pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.24, No.3, (2022), pp.7~11
https://doi.org/10.9714/psac.2022.24.3.007

Development of novel magnetic filter for paramagnetic particles in high gradient magnetic separation

Shigehiro Nishijima*, and Naoki Nomura

Department of Applied Nuclear Technology, Fukui University of Technology, Fukui, Japan

(Received 29 June 2022; revised or reviewed 14 September 2022; accepted 15 September 2022)

Abstract

We are conducting research and development of magnetic filters for magnetic separation targeting paramagnetic materials. In order to develop a new magnetic filter with a large magnetic gradient, stainless fiber (SUS430, 120 mm x 3 mm) with a triangular cross section was sintered with a high void ratio (~ 70%) and the magnetic filter (20 mm x 2 mm) was created. When this magnetic filter was used to perform magnetic separation of hematite (particle size 50 μ m) under a maximum magnetic flux density of 1.49 T, high separation rates were obtained.

Keywords: magnetic filter, large magnetic gradient, triangular cross section, high void ratio, hematite

1. INTRODUCTION

We are conducting research and development of magnetic filters for magnetic separation targeting paramagnetic materials. Although the paramagnetic material can be separated by the high gradient magnetic separation method, its application is challenging for industrial applications. This is because high speed mass processing or high magnetic field of large space is required.

Separation of paramagnetic materials has a wide range of applications such as separation of contaminated soil [1-2], separation of scale from the boiler water supply system [3-4], wastewater treatment [5-6] or recycling of rare earth materials [7-8], and all of which are expected to have potential applications. In fact, the superconducting high gradient magnetic separation method is expected to be used because it can separate paramagnetic substances with a small particle size.

Although highly advanced separation of paramagnetic material with a small amount can be performed, its industrial use is challenging. That is because there is a problem of mass processing. This is because the magnetic susceptibility of a paramagnetic material is considerably smaller than that of a ferromagnetic material and hence the magnetic force is small and high speed processing is inadequate needed for an industrial application. Even if it is used industrially, it becomes problem to use it from an economical point of view because the external magnetic field exceeds 10 T.

We investigated a new magnetic filter to solve this problem by increasing the magnetic gradient. A stainless fiber (SUS430, 120 μ m x 3 mm) with a triangular cross section was sintered with a high void ratio (~ 70%) to create a magnetic filter. When hematite (particle size 5 μ m) was magnetically separated using this magnetic filter under a maximum magnetic flux density of 1.49 T, and satisfactory results were obtained.

2. OUTLINE OF RESEARCH

In the experiment, hematite particles, which are paramagnetic materials, were used as separation targets and their magnetic separation efficiency was examined. Here, we tried to increase the magnetic field gradient created by the magnetic filter improving the separation efficiency. A new filter with a triangular cross section was devised to increase the magnetic field gradient. Then, magnetic separation was performed with an external magnetic field of about 1 T. The reason why the external magnetic field was set to 1T is that it is intended for industrial application.

The studies conducted in this work are divided into three parts. First, hematite, a paramagnetic substance of interest, was evaluated. This is because the magnetic separation efficiency of a paramagnetic material largely depends on external factors. Since the agglomeration state affects the separation efficiency, the agglomeration / dispersion situation was examined. The conditions for conducting the magnetic separation experiment in the dispersion state were clarified.

Secondly, a magnetic separation experiment of hematite under dispersion conditions was carried out. The external magnetic field was set to about 1T, and the magnetic separation efficiency at the magnetic field strength assuming social implementation was examined.

* Corresponding author: nishijima@fukui-ut.ac.jp

Based on the above experimental results, a ferromagnetic fine fiber with a triangular cross section was sintered into a magnetic filter, and a magnetic separation experiment of hematite was carried out.

3 . EVALUATION OF HEMATITE

3.1. Factors Affecting on Magnetic Force

High-gradient magnetic separation (hereafter magnetic separation) is a method in which a large magnetic force is generated by magnetic filters of a ferromagnetic material, and particles are attracted to the filter to separate them. The forces acting on the particles are mainly magnetic force and drag force. The drag force is a force acting on the particles with the flow of the media, and when the magnetic force exceeds the drag force, the particles can be attracted. The magnetic force Fm acting on a particle is expressed as follows in the one dimensional formula,

$$F_x = V\left(m_x \frac{\partial H_x}{\partial x} + m_y \frac{\partial H_y}{\partial x} + m_z \frac{\partial H_z}{\partial x} \right) \quad (1)$$

where V is the particle volume, Hx, Hy, Hz are the magnetic field in each direction, m_x, m_y, m_z are the magnetization of the particle in each direction, and hence the magnetic force is proportional to the magnetic gradient.

It can be seen from the equation, the magnetic susceptibility and volume of the object affect the separation efficiency. On the device side, the magnetic gradient and the magnetic field strength has an effect. Though the volume is a factor that affects the magnetic separation efficiency of the object, when the objects are fine particles, it largely depends on the pH of the suspension medium. This is because the fine particles are aggregated or dispersed by pH, and is reflected in the volume of the object. In this study, therefore, we first investigated the state of aggregation of hematite as the object, and clarified the conditions for performing the magnetic separation in the dispersed state.

3.2. Magnetic Separation Experimental Conditions

In a series of experiments, hematite, which is a paramagnetic particle, was used. First, the state of aggregation was investigated before the magnetic separation experiment. Since it is a paramagnetic material, the state of aggregation greatly affects the magnetic separation efficiency. Therefore, the ζ potential accompanying the change in the pH of the suspension medium was measured. Furthermore, we investigated the changes in particle size that accompany pH, and clarified the environment in which the dispersed state was realized. The magnetic susceptibility of hematite used in this experiment is 10^{-4} -10^{-3}, and the particle size is nominally about 5 μm.

In the experiment, the ζ potential of hematite was measured. For the ζ potential measurement, the ζ potential measuring device Model 502 manufactured by Nihon Rufuto Co., Ltd. was used. A DC stabilized power supply PMX110-0.6A (KIKUSUI) was used as the power supply device for electrophoresis. Toda Kogyo 180ED (particle size approx. 5 μm, magnetic susceptibility 2.0 x 10-4) was used as the hematite powder. Ultrapure water was used as the solvent for the suspension, and 0.1N nitric acid solution and 4N sodium hydroxide were used for pH adjustment.

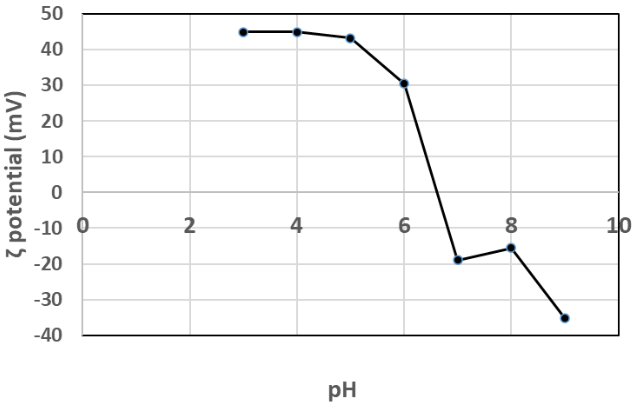


Fig. 1. pH dependence of hematite ζ potential.

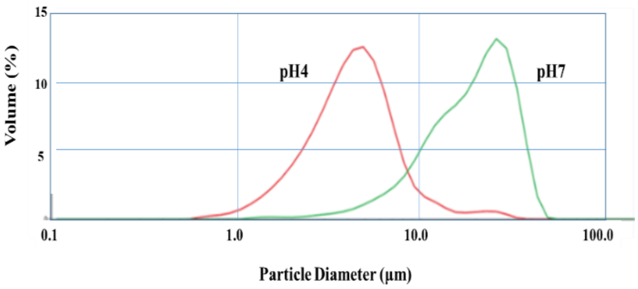


Fig. 2. Changes in hematite particle size distribution due to pH change. In pH 7, the peak is 30 μm, and in pH 4, it is 5 μm.

The measurement results of hematite ζ potential was shown in Fig.1. It became clear that the isoelectric point is between pH 6 and 7. This indicates that the electrical repulsion on the particle surface becomes small and aggregation occurs near the isoelectric point of pH 6 to 7.

Based on this result, the particle size distribution was measured at pH 4 or pH 7 using a particle size distribution meter (MASTERSIZER3000E 、 Hydro EV) .The measurement results were shown in Fig. 2. The peak value at pH 4 was 5 ㎛, while the peak value at pH 7 was about 30 ㎛. It is clear that aggregation occurs near the isoelectric point.

4. CONVENTIONAL FILTER

4.1. Conventional Filters

The magnetic separation experiment was performed using a conventional magnetic filter as a laminated cross-angle filter. The filter was constructed with two ferromagnetic nets with 20 mesh which are made of SUS430F wire having 0.35 mm in diameter , as shown in Fig. 3. A 1 mm spacer was placed between the nets to perform magnetic separation.

Fig. 4 shows a schematic diagram of the filter unit and a photograph of the magnetic separation device. In the magnetic separation experiment, a Halbach array magnet

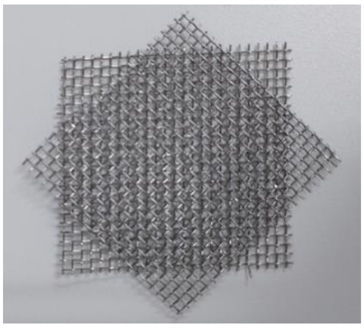
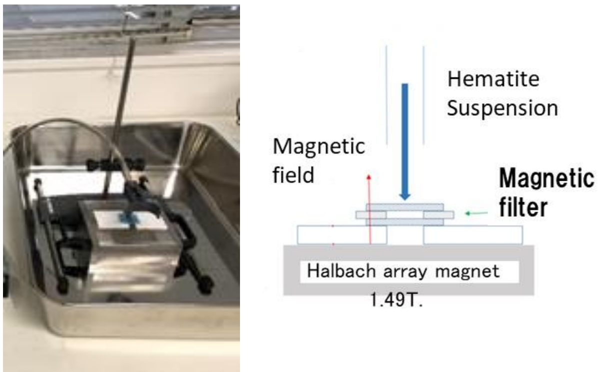


Fig. 3. Conventional cross-angle laminated magnetic filter. In the photo, two layers of mesh are laminated.



(a) (b)

Fig. 4. Magnetic separation experiment set up (a) and schematic diagram of magnetic filter section (b).

(1.49T manufactured by Neomax) was used as the magnetic field generation source.

The applied magnetic field strength to the magnetic filter changed with the distance from the magnet (1.4T in the closest case). In the experiment, it was confirmed that the magnetic field strength to the magnetic filter was 1T on average. The magnetic field direction and the flow direction of the suspension are parallel to each other. A magnetic separation experiment was conducted at a flow rate of 0.069 L / min. A suspension was prepared in 1 L containing 30 mg of hematite. A 0.1N nitric acid solution and 4N sodium hydroxide were used to adjust the pH of the suspension.

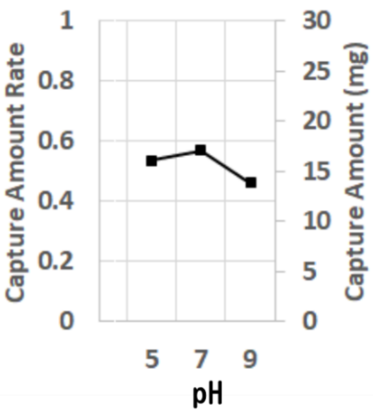
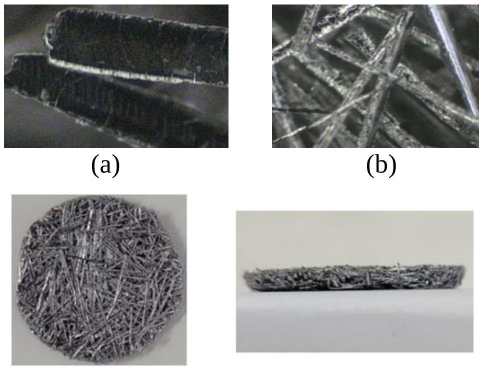


Fig. 5. pH dependence of magnetic separation efficiency with conventional magnetic filter.



(a) (b)

(c) (d)

Fig. 6. Newly developed magnetic filter; (a) triangular cross-sectional filament, (b) sintered filaments, (c) front view of sintered filter and (d) side view of sintered filter.

4.2. Magnetic Separation Results

Fig. 5 shows the results of magnetic separation with conventional filters. This figure shows the pH dependence of the magnetic separation efficiency as shown in catuture amount rate or capture amount of hematite. It can be seen that the separation efficiency increases when the pH is about 7. It is considered that this is due to the aggregation of hematite, which increases the volume and the magnetic force. However, the separation efficiency is not sufficient at around 50%, and further improvement in separation efficiency is desired.

5. NOBEL FILTER

5.1. Noble Magnetic Filter

As a method for improving the magnetic separation efficiency of a paramagnetic material, there is a method for increasing the magnetic gradient. As shown in equation (1), it can be seen that the magnetic force is proportional to the magnetic gradient, and then the magnetic gradient was paid attention in this study. To increase the high-gradient magnetic field region, a new magnetic filter obtained by sintering a stainless filament (SUS430, 120 μ m x 3 mm) having a triangular cross section was developed as shown in Fig.6(a). In this magnetic filter, since the filaments are triangular and columnar, it is conceivable that a high-gradient magnetic field region is concentrated in the ridge.

As compared with the conventional ferromagnetic mesh filter, the magnetic field region having a high gradient is increased, and the magnetic separation ability is considered to be improved. In order to use this filament to make an actual filter, these filaments were pressure sintered. In the process the filaments were slightly deformed as shown in Fig. 6 (b), the cross section remained triangular though. The final magnetic filter with a triangular cross-sectional filaments has a diameter of 20 mm and a thickness of 2 mm, and has a void ratio of about 70% (Fig. 6 (c)). Magnetic separation of paramagnetic hematite was performed using these filters.

5.2. Magnetic Separation with Noble Magnetic Filter

As an experimental device, a magnetic separation device in which magnetic filters were placed in a vinyl chloride

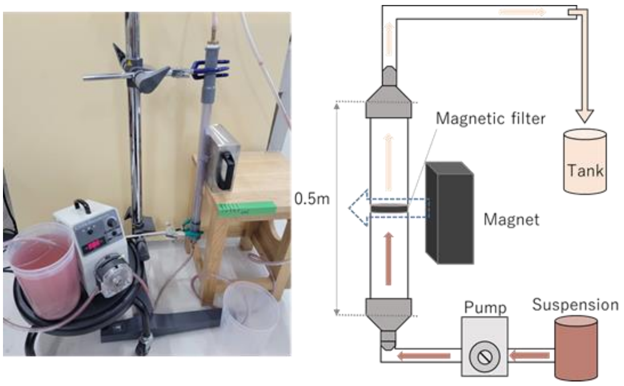


Fig. 7 Photograph and schematic diagram of magnetic separation experiment system.

pipe with an inner diameter of 20 mm and a length of 0.5 m was manufactured. A Halbach array magnet with a maximum magnetic flux density of 1.49T was used. The experimental set up was shown inFig.7. The magnetic field strength actually applied to the magnetic filter is 0.6 to 1.2T.

The hematite suspension was sent from the lower part of the magnetic separation device using a liquid feed pump (EYELARP-1000), and a magnetic separation experiment was carried out. The total amount of hematite suspension was 2 L, the pH was 4, and the amount of hematite was 10 mg. In this experiment, the direction of the magnetic field was perpendicular to the flow, and the experiment was conducted with changing the flow velocity. The pH of the suspension medium was 4, and this was a magnetic separation experiment in a dispersed state.

Fig.8 shows the relationship between the amount of hematite separation and the flow velocity. The number of filters was one in the experiment. From this figure, it was found that the magnetic separation capacity did not change so much though some deviation. That is, when the flow velocity is within a certain range, the separation capacity does not decrease. It could be considered that this is because the flow path of the suspension medium in the filter took a complicated path, and the flow velocity in the filter decreased even if the external flow velocity increased.

On the other hand, in the laminated cross-angle filter when the flow velocity is increased, the flow path resistance is increased and the pressure loss is increased. As a result, it is considered that the separation efficiency decreases with flow velocity.

Fig. 9 shows the filter number dependence of the separation efficiency of hematite. The flow velocity is 0.006 m / s. The experimental results showed that with two filters , the separation efficiency reached as high as 90% or more. When the number of filters is further increased, the hematite capture amount did not increase significantly.

Considering that the separation efficiency of the conventional mesh filter is about 50%, the separation efficiency has been improved markedly. A direct comparison of the experimental results cannot be made though, because the experimental conditions in the two were different. Even so the possibility of improving the separation efficiency is clear.

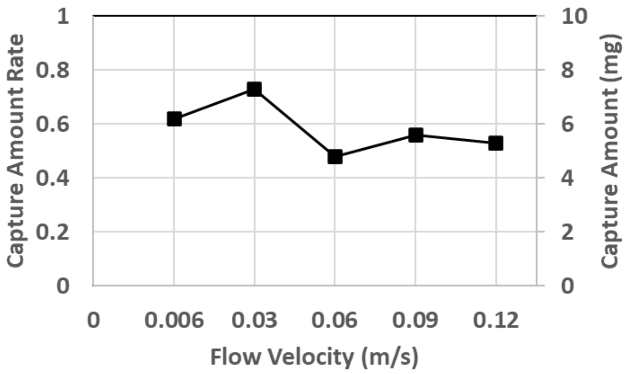


Fig. 8. Flow velocity dependence of hematite separation efficiency.

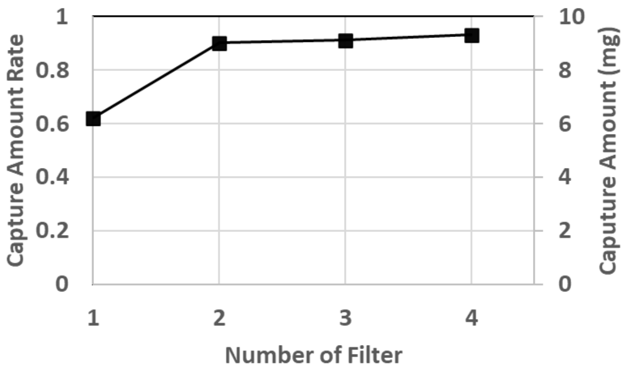


Fig. 9. Filter number dependence of hematite separation efficiency.

6. DISCUSSION

The reason why the newly developed filter has high separation efficiency was investigated by observing the state of hematite adhesion to the filter. Fig. 10 (a) shows the adhesion condition of hematite in the mesh filter, and (b) shows that in the triangular cross-sectional filter.

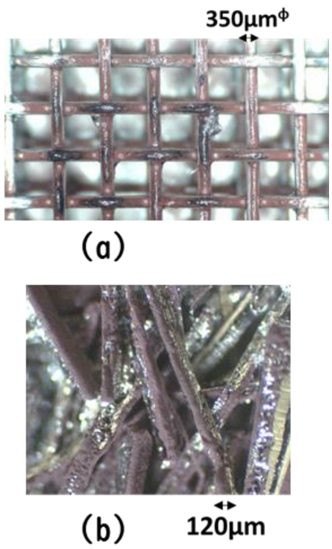


Fig.10. State of hematite adsorption to conventional filter (a) and newly developed filter (b).

In the case of a mesh filter, it is known that the magnetic gradient is high at the intersection of the vertical and horizontal filaments. As a results, when the ferromagnetic particle is magnetically separated, they accumulate in a columnar shape at the intersections. The same phenomenon was observed in the case of paramagnetic materials, and it can be seen that hematite is selectively attached to the intersections. This suggests that the place where the paramagnetic material can be attracted is determined and hence it is difficult to increase the amount of separation capacity.

On the other hand, in the triangular filter, it can be seen that hematite is attached not only to the ridge of the filter but also to the side surface. This is the reason why the separation capacity of the newly developed filter is high.

7. CONCLUSIONS

In this study a small-scale magnetic separation device was created, a magnetic separation experiment of hematite using a newly developed magnetic filter was performed and favorable results were obtained. The usefulness of the new magnetic filter was confirmed.

In the future, we plan to conduct detailed magnetic characteristic analysis of this magnetic filter and the experiments using superconducting magnets.

ACKNOWLEDGMENT

This work is partly supported by “Advanced Low Carbon Technology Research and Development Program (ALCA)” of Japan Science and Technology Agency (JST) under Grand JPMJAL1304

This study is partly based on the research conducted by Takuma Sakano, a graduate student in our laboratory.

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. Superco*nd., Vol.16, Issue: 2, June (2006) pp.1142 – 1145.

[6] H.Zhang, Z.Zhao, X.Xu and L. Li, “Study on industrial wastewater treatment using superconducting magnetic separation,” Cryogenics, Vol. 51, Issue 6, June 2011, pp. 225-228.

[7] 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.

[8] 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.