A Study on the Development of an Open-Gradient Magnetic Separator Under Dry Condition

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Abstract—This is an attempt to explore feasibility to develop an open gradient magnetic separator for mixed powder under dry condition. The magnetic separator proposed here is intended to separate the ferromagnetic particles from mixed powder, being based on the consideration that the separation efficiency depends upon changing systematically the particle sizes and its surface properties such as hydrophobicity and cohesive force. As a result, it is found that the separation efficiency became lower as the particle size of the mixed particles became smaller. This is supposed to be caused by the cohesive force between the particles of ferrite and alumina which are easily affected by the magnetic drag force and the gravity difference. But the result is encouraging because the separation efficiency will be enhanced if the magnetic gradient is increased and if air flow in the separator is optimized in the appropriate system of the open-gradient magnetic separator proposed in this paper.

Index Terms—Dry conditions, ferromagnetic, magnetic separation, paramagnetic, particle size.

I. INTRODUCTION

THE technology related to the air-solid fluidized bed, which is widely and successfully applied to various commercial processes, including chemical, pharmaceutical, agricultural, plastic, and food processing, deals with powdered materials. Powders in a fluidized bed have liquid-like properties as regards their density and viscosity [1], [2] and are separated based on the principle that a particle whose density is smaller than the bulk density of the fluidized bed floats and the heavier one sinks. With this process, the difference in gravity is the most important factor affecting the separation efficiency. However, in separating two particles with small difference in their densities, gravity separation is inadequate. In order to improve the efficiency in separating particles having a small difference in their densities but different magnetic properties, application of a magnetic field to the fluidized bed is considered. This paper tries to establish the design of a magnetically enhanced fluidized bed, or an open-gradient magnetic separator under dry condition.

Factors affecting the separation efficiency in the dryprocess are:

1) the size on the particles, or its volume,
2) the strength and gradient of the magnetic field,
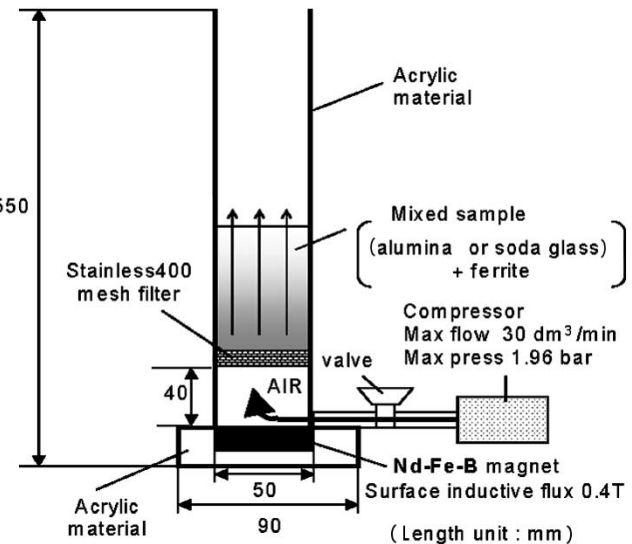
Fig. 1. Equipment for magnetic separation in dry process.

3) the flow rate of the air,
4) the properties of the particles.

The following equations express:

$$F_m = \frac{V_p}{2}(x_P - x_m)grad(H^2).\qquad(1)$$

V_P Particle Volume
μ_0 Vacuum Permeability
x_P Magnetic Susceptibility of a Particle
x_m Magnetic Susceptibility of the Air
H Magnetic Field Intensity

The above-mentioned factors 1) and 2) are related to the magnetic force. The factor 3) is related to the drag force. The factor 4) is the chemical properties of the particles such as the hydrophobicity and cohesive force. Clarification of the dependency of separation efficiency on these factors is indispensable for establishing the designing methodology of a magnetically enhanced fluidized bed. This paper reports an experimental study conducted on the effects of the size of the particles and their surface hydrophobicity on the separation efficiency with ferrite, alumina, which has strong cohesiveness, and soda glass particles.

II. EXPERIMENTAL METHOD

A. Apparatus

An experimental apparatus as shown in Fig. 1 was designed and constructed. Its main components are a separation chamber and an external compressor for supplying air to the chamber.

TABLE I
PARTICLE SIZE AND COMBINATION CONDITION

Condition	almina (45 μm)	soda grass (37 μm)	soda grass (100 μm)	Cu-Zn ferrite (44 μm)	Mn-Zn ferrite (8 μm)	Mn-Zn ferrite (1.8 μm)
1	25.0 g			25.0 g		
2	25.0 g				25.0 g	
3	25.0 g					25.0 g
4		25.0 g		25.0 g		
5		25.0 g			25.0 g	
6		25.0 g				25.0 g
7			25.0 g	25.0 g		
8			25.0 g		25.0 g	
9			25.0 g			25.0 g

The separation chamber consists of a neodymium magnet attached to the bottom of an acrylic resin rectangular tube. The field gradient of the magnet was 120 mT/cm, and placed 1 cm away from the bottom of the chamber in the perpendicular direction.

Compressed air was supplied to the mixed samples through a stainless 400-mesh filter placed at the bottom of the samples. The external compressor had a maximum flow rate of 30 $\mathrm{dm}^3/\min$ and a pressure of 1.96 bar to the separation apparatus.

B. Materials Used

Three kinds of ferrite particles were used as ferromagnetic materials and one kind of alumina ($\mathrm{Al_2O_3}$) and two kinds of soda glass particles as the paramagnetic materials. In order to investigate the effect of the sizes of the particles on the separation efficiency, ferrite and soda glass particles of different sizes as shown in Table I were used. As small particles flocculate in the air, the effect of the cohesiveness among the particles on the separation efficiency was also investigated. To clarify this, alumina/soda glass particles were used. The median size of the particles used in this study is shown in Table I.

In preparation for this test, 25.0 g of ferrite particles and 25.0 g of alumina/soda glass particles were mixed in a mortar and kept in a vacuum desiccator at 130°C for 12 hours previous to the experiment.

C. Separation Test

The ferromagnetic particles in the mixed sample were separated by a magnetic force generated by a permanent magnet while exposing the sample to compressed air from an external compressor. In a magnetic field, the paramagnetic particles are subjected to only gravity and ferromagnetic particles to both gravity and magnetic force. Thus ferromagnetic particles accumulate at the lower part of the separation chamber, and paramagnetic particles at the upper part of the chamber.

A mixture of 25.0 g of ferrite particles and 25.0 g of paramagnetic particles of alumina/soda glass were put into the separation chamber. The rate of mixture is shown in Table I. The operation lasted for 300 seconds.

The photograph and illustration in Fig. 2 show the separated results of a mixture of ferrite particles with a median size of 8 μm and alumina particles of 45 μm. It can be seen in Fig. 2 that the alumina particles remained at the upper part and the ferrite particles accumulated at the lower part of the chamber after 5
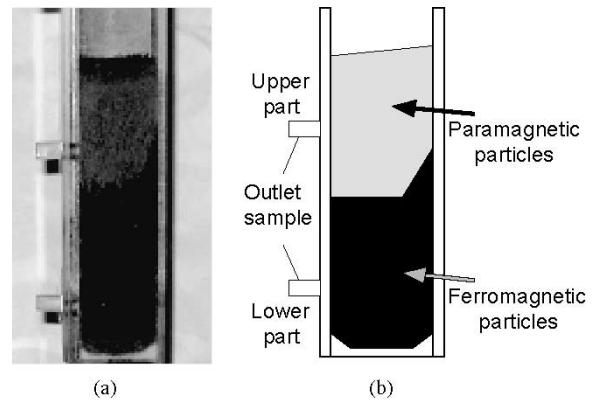

Fig. 2. Separation chamber (alumina: 45 μm and ferrite: 8 μm). (a) Picture; (b) illustration.

min of operation. It can also be seen in the photograph that the upper part of the separated alumina particles contain a small amount of ferrite particles and thus the color is gray.

D. Estimation of the Separation Efficiency

In order to estimate the separated amount of alumina/soda glass particles from the mixed sample, a magnetic balance was used [3]. About 1.0 g of the separated sample was taken out from the upper part of the sample and then the exact volume of the sample was weighed with a balance. The exact volume of the ferrite particles occupying the upper part of the separated sample was estimated with a magnetic balance. The separation efficiency for alumina/soda glass particles is calculated by:

$$\text{Separation efficiency for alumina (soda glass)} = \frac{\text{Mass of sample} - \text{Mass of ferrite}}{\text{Mass of sample at upper part}}. \quad (2)$$

Next, approx. 1.0 g of the separated sample was taken out from the lower part of the sample and then the exact volume of the sample was weighed in order to estimate the separated amount of ferrite particles. The exact volume of the ferrite particles remaining in the lower part of the separated sample was also estimated with a magnetic balance. The separation efficiency is given by (3):

$$\text{Separation efficiency for ferrite} = \frac{\text{Mass of ferrite}}{\text{Mass of sample at lower part}}. \quad (3)$$

III. EXPERIMENTAL RESULTS

A. Separation Efficiency for Alumina Particles

The separation efficiency was 50% for the mixture before separation, because the volume of alumina/soda glass particles was 25.0 g and that of ferrite particles was 25.0 g. Samples consisting of ferrite particles with a median size of 44, 8 and 1.8 μm, and alumina particles of 45 μm were separated and the result is shown in Fig. 3. For this separation operation, the flow rate of the air was 16 $\mathrm{dm}^3/\min$. In case of ferrite particles of 8 μm (test condition 2 in the Table I), the separation efficiency for alumina rose up to 90% within 1 minute after the magnetic
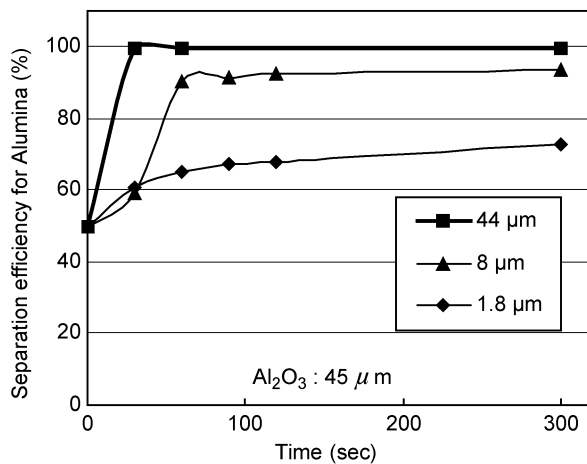
Fig. 3. Time dependency of separation (alumina: 45 μm) (16 dm^3/ min).

Fig. 4. Time dependence of separation (soda glass: 37 μm) (21 dm^3/ min).

separation started, and then improved to 93% in 5 minutes. For the larger size of the ferrite particles (median size: 44 μm, test condition 1 in the Table I), the obtained separation efficiency was close to 100% in about 30 seconds. In comparison with the smaller size of the ferrite particles such as 8 μm and 1.8 μm, the separation efficiency was higher, because the magnetic force is stronger due to the particle volume dependency in accordance with (1). In case of ferrite particles with the size of 1.8 μm, many ferrite particles were found to adhere to the surface of alumina particles at the beginning of the separation process, and the tearing off of the ferrite particles from the alumina surface gradually proceeded during the separation process due to the magnetic force. It is clear that when the size of the ferrite particles is small, the magnetic force working on the particles is so small and the adhering force so large that the separation efficiency becomes low. Evidently the influence of the cohesive force between the ferrite and alumina particles increases proportionally to the increase in the specific surface area of the ferrite particles. The size of the ferrite particles affects the separation efficiency, and the separation efficiency against the duration of the operation decreased with the decrease in its size.

B. Separation Efficiency for Soda Glass Particles

From an experiment with alumina, it was found that the influence of the cohesive force between the ferrite and alumina particles was strong and thus the separation efficiency decreased. In this experiment, soda glass particles close in size to the alumina particles were used in order to clarify the effect of the cohesive force on the separation efficiency. Since the surface properties of soda glass particles is known to be hydrophobic, the cohesive force between ferrite and glass particles can be considered to be much smaller than that of alumina particles.

Ferrite particles with the size of 44, 8, and 1.8 μm, and soda glass particles with the size of 37 and 100 μm were used corresponding to the separating conditions no. 4–6 and 7–9 in Table I. The separation efficiency for the above mixture was evaluated at a flow rate of air of 21 dm^3/ min. and the results are shown in Fig. 4. The separation efficiency for soda glass particles with the size of 37 μm was close to 100% after 30 seconds of operation for ferrite particles with the size of 44, 8 and 1.8 μm. This
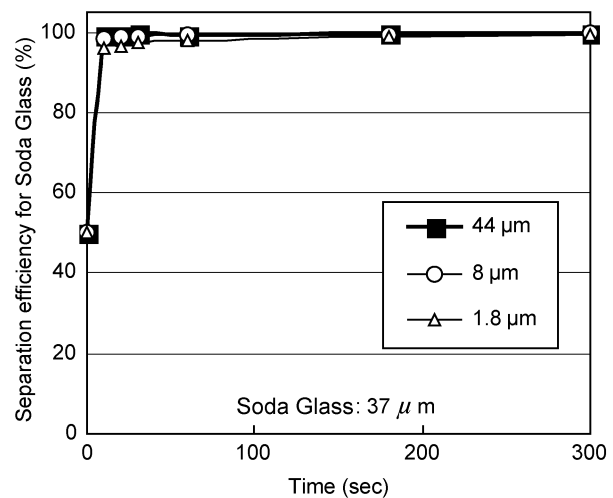

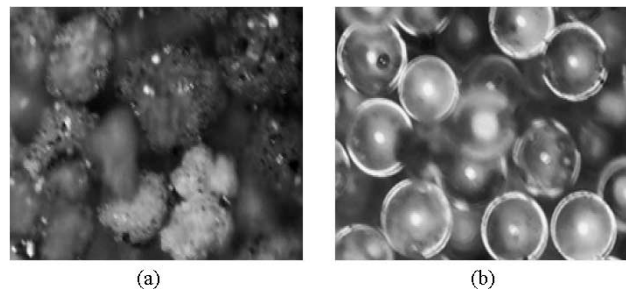(a)   (b)

Fig. 5. Observation by optical microscope ($\times$ 200). (a) Alumina: 45 μm; (b) soda glass: 37 μm.

process was terminated immediately after sending compressed air into the separation chamber. The separation efficiency for ferrite particles was 93, 84, and 84% for ferrite particles with the size of 44, 8 and 1.8 μm, respectively.

In the case of soda glass particles with the size of 100 μm, the separation efficiency for soda glass particles was close to 100%. On the other hand, the separation efficiency for ferrite particles was 93, 71, and 65% for ferrite particles with the sizes of 44, 8, and 1.8 μm, respectively.

An optical microscope photograph of the sample is shown in Fig. 5. The photograph in Fig. 5(a) is for alumina particles with the size of 45 μm and that in Fig. 5(b) is for soda glass particles with the size of 37 μm. It was obvious that the surface state of alumina and soda glass particles is so much different as to be assumed from the surface property with hydrophobicity. The photograph shows that the shape and size of alumina particles are not uniform, and many ferrite particles were distributed between alumina particles, and many small ferrite particles adhered to the surface of alumina particle. On the other hand, the photograph shows that the shape of soda glass particles is spherical, and many ferrite particles were not distributed between soda glass particles, and a few ferrite particles adhered to the surface of soda glass particle. When soda glass particles with a weak cohesive force are used as a paramagnetic material, it was found that separation of a the mixture consisting of ferrite and glass particles is much easier than that of ferrite and alumina particles. A mixture of ferrite and soda glass particles could not be
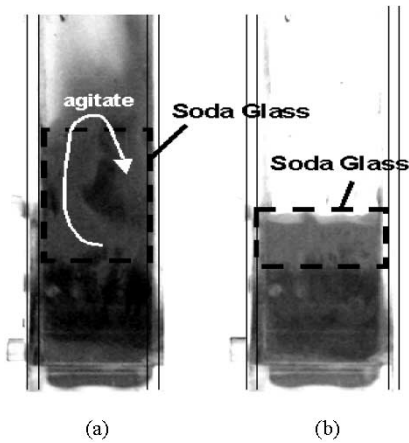
Fig. 6. Separation chamber (soda glass: 37 μm). (a) Pumping mode; (b) stopped mode.

separated when the magnet placed at the bottom of the chamber was removed. This fact shows that 1) magnetic drag force works effectively in this case and 2) the cohesive force between the particles strongly affects the efficiency in separation.

The separation of the sample particles consisting of ferrite and soda glass particles is shown in Fig. 6. Fig. 2 shows the case of a sample consisting of ferrite and alumina particles, whose alumina particles accumulated in the upper part of the chamber after the supply of compressed air was stopped. In case of a mixture of ferrite and soda particles, it was hard to maintain a separated state when the size of the soda glass particles was 37 μm. Due to the weak cohesive force between the ferrite and the soda glass particles, some amount of the glass particles fell down onto the bed of the separated ferrite particles after the supply of the air was stopped. The reason for the decrease in the separation efficiency for ferrite particles can be deduced from the fact that mixing of the separated particles occurred near the boundary between the bed of ferrite and glass particles.

Since the distribution of the magnetic field used affects the manner of aggregation of the ferrite particles on the bed in the chamber, improvement in the outlet for the samples in the apparatus is needed to avoid the remixing of particles after the flow of air is stopped.

IV. CONCLUSION

An air-blow type of magnetic separation apparatus was constructed for establishing the designing methodology of dry magnetic separation. The particle size dependency of ferromagnetic particles on the separation efficiency was investigated together with the effects of the cohesive force of the particles.

The samples employed in the present study were ferrite, alumina and soda glass particles having a diameter smaller than 45 μm. At the separation chamber in the developed apparatus, the mixed powder (ferrite and alumina/soda glass) is stirred by pressurized air and the ferrite particles are attracted with a magnet placed at the bottom of the apparatus. The ferrite and alumina particles are accumulated at the lower part and upper part of the separation chamber, respectively. It was confirmed that by adopting an air blow system, the mixed particles could be efficiently stirred and magnetic separation achieved in a short time. The alumina separation efficiency at the upper part was close to 100% when the particle size was relatively large (45 μm for alumina and 44 μm for ferrite). The smaller the size of ferrite, the lower the separation efficiency because the magnetic force is proportional to the volume of the particles. The effect of the cohesive force is found to be stronger when the mixture is ferrite and alumina whose diameter is smaller because the specific surface area of smaller diameter becomes larger. When the mixture consists of ferrite and soda glass, approximately 100% of separation efficiency is achieved because the cohesiveness of soda glass is very small. It was found that the separation efficiency depends on the chemical characteristics of the surface of the mixed particles.

The gradient of the magnetic field used in this experiment was not very high and the magnetic force not as high as in HGMS. To increase the magnetic force the magnetic gradient has to be increased and the gas flux optimized for establishing the design methodology of dry magnetic separation equipment.

REFERENCES

[1] N. I. Gelperin and V. G. Einstein, *Fluidization*, J. F. Davidson and D. Harrison, Eds. London: Academic Press, 1971, pp. 541–568.
[2] T. Shirai, *Rhudoso*. Kanazawa: Kagaku Gijyutusya, 1982, pp. 121–127.
[3] Y. Sakai, N. Kato, Y. Matuda, and T. Watanabe, "TML Annual Report Supplement I,", 2002.