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Development of recovery device for particulates in fluid by magneto-Archimedes separation

Tsutomu Ando [a,*], Noriyuki Hirota [b], Motoyasu Maie [a,1]

[a] Department of Mechanical Engineering, College of Industrial Technology, Nihon University, Narashino, Chiba 275-8575, Japan
[b] Fine Particles Engineering Group, Materials Processing Unit, National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan

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ABSTRACT

This paper proposes a novel recovery device and a suitable recovery method for magneto-Archimedes separation. Separation and recovery of mixed colored glass particles in fluid was demonstrated using this developed device, which has some compartments divided by movable partitions. One compartment used for levitation and separation is located on the central axis of the bore in the superconducting magnet, and the other compartments which store captured particles are located in the off-centered position. Because the captured particles remain around the center due to the restoring force to the center, this device realized a smooth recovery operation without getting stuck. The recovery ratio was also quantitatively examined by counting glass particles with two recovery methods. One recovery method is based on direct separation of randomly mixed colored glass particles just after their levitation. The other is based on differently levitated colored glass particles collected during a second levitation starting from a stack of glass particles formed on the difference in colors after sorting during first levitation. The recovery ratio with the latter was 25% higher than that with the former.

1. Introduction

With developments in superconducting technology, the advent of cryo-cooler-operated superconducting magnets that produce magnetic fields of over 10 T make it possible to move feeble magnetic materials without contact and to show various interesting physical phenomena [1–14]. By actively using these intrinsic magnetic properties all materials possesses, industrial application of new methods of material processing [15–18] and new technologies of substance separation [19,20] have been investigated.

High gradient magnetic separation and magneto-Archimedes separation are used for separation of feeble magnetic materials, using magnetism. Though magnetic levitation of diamagnetic materials is possible [1], an extraordinary high and steep magnetic field gradient to levitate many diamagnetic materials is necessary, which is not practical. High gradient magnetic separation can separate paramagnetic particles from the medium [21], but this method is basically used much for isolation of ferromagnetic materials [22–28], and can only capture one targeted material. In addition, this method can separate the targeted material continuously, but therefore, it is required that the medium is flowing. On the other hand, magneto-Archimedes separation [26,29–37] can separate a large variety of feeble magnetic particles of both para and diamagnetic materials simultaneously without the flow, but therefore, this method was mainly applied to batch processing than continuous processing. Though the recovery rate of high gradient magnetic separation depends on the magnetic susceptibility, size of particle, and the flow rate, magneto-Archimedes separation can realize recovery of 100% in principle without depending on those. In general, electromagnet is applied in high gradient magnetic separation, but superconducting magnet is used in some cases [22–25,27]. When superconducting magnet is applied, energy consumptions in both of high gradient magnetic separation and magneto-Archimedes separation are almost zero in recovery operation because superconducting magnet does not consume energy in superconducting state except the cooling of superconducting magnet. High gradient magnetic separation is currently tried on the water purification as a major magnetic separation and recovery method. However, magneto-Archimedes separation has not been put to practical use because recent research toward such use has been only conducted on food processing [35] and the others remain fundamental study [36,37].

Magneto-Archimedes separation takes advantage of the difference in levitation position determined by the differences in density

* Corresponding author at: Nihon University, 1-2-1 Izumi-cho, Narashino, Chiba 275-8575, Japan. Tel.: +81 47 474 2338; fax: +81 47 474 2349.
E-mail address: ando.tsutomu@nihon-u.ac.jp (T. Ando).
[1] Present address: Ibaraki Auto parts Center Co., Ltd., Ishioka, Ibaraki 315-0124, Japan.

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and magnetic susceptibility of material from the surrounding medium. The greatest advantage of this method can separate not only heterogeneous substances but also common base materials whose levitation positions differ due to the inclusion of impurities or additives in minute amounts. Unlike other separation methods, this method is unique in that it can separate multiple substances simultaneously. Moreover, it is easy to use without filters because the separated substance is isolated without having it physically contact other substances. Therefore, not only in scarce material recycling, this separation method has a large amount of potential as a separation and analysis method in the medical, chemical and biological fields [31–37]. However, quantitative evaluation of the recovery ratio with this method has not yet been reported.

A separation and recovery experiment of colored glass particles in fluid was conducted by using a device developed for magneto-Archimedes separation, and quantitative evaluation of the recovery ratio is reported. Two recovery methods were used and their recovery ratios were compared. On a basis of these results, this paper proposes a suitable recovery method for separation based on magneto-Archimedes levitation.

2. Materials and experimental system

Three types of colored glass particles; pink, green and brown, of around 1 mm in diameter were used. The volume magnetic susceptibility and density of these colored glass particles were measured by using SQUID (MPMS-5) of Quantum Design Inc. and dry-type density meter (Accupyc 1330) of Micrometrics Instrument Corporation, respectively, as shown in Table 1. As a medium, 8 wt.% $MnCl_2$ aqueous solution was used and its physical properties were calculated based on scientific data as shown in Table 2. The volume magnetic susceptibility of $MnCl_2$ aqueous solution of a certain concentration was obtained from those of pure $MnCl_2$ and water (H_2O) [38] in consideration of the density. Here the density was obtained from the fitting curve based on the measured values of the aqueous solution of multiple concentrations. A superconducting magnet manufactured by Sumitomo Heavy Industries, Ltd., which generates a maximum magnetic flux density of 12 Tesla (T), was used. Fig. 1 shows a schematic view of the experimental setup. The area surrounded by dashed lines shows the operational zone. The bottom of the operational zone ($z = 0.1$ m) is the initial position of particles and corresponds to the bottom of the experimental apparatus.

Table 1
Physical properties of colored glass particles; measured values.

Color of glass particle	Density ρ_p ($\times10^3$) (kg/m^3)	Volume magnetic susceptibility χ_p ($\times10^{-6}$) (– (SI))
Pink	2.497	−8.27
Green	2.509	−2.02
Brown	2.512	2.33

Table 2
Physical properties of medium; calculated values based on scientific data [38].

Medium	Density ρ_f ($\times10^3$) (kg/m^3)	Volume magnetic susceptibility χ_f ($\times10^{-4}$) (– (SI))
$MnCl_2$ aq. (8 wt.%)	1.06	1.13

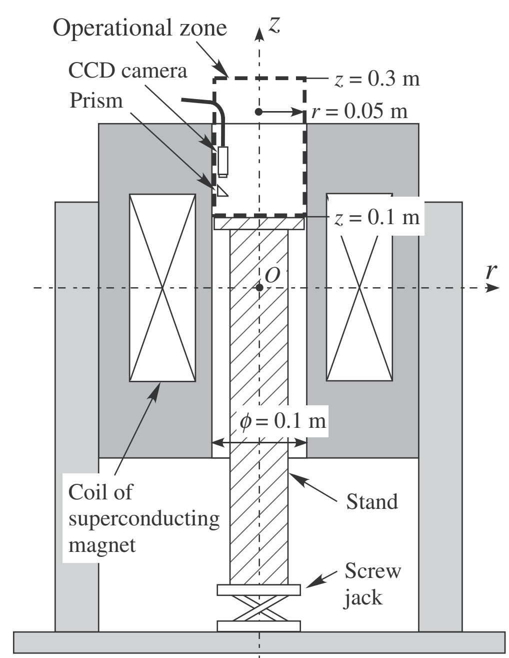

Fig. 1. Schematic of experimental configuration.

3. Magneto-Archimedes separation

3.1. Confirmation of physical phenomena

Magneto-Archimedes separation was conducted in a measuring cylinder to confirm only physical phenomena. Fig. 2 shows a series of images in the separation process. One division of the scale on the measuring cylinder was approximately 1.4 mm in length. The initial situation without magnetic field, 0 T, is shown in Fig. 2(*a*). Here mixed colored glass particles in three types are laid in the medium of 8 wt.% $MnCl_2$ aqueous solution. When the applied magnetic field was increased gradually from 0 T, the pink glass particles began to levitate first, as shown in Fig. 2(*b*). At the same time, the green and brown glass particles moved to the center but still remained at the bottom as the magnetic force in the vertical direction, which acts on these glass particles, was smaller than their relative weight with respect to the surrounding medium. When the applied magnetic field was increased further, the green glass particles began to levitate, as shown in Fig. 2(*c*). At the same time, the brown glass particles remained at the bottom, as in the previous situation, due to the lack of magnetic force in the vertical direction. As the applied magnetic field was increased further, all the glass particles remaining at the bottom finally levitated. Fig. 2(*d*) and (*e*) shows the situation at 8 and 10 T, respectively. At the beginning of levitation (Fig. 2(*c*) and (*d*)), the colored glass particles of each color gathered into a cluster at the center of the bore of the superconducting magnet, but they then spread radially (Fig. 2(*e*)). In this experiment, the colored glass particles levitated in the order of pink, green, and brown, and this order indicates the lightness in relative weight of particles including magnetic property. Then, the distances between the three levitation positions in Fig. 2(*e*) were smaller than those in Fig. 2(*d*).

As the introduction in Section 1 explained, magneto-Archimedes levitation does not depend on particle size in principle. In the case that the surrounding medium is fluid, it has been confirmed that particles of more than 20 μm were separated [39]. However, in the case of particle size of less than 20 μm, it is difficult to separate and collect all particles because the levitation point of particles is uncertain by Brownian motion of particle.