. The newly developed magnetic filter consists of a transparent vinyl chloride tube with an inner diameter of 20 mm and a length of approximately 150 mm. At the center of the tube, 22g of filament, the same weight as a conventional filter, is enclosed in a space of 50mm in length, as shown in the right figure of Fig. 2(c). A magnetic filter was produced by stuffing filaments with a triangular cross-section (about 17.6% by volume) and sandwiching them with filters of 20 mm diameter mesh (80 meshes, wire diameter 0.1 mm) at both ends.

4.3. Apparatus for Magnetic Separation

A pipe for magnetic separation was prepared by placing a fabricated magnetic filter in the center of a PVC pipe with an inner diameter of 20 mm and a total length of 1000 mm as shown in Fig. 3. In the experiment, a magnetic separation pipe with a conventional and a newly developed filter was placed inside the superconducting magnet to perform magnetic separation. It should be noted that the fluid to be separated is flowed upward from the bottom, so that air bubbles do not affect the separation efficiency.

Fig.4 shows a setup of the magnetic separation experiment using superconducting magnets. This figure also shows a schematic diagram for understanding. A magnetic separation experiment was performed by applying a maximum magnetic flux density of 2 T.

An α-Fe_2O_3 suspension (50 ppm) of pH 6 was passed through the magnetic separation channel at a flow rate of 3.5 mm/s by a constant liquid feed pump (ELEYA RP2100). After passing suspension, the liquid that passed through the magnetic filter was recovered, suction filtered (pore size 0.45 μm, membrane filter manufactured by ADVANTEC), and its dry weight was measured as particles not captured by the magnetic filter. The separation efficiency was calculated from the initial input amount of 50 mg of hematite particles. High-gradient magnetic separation experiments were conducted under the same experimental conditions for both the triangular section filter and the mesh magnetic filter, and the results were compared.

Fig. 3. Piping for magnetic separation. Developed magnetic separation filter is placed in the center.

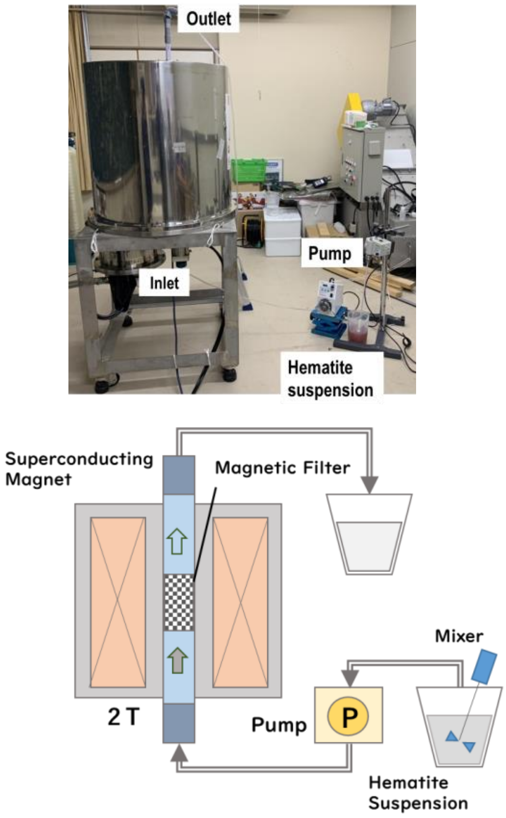


Fig. 4. Superconducting magnetic separation experiment system (upper) and its schematic diagram (bottom).

Here the experimental conditions were summarized.

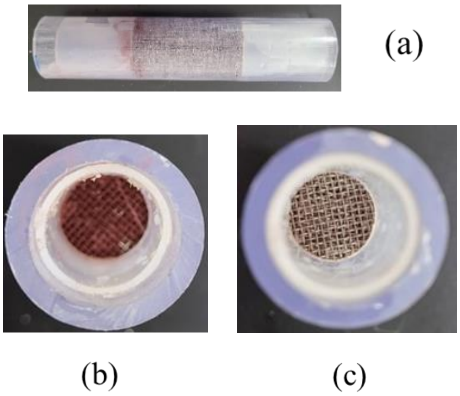


Fig. 5. Mesh filter after magnetic separation, (a) side view, (b) bottom view, and (c) top view.

The weight of the two types of magnetic filter were same as 22g. The flow rate of the suspension was 3.5mm/s, external magnetic flux density was 2T and 1L 50ppm hematite suspension was separated. The conditions described above were identical in the two experiments.

5. RESULTS

5.1. Magnetic Separation by Mesh Filter

Fig. 5 shows the mesh-filter after the magnetic separation of hematite. These are photographs of the side view (a), the bottom view(b), and the top view (c) of the filter after magnetic separation.

In (a), the suspension flows from the left to the right. From this photograph, it can be seen that a large amount of hematite is trapped on the inflow side. Reflecting this, much hematite adheres to the bottom of magnetic filter (b) and no hematite adheres to the top magnetic filter (c).

After magnetic separation the captured hematite was washed out from magnetic filter and then the hematite in the wash water was separated again with a membrane filter. Fig.6 (a) showed the hematite deposited on the membrane filter. It can be seen that a large amount of hematite is separated. Fig.6 (b) shows the result of filtered particles with a membrane filter that flowed out without being magnetically separated. Weighing the hematite on this membrane filter (Fig6 (b)) revealed a separation efficiency of 97.8%. Although the separation efficiency was 97.8%, it has red color indicating that a small size of micro-particles could not be captured magnetically.

Microscopic observation of the outflowing suspension confirmed that particles with a particle diameter of 3 μm or less flowed out as shown in Fig.7. Although the amount of hematite that escaped was not large enough to measure the particle size distribution, microscopic photo revealed the small sized hematite existed in the flow out suspension.

5.2. Triangular Cross-Section Filter

Fig. 8 shows the results of magnetic separation using a triangular section filter. Side-view photo of the filter after magnetic separation (a), bottom view (b), and top view (c), are presented in the photos.

The hematite separation efficiency using the triangular cross-section filter was 99.8%. Considering the residual particles in the magnetic separation device, it can be said that magnetic separation was almost completely possible under 2T of external field.

In addition, as can be seen from the side view Fig8 (a), a relatively large amount of hematite was deposited near the inlet, but hematite reached deep inside the filter. This is because filaments are not perfectly aligned perpendicular to the flow, but are slightly misaligned and have a parallel component to the flow.

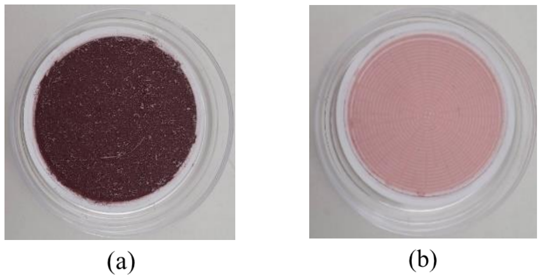


Fig. 6. Magnetic separation results using a conventional magnetic filter. (a) Magnetically separated hematite, (b) Hematite flowed out without separation.

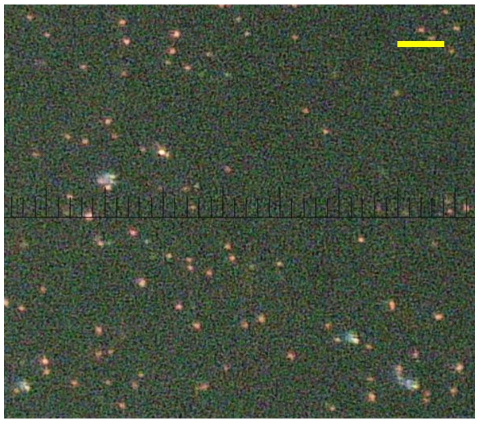


Fig. 7. Hematite particles flowed out during magnetic separation with a mesh filter. Scale is 10 μm. The brown dots of uniform size in the photograph are hematite.

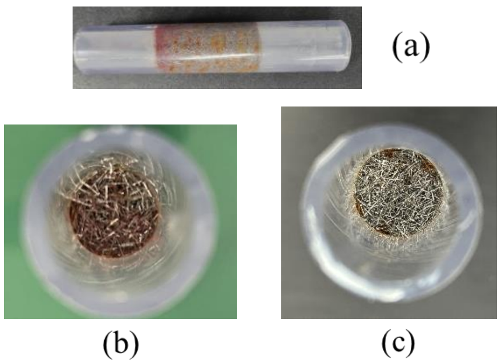


Fig. 8. Photos of hematite adsorption on the triangular section filter., (a) Side view, (b) bottom view, and (c) top view.

(a) (b)

Fig. 9. (a) shows the separated hematite that was washed and separated again with a membrane filter. The (b) was obtained by similarly separating the outflowing suspension with a membrane filter.

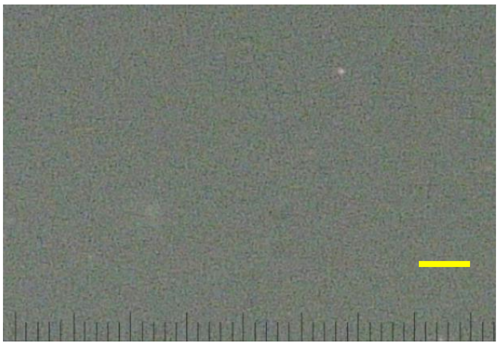


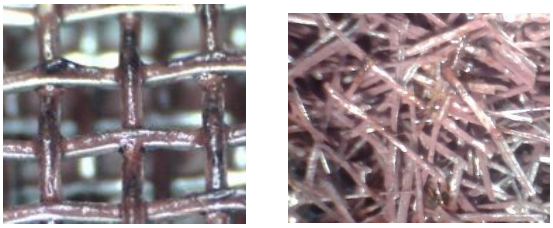
Fig.10. Hematite particles flowed out during magnetic separation with a triangular cross-section filter. Almost no particles were found. (Scale is 10μm.)

The amount of separated hematite, Fig. 9(a), does not change much from Fig. 5(a). This is also suggested by the separation efficiency. Fig.9(b) showed clearly that almost no hematite escaped, unlike the mesh filter shown in Fig.6 (b). A slightly yellowish color is visible in this photo, which is the color of iron oxide due to oxidation of the filter. When this membrane filter was washed and the wash water was observed with a microscope. The observation results were presented in Fig.10. It was confirmed that most of the hematite including particles less than 3 μm were separated.

Table 1 shows a comparison of the separation efficiency of the two filter systems. Although the difference in separation efficiency is small, the triangular cross-section filter has characteristics in that even small-sized hematite particles can be removed.

TABLE 1
PERFORMANCE COMPARISON OF TWO FILTER SYSTEMS

Fiter Type	Filter Specification	Separation Efficiency(%)
Conventional Filter	φ0.3mm, 20mesh, 100 sheats	97.8
Triangular Cross-Section Filter	equivalent diameter: 120μm, length 3mm	99.8



(b)

Fig. 11. Observation of hematite on each filter, (a) mesh filter, and (b) triangular section filter.

6. DISCUSSIONS

The triangular cross-section filter enabled the magnetic gradient to be increased, which made it possible to separate the fine hematite particles, resulting in a significant reduction in the amount of outflow hematite. Although the conventional mesh filter has a high magnetic separation efficiency of 97.8%, the magnetic gradient is not large enough to separate the particles of 3 μm or less.

On the other hand, the triangular cross-section filter had a large magnetic gradient at the edge, and it can be said that even paramagnetic hematite with a size of 3 μm or less could be separated. It was thought that the magnetic gradient would be high only at the edge and then was concerned about the amount hematite could be adsorbed as a filter would be small. In fact, much hematite can be separated. It is considered that this is because the magnetic gradient is high even on the side of the triangular filter and the hematite can be captured, so that a large amount of hematite can be separated. This is a phenomenon predicted by FEM analysis.

Fig. 11 shows how hematite adheres to the mesh filter and triangular section filter. In the mesh filter, a relatively large amount of hematite is deposited due to the high magnetic gradient at the intersection of the filaments. In the triangular cross-section filter, hematite is deposited not only on the edge but also on the side, which is the reason why the filter showed high amount of hematite capture.

7. CONCLUSION

we constructed a small scale superconducting magnetic separation device and performed magnetic separation on hematite using a new magnetic filter and obtained positive results. The conclusions obtained are as follows.

The use of a triangular cross-section filter can increase the magnetic gradient, so even in a relatively low external magnetic field of 2 T, hematite with a small particle size less than 3μm could be separated.

A large amount of hematite could be separated with a triangular cross-section filter. This is because the side of the triangular filter has a high magnetic gradient and can trap hematite.

REFERENCES

[1] K. Sekiya, H. Kuwahara,Y.Yoshida; S. Igarashi,N. Nomura, F. Mishima;Y.Akiyama and S. Nishijima, “Study on Decontamination of Contaminated Soils by Magnetic Separation” *IEEE Trans. Appl. Supercond.*,vol. 24, no. 3, pp. 1-5, June 2014..

[2] K.Yukumatsu, N.Nomura, F.Mishima, Y.Akiyama, and S. Nishijima,” Development of volume reduction method of cesium contaminated soil with magnetic separation,” *Progress in Superconductivity and Cryogenics* Vol.18, No.1, (2016), pp.10~13.

[3] M.Hiramatsu1, J Yamamoto1, Y. Akiyama1, F.Mishima , S. Nishijima, H.Okada , N.Hirota, T.Yamaji , H.Matsuura, S.Namba, T. Sekine, Y.Kobayashi and M Seto, “Removal of Scale from Feed-water in Thermal Power Plant by Magnetic Separation -Analysis of Oxygenated Treatment Scale,” 2019 J. Phys.: Conf. Ser. **1293** 012079.

[4] K.Akiyama, T. Mori, T.Terai, Y.Akiyama, H.Okada, N.Hirota, T. Yamaji, H. Matsuura, S. Namba, T. Sekine, F. Mishima, S. Nishijima, “Removal of Iron Oxide Scale From Boiler Feed-Water in Thermal Power Plant by Magnetic Separation-Separation Conditions of Oxygenated Treatment Scale,” IEEE Trans. Appl. Supercond, ,vol. 31, no. 5, pp. 1-4, Aug. 2021.

[5] S.Nishijima and S.Takeda, “Superconducting high gradient magnetic separation for purification of waste water from paper factory, IEEE Trans. Appl. Supercond., Vol.16, Issue: 2, June (2006) pp.1142 – 1145.

[6] F. Mishima, T. Terada, Y. Akiyama, S. Nishijima,”High Gradient Superconducting Magnetic Separation for Iron Removal form the Glass Polishing Wasete,”IEEE Trans. Appl. Supercond.,Vol, 21 Issue: 3, June (2011) pp. 2059- 2062.

[7] P.Boelens, Z.Lei, B.Drobot, M. Rudolph, Z.Li , M. Franzreb, K.Eckert and F.Lederer, “High-Gradient Magnetic Separation of Compact Fluorescent Lamp Phosphors: Elucidation of the Removal Dynamics in a Rotary Permanent Magnet Separator,” *Minerals* 2021, 11, 1116.

[8] F.Mishima, N.Nomura, S.Nishijima, “Magnetic separation device for paramagnetic materials operated in a low magnetic field”, Progress in Superconductivity and Cryogenics, Vol.24, No.3, (2022), pp.19-23