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Research on high gradient magnetic separation of pneumatic conveyed powder products: Investigation from the viewpoint of interparticle interactions

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ABSTRACT

The separation and removal of the metallic debris originating from pipe of manufacturing line are required in the manufacturing process of the fine particle products. In this study, we develop a high gradient magnetic separation system (HGMS) under a dry process by using a superconducting magnet to remove ferromagnetic particles such as the material stainless steel (SUS). To avoid the obstruction of the separation part by aggregation of the processed material, we develop a magnetic separation system using a pneumatic conveying as a new transportation method of the particles.

The magnetic separations were experimented under the same conditions on different days, but the results were different. The reason is considered to be the difference in adhesion force between the particles due to a change of humidity, we have measured the adhesion forces between the ferromagnetic particles and the paramagnetic medium particles using AFM (Atomic Force Microscope) while changing the humidity. As a result, the adhesion force between the particles increased with the increasing of humidity. Furthermore, we saw that the effect of relative humidity was larger in the adhesion force of alumina with larger cohesive property. Based on these results, an appropriate condition of the separation experiment was clarified. And a dehumidification mechanism was introduced.

1. Introduction

In manufacturing processes of fine powder products such as foods, medicines or industrial materials, there is an issue of interfusion by metallic debris originated from manufacturing lines such as pipes and moving parts, separation and removal of these impurities are required. To solve the problem, we have developed a high gradient magnetic separation system (HGMS) under dry process by using a superconducting magnet to separate the ferromagnetic particles such SUS particles. Generally, dry separation has the advantage that drying process is not required in comparison with wet separation. However, in dry HGMS method, a blockage of magnetic filters due to aggregation and deposition of the powders is a serious problem. Our previous study reported the possibility to reduce the blockage by using filters designed with consideration of a repose angle for the powders [1]. In this study, for the fundamental resolution of the blockage, we have developed a magnetic separation system using a pneumatic conveying as a new transportation method of particles [2–6].

In this paper, we examine the reason of difference in results of magnetic separation efficiency on different days despite of same experimental conditions. One of the possibilities is considered to be a change in an interparticle interaction depending on relative humidity, thus adhesion forces acting between the ferromagnetic particle and the paramagnetic medium particle are measured using AFM (Atomic Force Microscopy). Since we had already succeeded to measure the adhesion force between single particles [7]. A further investigation for a relationship between relative humidity and the adhesion forces was conducted. Based on the relation between the adhesion forces and relative humidity, appropriate experimental conditions and a design of magnetic separation system are discussed.

2. Theory of magnetic separation

The magnetic separation is a method to capture and to separate targeted particles selectively by the difference of magnetic forces acting on the ferromagnetic and the paramagnetic particle. In the magnetic separation from a fluid, forces acting on a ferromagnetic particle are mainly a magnetic force, a drag force and a gravity force. These forces are respectively shown by Eqs. (1)–(3),

$$\mathbf{F_M} = \frac{4}{3}\pi \mathbf{r_p^3}(\mathbf{M}\cdot\nabla)\mathbf{H} = \frac{4}{3}\pi \mathbf{r_p^3}\left(\mathbf{M_x}\frac{\partial}{\partial \mathbf{x}} + \mathbf{M_y}\frac{\partial}{\partial \mathbf{y}} + \mathbf{M_z}\frac{\partial}{\partial_z}\right)\mathbf{H} \quad (1)$$

$$\mathbf{F_D} = \mathbf{C_D}\frac{1}{2}\rho \mathbf{U^2}\frac{\pi}{4}\mathbf{r_p^2} \quad (2)$$

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$$\mathbf{F_G} = \rho_\mathbf{p}\frac{\mathbf{4}}{\mathbf{3}}\pi\mathbf{r_p^3 g} \tag{3}$$

where $\mathbf{M}$ is the magnetization (Wb/m^2), $\mathbf{H}$ is the external magnetic field intensity (A/m), C_D is the drag coefficient (–), ρ is the medium density (kg/m^3), $\mathbf{U}$ is the flow velocity (m/s), r_p is the particle radius (m), ρ_p is the particle density (kg/m^3) and $\mathbf{g}$ is the gravity acceleration (m/s^2). The resistance coefficient C_D is determined by Reynolds number Re(-). The Reynolds number is a ratio of 4 fictitious force and a viscous force in the fluid as shown as follows:

$$Re = \frac{Ud}{\nu} \tag{4}$$

where U is the flow velocity (m/s), d is the characteristic length (m) (here corresponds to particle diameter), ν is the kinetic viscosity (m^2/s). When the Reynolds number is small enough ($Re < 1$) in a laminar flow, the drag force can be calculated by the following Eq. (5) which is indicated as Stokes' resistance law:

$$\mathbf{F_D} = \mathbf{6}\pi\mu\mathbf{r_p U} \tag{5}$$

and μ is the viscosity of the medium (Ps·s). The possibility of magnetic separation can be basically estimated from a balance among the magnetic force, the drag force and the gravity force. In order to achieve the magnetic separation, the magnetic force should be bigger than the resultant of the drag force and the gravity force.

When the ferromagnetic and the paramagnetic particles are adhered to each other to form aggregate, the aggregate are attracted by magnetic force $\mathbf{F}_M$, and they would be dispersed only when the drag force $\mathbf{F}_D$ as a shear stress is bigger than the adhesion force $\mathbf{F}_A$ acting between the ferromagnetic and paramagnetic particles. However, when the drag force is bigger than the magnetic force, the ferromagnetic particle are blown away without being separated to magnetic filters. If the drag force is smaller than the adhesion force, the ferromagnetic particle will be separated together with the medium particles as the aggregate without dispersion. In order to separate the ferromagnetic particles selectively by magnetic separation, the following Eq. (6) must be satisfied.

$$\mathbf{F_M} > \mathbf{F_D} > \mathbf{F_A} \tag{6}$$

The drag force $\mathbf{F}_D$ acting on the aggregates should be larger than the adhesion force between the particles $\mathbf{F}_A$, and also smaller than the magnetic force $\mathbf{F}_M$. To determine experimental conditions based on the above relation, it is necessary to evaluate the adhesion force $\mathbf{F}_A$. In addition, the adhesion force could be strongly influenced by the relative humidity [9]. Therefore, in this study, the magnetic separation experiment was conducted, and differences of results in separation efficiency were discussed considering the changes in the adhesion forces because of the humidity. In order to consider the appropriate separation processing conditions, we have examined the relationship between humidity and the adhesion force acting between the paramagnetic and ferromagnetic particles.

3. Magnetic separation experiment

3.1. Experimental method

In this experiment, two kinds of the particles with different cohesiveness were used as powder medium. Sample A was alumina particles with high cohesiveness (average particle diameter 5 μm) including ferromagnetic SUS beads (average particle diameter 35 μm, SUS304) at a rate of 0.1 wt.%. Sample B was silica particles with low cohesiveness (average particle diameter 20 μm) including the above-mentioned ferromagnetic SUS beads at the rate of 0.1 wt.%. In this study, a superconducting solenoid magnet (100 mm in bore diameter and 460 mm in length) was used for the magnetic separation apparatus designed for powder separation. The experimental apparatus is the same that we published in our previous papers [7]. This system consists of fluidized bed part (200 mm in flow path and 16 mm in pipe diameter) and magnetic separation part (600 mm in flow path and 16 mm in inner diameter). First of all, in the fluidized-bed part, the powder samples and moving mediums (3 g of polystyrene pellets, 1 mm in diameter) were fluidized by blowing compressed air at flow late of 1 L/s. The air flow velocity was decided to 5 m/s considering the adhesion force obtained from adhesion measurements by atomic force microscope (AFM). And then, only dispersed particles through 80 mesh filter were conveyed into the bore of the superconducting magnet. In the magnetic separation part, a magnetic filter (5 meshes, SUS430) was inserted under an external magnetic field of 2.0 T, and ferromagnetic SUS304 beads were separated selectively. The particles which were not captured by the magnetic filter were fed into the upper part of the superconducting magnet, and were collected into a bag which prevents back-flow.

3.2. Results and discussion

Fig. 1 and Table 1 respectively show the experimental results and the experimental conditions. High separation efficiency of 90% in both Sample A and B were obtained. This result indicates a usefulness of this magnetic separation system. As expected, the impurities included in Sample B were separated completely by magnetic separation on both days. On the other hand, considering the separation efficiency of ferromagnetic impurities in Sample A, the separation efficiency on Day 2 was much higher than that on Day 1. The reason is considered to be the lower relative humidity on Day 2. Extremely large aggregates are not formed due to higher dispersion of alumina particles in the low-humidity atmosphere, which makes the separation efficiency in Day 2 higher. To verify this idea, we have investigated adhesion forces between the particles while changing humidity.

For the removal of impurities in food products, separation efficiency of 100% is required. The reason why the separation efficiency do not accomplish 100% could be that the particles were not dispersed sufficiently in the fluidized bed, and were blown away without being captured by magnetic filters because of a bigger drag force than magnetic force. On the basis of these results, it is necessary to improve the magnetic separation equipment and conditions.

4. Adhesion measurements

4.1. Experiment

The adhesion forces acting between the paramagnetic and ferromagnetic particles used in this study were measured. Before

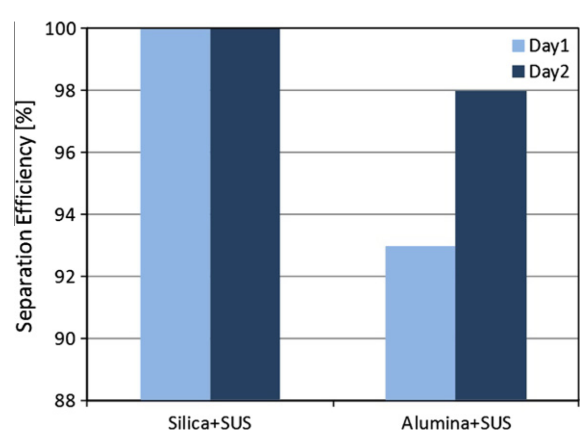

Fig. 1. Separation efficiency of Sample A and B.