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# Highly efficient magnetic separation using five-aligned superconducting bulk magnet

Hiroyuki Fujishiro<sup>1</sup>, Takashi Miura<sup>1</sup>, Tomoyuki Naito<sup>1</sup> and Hidemi Hayashi<sup>2</sup>

<sup>1</sup> Faculty of Engineering, Iwate University, Morioka 020-8551, Japan <sup>2</sup> Kyushu Electric Power Co., Inc., Fukuoka 815-8520, Japan

E-mail: fujishiro@iwate-u.ac.jp

Abstract. We have constructed the highly efficient magnetic separation system using fivealigned superconducting bulk magnets, which has ten usable magnetic poles on both sides in open space. We applied the bulk magnet system to the magnetic separation of ferromagnetic particles (magnetite; Fe<sub>3</sub>O<sub>4</sub>) and paramagnetic ones ( $\alpha$ -hematite; Fe<sub>2</sub>O<sub>3</sub>) dispersed in water for various average particle diameters *d*, flow speeds V<sub>F</sub> and initial concentrations C<sub>0</sub> of the particles. The multi-bulk magnet system has been confirmed to be effective for the magnetic separation and the efficiency of the magnetic separation per one magnetic pole has been estimated using the theoretical relation.

#### 1. Introduction

The magnetic separation technique using permanent, electro and superconducting magnets has been used to purify the dirty water for the environmental cleaning and to separate magnetic materials from the industrial waste. Recently, a superconducting bulk magnet, on which the trapped magnetic field  $B_T$ is as high as a few Tesla, has been developed because of the enhancement of superconducting characteristics of the bulk materials and the improvement of magnetizing techniques. The maximum trapped field  $B_T^{FC}$  of 17 T at 29 K has been achieved on the bulk by the field-cooled magnetization (FCM) using a superconducting magnet (SM) [1]. The investigations of the magnetic separation using the superconducting bulk magnet as high as a few Tesla have been reported [2-4]. Under the magnetic field  $B=\mu_0 H$ , the magnetic force  $F_M$  for the spherical particles of b in radius with susceptibility  $\chi_f$  can be represented in the following [4],

$$F_{M} = \frac{4}{3}\pi b^{3} \mu_{0} \frac{9(\chi_{p} - \chi_{f})}{(3 + \chi_{f})(3 + \chi_{p})} HgradH$$
(1)

In the equation, to increase the magnetic force  $F_M$  using superconducting bulk magnets, it is necessary to enhance not only the magnetic field H, but also magnetic field gradient (grad H) generated on the bulk. The increase of the number of bulk magnet is also an another solution to enhance the efficiency of the magnetic separation. We have developed two- and five-aligned superconducting bulk magnet system [5, 6]. The system has usable surface on both sides in open space, which can be realized only by the pulsed field magnetization (PFM) technique using a split-type copper coil. The PFM is a suitable technique to magnetize the superconducting bulk for practical applications because of an

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inexpensive and mobile experimental setup with no use of SM. However, the trapped field  $B_T^P$  by PFM was pretty small, compared with  $B_T^{FC}$  because of the large temperature rise by the dynamical motion of the magnetic flux. We have investigated the enhancement of  $B_T^P$  on the superconducting bulk magnetized by PFM and have succeeded the highest field trapping of 5.20 T on the GdBaCuO bulk of 45 mm in diameter at 30 K, and of 2.53 T on the vacuum sheath using a solenoid copper coil [7]. For the five-aligned superconducting bulk magnet system, the magnetic field higher than 2.3 T has been attained on the vacuum sheath for each bulk, which has 10 usable magnetic poles on both sides and has a potential for new practical applications [6].

In this paper, as a feasible experiment, we apply the five-aligned bulk magnet system to the highly effective magnetic separation of ferromagnetic particles (magnetite;  $Fe_3O_4$ ) and paramagnetic ones ( $\alpha$ -hematite;  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>) dispersed in water. The relation has been investigated between the magnetic separation efficiency and the several parameters such as an average particle diameter *d*, a flow speed  $V_F$  and an initial particle concentration  $C_0$  dispersed in water.

### 2. Experimental procedure

Figure 1(a) shows the schematic view of experimental setup for the magnetic separation used in this study. Figure 1(b) shows the structure of the five-aligned superconducting bulk magnet and the separation container passing through the wastewater. The ferromagnetic Fe<sub>3</sub>O<sub>4</sub> particles (average particle diameter *d* of 3.2  $\mu$ m, 0.5  $\mu$ m and 0.1  $\mu$ m) were dispersed in water with initial concentrations of *C*<sub>0</sub>=400, 200, 100 ppm and were stirred by pumping and air bubbling in a tank of 20 litre. The susceptibility  $\chi_p$  of the Fe<sub>3</sub>O<sub>4</sub> particles was 2.5 x 10<sup>-4</sup> (emu/mol/Oe) at 300 K, which was independent of the particle size. The flow speed *V*<sub>F</sub> was changed up to 5 L/min by controlling the valves of B1 and B2. Two separation containers made by acrylic resin were faced to the both sides of the five-aligned bulk magnets and the magnetic poles was extracted from the valve B3 and the final purified water after passing the ten magnetic poles was collected. In figure 1(b), the dimension of the separation container is 80 mm in height and 30 mm in thickness. To make wastewater flow near the magnetic poles effectively, the partition walls were inserted in the containers.

The magnetic separation experiment of paramagnetic hematite ( $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>) particles (d=1.0 µm) were



**Figure 1.** (a) The schematic view of the magnetic separation system used in this study. (b) The structure of the five-aligned superconducting bulk magnet system and the separation container passing through the wastewater in which the partition walls were inserted.

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performed by the high gradient magnetic separation (HGMS) method using filters composed by ferromagnetic fine wires, which can create high gradient magnetic field [8]. The concentration of hematite powder was  $C_0=500$  ppm in water and the flow speed  $V_F$  was changed up to 3 L/min. The susceptibility  $\chi_p$  of the  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> particles was 5.0 x 10<sup>-7</sup> (emu/mol/Oe) at 300 K. In all the experiments, the particle concentration *C* in purified water was measured by the visible spectrophotometer.

As shown in figure 1(b), *c*-axis oriented five rectangular-shaped GdBaCuO bulks  $(34 \times 34 \times 15 \text{ mm}^3)$ , Nippon Steel Co., Ltd.) were tightly fastened with the copper bar from the side face (along the *ab*-plane) and the bar was attached to the cold stage of a Gifford McMahon (GM) cycle helium refrigerator [9]. An interval between the bulks was 60 mm. The temperature of the bulk was controlled at 40 K. The pulse field of  $B_{ex}=5.5 \text{ T} \sim 6.0 \text{ T}$  with a rise time of 12 ms was applied to the zero-field cooled bulks using a split-type copper coil dipped in liquid N<sub>2</sub>. After the completion of magnetizing a bulk, the magnetizing coil was moved in parallel and another bulk was magnetized in turn in the same manner. The successive pulse applications with identical strength (SPA) were performed to enhance  $B_T^P$  [9]. The line scan profile of the magnetic field  $B_T(x, z)$  was measured using an axial-type Hall sensor (F W Bell, BHA921) for the distance z=0, 3 and 6 mm from the vacuum sheath surface.

#### 3. Theoretical estimation

When we assume the initial particle concentration in water as  $C_0$  and the magnetic separation efficiency per one magnetic pole as k ( $0 \le k \le 1$ ), the particle concentration C in purified water after passing through the *n*-magnetic poles is defined as

$$C/C_0 = (1-k)^n.$$
 (2)

The results of the calculation are indicated in figure 2. Even though the k value is as low as 0.3, the final C value can be decreased to  $0.0282C_0$  for n=10. These results suggest that the weak-ferromagnetic and/or nano-sized ferromagnetic particles can be separated under weak  $F_M$  using the system, and that the system can separate the ferromagnetic particles under large flow speed  $V_f$ .

#### 4. Results and discussion

#### 4.1. Characteristics of five-aligned bulk magnets

Figure 3(a) shows the line scan profiles of the trapped field  $B_T(z)$  in open space, along the direction through the centre of the bulk after the magnetization of the five bulks (#1~#5). The  $B_T(z)$  profile changes periodically and the maximum  $B_T(z)$  value was 1.8 - 2.2 T at the vacuum sheath surface (z=0 mm). The  $B_T(z)$  value decreased with increasing z, and was 1.1 - 1.4 T at z=3 mm and 0.7 - 0.8 T at





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**Figure 3.** The line scan profiles of (a) the trapped field  $B_T(z)$ , (b) the magnetic gradient dB(z)/dx and (c) the B(z)dB(z)/dx values in open space, along the direction through the centre of the five-aligned bulk magnets from #1 to #5.

z=6 mm. Figures 3(b) and 3(c) show the dB/dx and BdB/dx profiles for the same bulk system. The magnetic gradient dB/dx was as large as 150-200 T/m. The maximum BdB/dx was 250-300 T<sup>2</sup>/m and 50-70 T<sup>2</sup>/m at z=0 mm and z=6 mm, respectively, which contributes directly to  $F_{\rm M}$  as shown in equation (1). These specific values are about 10 times as large as those for the Nd-Fe-B permanent magnet and are important parameters for the magnetic separation.

## 4.2. Magnetic separation of magnetite ( $Fe_3O_4$ ) particles

Figures 4(a) and 4(b) show the flow speed  $V_f$  dependence of the magnetite concentration *C* in purified water passing through the 5 or 10 magnetic poles for various *d* of the Fe<sub>3</sub>O<sub>4</sub> particles for the initial concentration of  $C_0$ =400 ppm and 100 ppm, respectively. In figure 4(a), the concentration *C* of the Fe<sub>3</sub>O<sub>4</sub> particles with *d*=3.2 µm and *d*=0.5 µm decreases to 6 – 8 ppm in purified water passing through the 10 magnetic poles for  $V_f$ =1 L/min, and increases slightly with increasing  $V_f$ . The concentration *C* for *n*=5 was higher than that for *n*=10. For the Fe<sub>3</sub>O<sub>4</sub> particles with *d*=0.1 µm, however, the decrease in the concentration *C* by the magnetic separation was not so large because of the smaller  $F_M$  by smaller *d* of the Fe<sub>3</sub>O<sub>4</sub> particles; the concentration *C* decreases to 170 ppm for *n*=5 and to 60 ppm for *n*=10 in purified water for  $V_f$ =1 L/min. Since the susceptibility  $\chi_p$  of magnetite powder was independent of *d*,  $F_M$  is proportional to  $d^3$  as shown in equation (1). As a result, the efficiency of the magnetic separation should increase with increasing *d*. However, the efficiency for the *d*=0.1 µm, 0.5 µm and 3.2 µm was (1/60):(1/6):(1/8) for *n*=10 and  $V_f$ =1 L/min. The discrepancy comes from the insufficient mixing of the magnetic particles dispersed in water. In figure 4(b) for  $C_0$ =100 ppm, the



**Figure 4.** The flow speed  $V_{\rm f}$  dependence of the magnetite (Fe<sub>3</sub>O<sub>4</sub>) concentration C in purified water passing through the 5 or 10 magnetic poles for various d of the magnetite particles for the initial concentration of (a)  $C_0$ =400 ppm and (b)  $C_0$ =100 ppm, respectively.

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similar  $V_{\rm f}$  dependence of the concentration C can be seen.

## 4.3. Estimation of magnetic separation efficiency k per one magnetic pole

In this subsection, we estimate the magnetic separation efficiency k per one magnetic pole for the typical experimental results using equation (2). Figures 5(a) and 5(b) show the normalized concentration  $C/C_0$  as a function of the number of the magnetic pole, n, for the results of  $d=0.5 \mu m$  and  $d=0.1 \mu m$ , respectively. In these figures, calculated results using equation (2) are also shown for various k values. In figure 5(a), the  $C/C_0$  for the condition ( $C_0=100 \text{ ppm}$ ,  $V_f=5 \text{ L/min}$ ) changes in accordance with the equation (2) and the k value was estimated to be 0.2. The results for other conditions suggest that the k value was estimated to be 0.3-0.4 for n=5, but decreased slightly for n=10. These results come from the structural imperfection of the magnetic separation container and insufficient dispersion of the particles. In figure 5(b) for  $d=0.1 \mu m$ , the k values are smaller than that for  $d=0.5 \mu m$ ; the k values of  $C_0=400 \text{ ppm}$  for  $V_f=1 \text{ L/min}$  and 5 L/min (n=10) are 0.18 and 0.08, respectively, and, decreases with decreasing  $C_0$ .

# 4.4. Magnetic separation of hematite ( $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>) particles

Figure 6(a) shows the flow speed  $V_{\rm f}$  dependence of the concentration *C* of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> particles (*d*=1.0 µm) in purified water passing through the 5 or 10 magnetic poles for the initial concentration of  $C_0$ =500 ppm. In the high gradient magnetic separation (HGMS), the particles are filtered by fine wires without magnetic field. The results of the filtering effect are also shown in figure 6(a), in which the concentration *C* for *n*=10 at  $V_{\rm f}$ =1 L/min decreases to 180 ppm without magnetic field and 60 ppm with magnetic field, respectively. The concentration slightly increases with increasing  $V_{\rm f}$  and for *n*=5. Figure 6(b) shows the normalized concentration  $C/C_0$  as a function of the number of the magnetic pole. The *k* value was estimated to be 0.11 for  $V_{\rm f}$ =3 L/min and 0.18 for  $V_{\rm f}$ =1 L/min with magnetic field.

## 5. Summary

We have constructed the highly efficient magnetic separation system using five-aligned superconducting bulk magnets, which have ten usable magnetic poles on both sides in open space. We applied the system to the magnetic separation of ferromagnetic particles (magnetite; Fe<sub>3</sub>O<sub>4</sub>) and paramagnetic particles ( $\alpha$ -hematite; Fe<sub>2</sub>O<sub>3</sub>) dispersed in water for various average particle diameters *d*, flow speeds  $V_{\rm F}$  and initial concentrations  $C_0$  of the particles. Important experimental results and conclusions are summarized as follows.

1) The magnetic separation of magnetite with  $d=0.5 \ \mu m$  was the most effective and the separation efficiency decreases with increasing  $V_{\rm f}$  and with decreasing the number of the magnetic pole *n*.



**Figure 5.** The normalized concentration  $C/C_0$  as a function of the number of the magnetic pole *n* for the results of (a)  $d=0.5 \mu m$  and (b)  $d=0.1 \mu m$ , respectively.



**Figure 6.** (a) The flow speed  $V_{\rm f}$  dependence of the concentration *C* of hematite ( $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>) particles (d=1.0 µm) in purified water passing through the 5 or 10 magnetic poles for the initial concentration of  $C_0$ =500 ppm. The results without magnetic field are also shown. (b) The normalized concentration  $C/C_0$  as a function of the number of the magnetic pole for  $V_{\rm f}$ =1 and 3 L/min.

- 2) The experimental results roughly follow the equation (2). The magnetic separation efficiency k per one magnetic pole can be estimated for each experimental condition using the relation.
- 3) The magnetic separation effect by the high gradient magnetic separation (HGMS) was confirmed using paramagnetic  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> particles.
- 4) The multi-bulk magnet system has been confirmed to be effective for the magnetic separation. The higher efficient separation, the separation for higher  $V_{\rm f}$  by the improved separation container and the larger  $F_{\rm M}$  are in progress.

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