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Magnetic separation device for paramagnetic materials operated in a low magnetic field

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Abstract

We have been developing a magnetic separation device that can be used in low magnetic fields for paramagnetic materials. Magnetic separation of paramagnetic particles with a small particle size is desired for volume reduction of contaminated soil in Fukushima or separation of iron scale from water supply system in power plants. However, the implementation of the system has been difficult due to the needed magnetic fields is high for paramagnetic materials. This is because there was a problem in installing such a magnet in the site. Therefore, we have developed a magnetic separation system that combines a selection tube and magnetic separation that can separate small sized paramagnetic particles in a low magnetic field. The selection tube is a technique for classifying the suspended particles by utilizing the phenomenon that the suspended particles come to rest when the gravity acting on the particles and the drag force are balanced when the suspension is flowed upward. In the balanced condition, they can be captured with even small magnetic forces. In this study, we calculated the particle size of paramagnetic particles trapped in a selection tube in a high gradient magnetic field. As a result, the combination of the selection tube and HGMS (High Gradient Magnetic Separation-system) can separate small sized paramagnetic particles under low magnetic field with high efficiency, and this paper shows its potential application.

Keywords: magnetic separation, paramagnetic particle, selection tube, HGMS, low magnetic field

1. INTRODUCTION

We have been developing a magnetic separation system that can be used at low magnetic fields for paramagnetic materials [1].

Magnetic separation methods for paramagnetic particles with small particle diameters are desired for the volume reduction of contaminated soil generated by the Fukushima nuclear power plant accident [2] and for the separation of scale from the water supply facilities of power plants [3].

However, since magnetic separation of paramagnetic particles requires the high magnetic field of a superconducting magnet of 7 T or more, there are difficulties in implementing such a system, including enlarging the bore diameter for mass processing. In addition, installing such a magnet onsite (at the site) poses problems in terms of installation and management costs as well as automated operation and management, and there is an industrial need to increase the separation efficiency of paramagnetic particles without using a high magnetic field as much as possible.

Therefore, we proposed a magnetic separation system that combines a selection tube and magnetic separation, which can separate paramagnetic particles with small particle diameters in a low magnetic field [1].

This paper reports on a selection tube magnetic separation system, comparing its classification performance and processing speed with that of conventional selection tube classification [4, 5], and shows the effectiveness of selection tube magnetic separation.

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2. OPERATING PRINCIPLE AND PHYSICAL THEORY OF SELECTION TUBE

Figure 1 shows the theory of separation technology using selection tubes. As shown in the figure, the selection tube uses the resultant force acting on the particles due to the relationship between the sedimentation speed of the particles suspended in the liquid and the rising speed of the working medium sent from the bottom of the device. This is a device that sorts the particles according to particle size. Drag force $\mathbf{F}_{\mathrm{D}}$, buoyancy force $\mathbf{F}_{\mathrm{B}}$ and gravity force $\mathbf{F}_{\mathrm{G}}$ act on the particles in the selection tube. The resultant force acting on this particle is shown in Eq (1). In addition, the terminal velocity $\boldsymbol{v}_{\mathrm{s}}$ derived from this equation when the velocity $\boldsymbol{v}_{\mathrm{f}}$ of the fluid (working medium) is 0 is shown in Equation (2). By injecting an ascending flow $\boldsymbol{v}_{\mathrm{up}}$ of the same velocity from the bottom of the selection tube, the particles become seemingly weightless and float in the tube.

$$\mathbf{F} = \frac{4}{3}\pi r^3(\rho_p - \rho_f) - 6\pi\eta r(\boldsymbol{v}_{\mathrm{f}} - \boldsymbol{v}_p) \qquad (1)$$

$$\boldsymbol{v}_s = \frac{2r^2(\rho_p - \rho_f)g}{9\eta} \qquad (2)$$

Here, r is the particle radius [m], ρ_p is the density of the

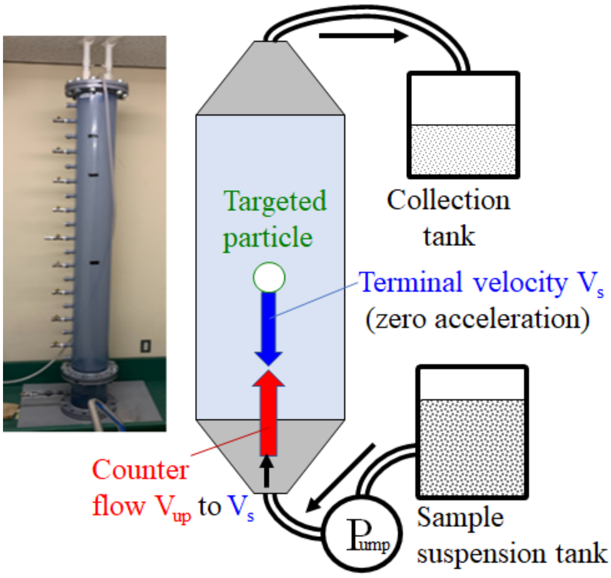

Fig. 1. Schematic illustration and photo of selection tube.

particle [kg/m³], ρ_f is the density of the fluid [kg/m³], g is the acceleration of gravity [m/s²], η is the viscosity of the fluid [Pa•s], $\boldsymbol{v_f}$ is the velocity of fluid [m/s], and $\boldsymbol{v_p}$ is the velocity of the particle [m/s].

3. THEORY OF MAGNETIC SEPARATION

For magnetic separation, the particles to be separated are subjected to the magnetic force F_M, which attracts them to the magnetic field source (in the case of high-gradient magnetic separation, the magnetic filter fine wire), and the drag force F_D, which is a resistive force from the fluid, acting on them, expressed as Eq (3) and (4), respectively. where B is the external magnetic field [T], r is the objective particle radius, χ is the magnetic volume susceptibility, μ_0 is the magnetic permeability of the vacuum [H/m], η is the viscosity of the fluid [kg/m•s], and $\boldsymbol{v_f}$ - $\boldsymbol{v_p}$ is the relative velocity[m/s] between the fluid and the object.

If the magnetic force F_M is greater than the drag force F_D, magnetic separation is possible. Considering particles suspended in a selection tube, it can be assumed that there is equivalently no drag force, so the magnetic force becomes dominant and magnetic separation is expected to be possible even by very low magnetic forces. This is the basic concept of magnetic separation of paramagnetic particles in low magnetic fields.

$$\mathbf{F_M} = \frac{4}{3}\pi r^3 \frac{\chi}{\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B} \tag{3}$$

$$\mathbf{F_D} = 6\pi r\eta\left(v_f - v_p\right) \tag{4}$$

4. EXAMINATION OF MAGNETIC SEPARATION IN A SELECTION TUBE

The magnetic selection tube is a method to capture the target particles even with a small magnetic force

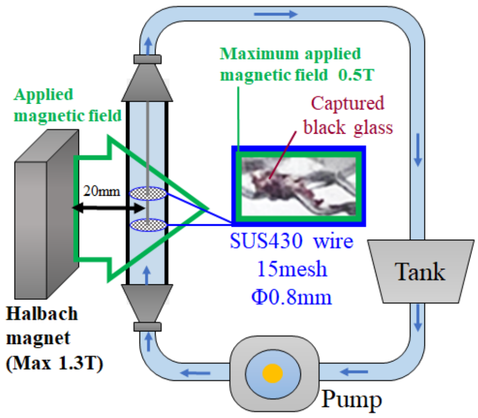

Fig. 2. Schematic illustration of magnetic separation system in a selection tube with an applied magnetic field of 0.5T. "

(externally applied magnetic field of about 0.5 T) by utilizing the phenomenon that the gravity acting on the particles and the drag force are balanced with upward flow (Fig. 2).

The magnetic selection tube is thought to have other significant advantages besides those mentioned above. It is expected to reduce the dispersion of cutoff particle size due to the flow velocity distribution in the selection tube.

The upward velocity in the selection tube has a spatial distribution, with a parabolic velocity distribution that is maximum at the center of the tube and zero at the wall surface. Therefore, the diameter of particles suspended in the tube, as estimated by equations (1) and (2), has a spatial distribution. In other words, the size of particles that settle in the center of the tube is large, and the size of particles that settle closer to the wall is small. Thus, the separation efficiency of the selection tube, which separates particles below a certain size (called the cut-off particle size), is reduced. This is the essential problem with selection tubes.

We have pointed out that magnetic selection tube could solve this problem, which is examined in detail in this paper. As an approach to this problem, we considered the following steps.

(1) Particle size allowed to be suspended for the velocity distribution in the selection tube.

(2) Suspendable particle size under the same velocity distribution and applied magnetic field.

The purpose of (1) was to quantify the basic problem of the selection tube, and (2) was to examine the possibility of using a magnetic selection tube to cover the weak points of the selection tube.

4.1. Investigation of the distribution of particles suspended in the selection tube

The calculation was performed for the case of a paramagnetic black glass particle (specific gravity 3.1, particle diameter 240 μm) as a target and pumped into a selection tube (inner diameter 20 mm) at an average flow velocity of 3.5 cm/s.

To determine the average flow velocity of inlet fluid from the bottom of the selection tube, the radial flow velocity distribution in the tube (from the wall to the center

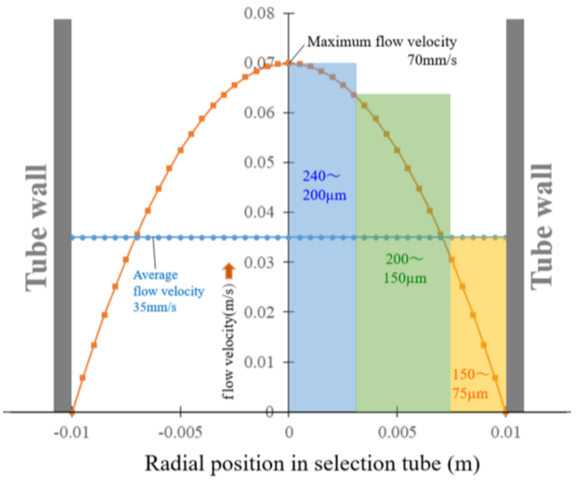

Fig. 3. Flow velocity distribution in the selection tube and particle sizes capable of suspending in the radial direction. The bold gray line in the figure shows tube walls of the selection tube, the yellow, green, blue area shows the suspended particles of 75 to 150 μm, 150 to 200 μm and 200 to 240 μm, respectively. The blue line shows the average flow velocity, and the orange line shows the velocity at the radial position.

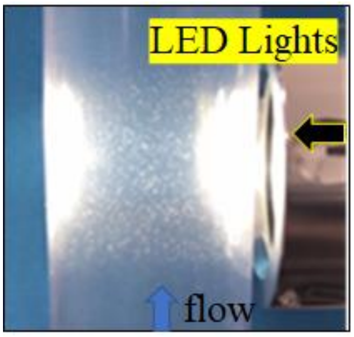

Fig. 4. Photographs of black glass particles (white dots) suspended in a selection tube.

of the tube) at the 20 mm inner diameter shown in Fig. 3 The particle size that could be suspended in the selection tube using Equation (2). The maximum suspended particle size was set to 240 μm (75 μm near the pipe wall).

Fig. 4 shows a photograph of an actual experiment in which black glass particles were suspended using a selection tube.

The particles in the selection tube that are smaller sized than the particles suspended in the tube will flow out of the system.

As shown in the above calculation, the cutoff particle size is set to 240 μm at the maximum flow velocity (a setting where only particles of 240 μm or less are outflowed), but in reality, the cutoff particle size near the wall is 75 μm (actually even smaller) according to the above calculation due to decreased flow velocity as closer to the tube wall. In this means that particles smaller than 75 μm will be flowed out of the system. Hence, the classification of the selection tube alone is not highly efficient, and multiple treatments at various flow velocities are necessary.

4.2. Investigation of the distribution of particles suspended in a selection tube applied magnetic force

In our previous report [1], we performed magnetic separation of a selection tube by applying a high gradient magnetic field, and magnetic separation of colored glass showing paramagnetic particles was possible at 0.5 T (gradB: 625 T/m, the magnetic field gradient was calculated using FEM software ANSYS18.1.). We also reported that the size distribution of particles that could be classified changed with the magnetic field applied.

In the present study, we examined in detail of the cut-off particle size when a similar high gradient magnetic field was applied to particles suspended in the selection tube.

By applying a downward magnetic force to the drag force of particles suspended in the selection tube at an upward flow (= terminal velocity), the diameter of particles that can move downward and be captured was calculated.

4.2.1. Change in suspended particle size under magnetic field

In this calculation, it was assumed that a system utilized downward magnetic force to attract particles with paramagnetic properties (volume magnetic susceptibility of 3.17×10^{-4}). The flow velocity in the tube was set to an average flow velocity of 35 mm/s, as in Fig. 3.

The flow velocity distribution at the radial position in the tube (from the wall to the center), and fig. 5 shows the suspended particles size of each radius position in case of the flow field and/or by varying the applied ideal high gradient magnetic field 0.5, 1 and 2 T.（gradB are about 625, 1250, 2500T/m, respectively.）

The calculations are based on the assumed formation of an ideal high gradient magnetic field at the bottom of the separation area in the selection tube.

The green plots in the figure are the results without magnetic field applied and show the particle size (figure vertical axis) of particles that can be suspended at each radius position.

For example, at r = 0, the cut-off particle size is 240μm, it means that larger particles will not flow out (smaller particles will flow out). At r = 0.005m, the cut-off particle diameter is 210μm. As can be seen from this figure, the diameter of particles that flow out can be estimated to be between 0 ～ 240 μm.

On the other hand, the cut-off particle diameter at r = 0.0095m is 75μm, which means that at this location, particles larger than 75μm will stay in the tube.

This means that particles below the parabolic curve in Fig. 5 will remain in the tube, and particles above the curve can be understood to flow out. (Notice : the Z-axis in this figure is pointing downward).In addition, the cases with magnetic fields of 1T applied are shown in the red plots. At the center of the selection tube (r= 0), the cut-off particle size is 60 μm, and the outflow particles sizes from under 60 μm. As in the discussion above, particles below this curve remain in the tube and particles above the curve flow out.

It is obvious with these figures that as the magnetic field is applied, the difference in cut-off particle diameters between the center and near the tube wall is decreasing. This means that the dispersion of the diameter of the

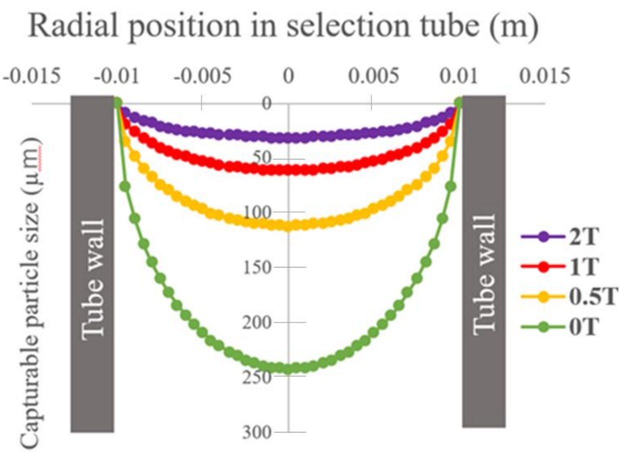

Fig. 5. Particle size that can be captured in the separation tube (applied magnetic fields 0, 0.5, 1, 2 T).

TABLE 1
SIZE OF SUSPENDED PARTICLES IN THE SELECTION TUBE UNDER MAGNETIC FORCE.

applied magnetic field (T)	particle size (μm)		
	r = 0	r' = 0.0095	r - r'
0	240	75	165
0.5	110	34	76
1	60	19	41
2	30	9	21

outflowing particles becomes smaller, allowing for precise classification.

Table 1 shows the particle diameters capable of suspending at the tube center r = 0 and r = 0.0095 (0.5 mm from the tube wall) under a magnetic field applied to the selection tube.

Result from these calculations, it was quantitatively clarified that the application of a downward magnetic field to the selection tube can reduce the particle diameter that flows out of the tube system, thereby reducing the size difference between the particles in the slow flow region near the tube wall and those in the high velocity region and enabling highly accurate classification. (Applying a magnetic field of 0 to 2 T reduced the difference in suspended particle size distribution in the tube from 165 to 21 μm.).

4.2.2. Flow velocity to allow particles to be suspended in the tube

In selection tube classification, when attempting to suspend the smaller particles in the tube, the terminal velocity is also decreasing, as well as the velocity of the up-flow. As a result, the throughput is reduced. Table 2 compares the flow velocities when the particle size suspended at r = 0 when a magnetic field is applied (at 0.5 T, 1 T, and 2 T) and when the particle size is suspended in the selection tube (at 0T).

TABLE 2
COMPARISON OF MAXIMUM FLOW VELOCITIES IN A SELECTION TUBE UNDER APPLIED THE MAGNETIC FORCE.

	particle size (μm)		
maximum flow verocity with magnetic field 70.0 (mm/s)	110 [0.5T]	60 [1T]	34 [2T]
maximum flow verocity without magnetic field (mm/s)	14.5	4.3	1.4

TABLE 3
COMPARISON OF PARTICLE SIZE AND MAXIMUM FLOW VELOCITY IN A SELECTION TUBE FOR SMALL PARTICLE SIZE.

	particle size (μm)	maximum flow velocity (μm/s)
without magnetic field (0T)	0.8 ~ 5	30
with magnetic field (2T)	1.6 ~ 5	225

As the magnetic force is act on the opposite direction to the flow , if the same size particles are attempted to suspend, highly precise classification can be performed by using applied magnetic field from the results of 4.2.1 also, the flow velocity is higher and the throughput is larger.

5. APPLIED TO SMALL DIAMETER PARAMAGNETIC PARTICLES

The case of small size particles of a few μm in diameter classified in a selection tube with a magnetic field applied was examined in the same way.

Table 3 shows the results of an attempt to classify particles with a secondary particle size of 5 μm in the selection tube under magnetic field of 2 T.

For smaller particle sizes, there is no significant difference in the suspended particle size distribution.

As smaller particle size decreases, the effect of magnetic force is also lower. However, the throughput can be increased more than 7 times.

The Reynolds number becomes small in this flow velocity region, so it is possible to expand the diameter of the selection tube to a few meters. (Reynolds number ≈ 400 in the case of a tube diameter of 2 m and a flow velocity of 0.2 mm/sec).

The effect of an applied magnetic field on the selection tube to increase the throughput is particularly important for small particle sizes classification

6. CONCLUSIONS

We proposed a magnetic separation system that combines a selection tube and magnetic separation, which can separate paramagnetic particles with small diameters at low magnetic fields, and compared its classification performance and processing speed with that of conventional selection tube classification.

As a result, it was confirmed that the application of magnetic force to the selection tube enables highly precise classification of particles that can be suspended in the tube, and that an improvement in processing speed can be expected.

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