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Magneto-Archimedes levitation and its application

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A novel magnetic-separation method, which uses the magneto-Archimedes levitation technique, has been introduced and evaluated. Magneto-Archimedes levitation is an easy way to attain the levitation of feeble magnetic materials by ordinal superconducting magnets with the aid of the magnetically induced buoyancy force that comes from its surroundings. The stable levitation position in a magnetic field depends on the materials because it is determined by the difference in volume magnetic susceptibilities and densities between objects and surroundings. By using this feature, we have successfully demonstrated a novel magnetic separation technique. The samples levitated were NaCl-KCl grain mixtures and colored glass particles. When they were levitated with the magneto-Archimedes technique, the initial mixture underwent separation into each kind of the ingredient particle aggregates. In this study, conventional diamagnetic levitation and magneto-Archimedes levitation are compared, and the novel magnetic separation and its features are demonstrated.

Introduction

Magnetic levitation of diamagnetic materials such as water or plastics was first attained by Beaugnon and Tournier.1) This technique is attractive in the fields of material processing, crystallization, or microgravity research. However, diamagnetic levitation needs an extraordinarily high magnetic field because the magnetic susceptibility of the diamagnetic materials is very small. For example, the first demonstration of diamagnetic levitation 1) was performed by using a Bitter-type hybrid magnet with a field of over 20 T. There are only limited numbers of institute that can access to such a strong magnet. Hence, it is difficult to apply diamagnetic levitation for practical industrial processes. Another method is called magneto-Archimedes levitation.2, 3) By this technique, levitation can be achieved easily by using a common superconducting magnet. Moreover, even paramagnetic materials can be levitated by controlling the surroundings of the object.

One of the most remarkable characteristics of magnetic levitation is that there is only one position in which an object is stably levitated. When a levitating object in magnetic fields is moved away from a position of equilibrium, a restoration force is at work. This stable point is determined by its volume magnetic susceptibility and density. Therefore, different substances levitated in the field have different equilibrium positions of levitation and can thus be separated. By the application of the magneto-Archimedes levitation technique, we realized a novel separation method for feeble magnetic materials, that is, dia- and para-magnetic materials.4) After that, the trials to apply this technique for practical use were started.4, 5) In this paper, we first describe the principle of magneto-Archimedes levitation and magneto-Archimedes separation. We then show two examples of this novel separation technique and discuss its advantages.

Diamagnetic levitation and magneto-Archimedes levitation

Diamagnetic levitation is based on the balance in a magnetic force, created by a repulsive force from a field and a gravitational force. The conditions for levitation of a substance with a density ρ and a volume magnetic susceptibility χ are expressed as:

$$-\rho g + \frac{\chi}{\mu_0} B \frac{\partial B}{\partial z} = 0, \tag{1}$$

where g is the acceleration of gravity, μ_0 is the permeability of vacuum, B is the field intensity, and z is the vertical position. Even in the case of water, which can be easily levitated due to its relatively low density and large diamagnetic susceptibility, the value of the product of the field and its gradient, $B \cdot dB/dz$, must be as large as $1400\,\mathrm{T}^2/\mathrm{m}$, while an ordinary superconducting magnet with a field of 10 T and a room-temperature bore of $100\,\mathrm{mm}\phi$ can commonly achieve only about $400\,\mathrm{T}^2/\mathrm{m}$. As a result, diamagnetic levitation requires a very strong magnet.

A stone becomes lighter in water than in air because buoyancy acts on the stone, according to the Archimedes principle. Magneto-Archimedes levitation applies this principle to levitation in a magnetic field. In this case, the influence of the surroundings was taken into account. By considering the contribution of the effect of medium gas (or liquid), the conditions for magneto-Archimedes levitation are expressed as follows:

$$-\rho_1 g + \frac{\chi_1}{\mu_0} B \frac{\partial B}{\partial z} + \rho_2 g - \frac{\chi_2}{\mu_0} B \frac{\partial B}{\partial z} = 0, \tag{2}$$

where ρ_1 and χ_1 are the density and susceptibility of the levitating substance, respectively, and ρ_2 and χ_2 are those of the medium gas (or liquid) around it. In diamagnetic levitation, the latter two terms on the left-hand side in Eq. (2) have been neglected. Under the magnetic field, if the surroundings are sufficiently paramagnetic, the medium gas (or liquid) is drawn towards the field center. If the force is directed downward, then the effective weight of the surroundings will increase. If that occurs, the requirements for magnetic levitation are lowered. For example, by using pressurized oxygen gas of 10 atm as the surroundings, water can be levitated with an ordinal superconducting magnet with a field of 10 T in which $B \cdot dB/dz$ is about 400 $\mathrm{T^2/m}$.[2, 3)]

A stable levitation position in magneto-Archimedes levitation is determined by the ratio of the difference of the magnetic susceptibilities to that of the densities between the objected material and its surroundings. Therefore, different substances levitated in the field have different equilibrium positions. Even if some materials were levitated accidentally in the same position under certain conditions, it would be possible to change the stable point and to separate the materials by changing the properties of the surroundings. This appears to be a novel and useful way to separate the materials. The potential of this magneto-Archimedes separation was evaluated through the following experiments.

Experimental

The magnets used in this study were two cryo-cooler-operated superconducting magnets (Sumitomo Heavy Industries; HF-10-100VHT and HF-12-100VHT). Both of them have a room-temperature bore with a diameter of 100 mm and an axis that is parallel to the gravitational force. One of them can generate a 10 T magnetic field at the center, and the maximum $B \cdot dB/dz$ is 420 $\mathrm{T^2/m}$ (HF-10-100VHT); on the other hand, the other can generate 12 T, and the maximum $B \cdot dB/dz$ is 560 $\mathrm{T^2/m}$ (HF-12-100VHT).

We carried out two kinds of separation experiments. The first was the separation of sodium chloride (NaCl) and potassium chloride (KCl) grains in a pressurized-oxygen atmosphere. Their volume magnetic susceptibilities and densities were $\chi_{\mathrm{NaCl}} = -1.406 \times 10^{-5}$ (in SI unit) and $\rho_{\mathrm{NaCl}} = 2.164 \times 10^3\ \mathrm{kg/m^3}$ for NaCl and $\chi_{\mathrm{KCl}} = -1.250 \times 10^{-5}$ and $\rho_{\mathrm{KCl}} = 1.988 \times 10^3\ \mathrm{kg/m^3}$ for KCl, respectively. To levitate these substances, the oxygen-medium gas must be pressurized higher than in the case of water because the density of a solid substance is usually greater than that of water. For this experiment, a 10 T superconducting magnet was used. Oxygen gas was introduced into a glass tube into which a powder mixture of NaCl and KCl had been previously placed and pressurized to 32 atm. When placed into a magnet bore, the glass tube was shaken lightly to separate the particles. After that, the position of levitation was observed.

The second experiment was the separation of colored-glass particles in a solution of manganese chloride. In glass, color is usually given by doping with impurities. Therefore, glasses with different colors should be different in density and in magnetic susceptibility. Furthermore, they should be separated by means of magneto-Archimedes separation. In our experiment, four colors of glass particles (red, blue, yellow, and black) were used (Satake Glass Co., Ltd.). The densities and magnetic susceptibilities of the particles were measured using a pycnometer and a SQUID (Quantum Design, MPMS-5), respectively, and the results were as follows: red: $\chi = -13.3 \times 10^{-6}$, $\rho = 2.546 \times 10^3\ \mathrm{kg/m^3}$, yellow: $\chi = -9.27 \times 10^{-6}$, $\rho = 3.208 \times 10^3\ \mathrm{kg/m^3}$, blue: $\chi = -2.20 \times 10^{-6}$, $\rho = 3.171 \times 10^3\ \mathrm{kg/m^3}$, and black: $\chi = +317 \times 10^{-6}$, $\rho = 3.199 \times 10^3\ \mathrm{kg/m^3}$. For this experiment, a 12 T magnet was used. The glass fragments were riddled with a $1 \times 1\ \mathrm{mm^2}$ mesh in advance, and smaller particles were used. Each of the glass-particle aggregates of about 0.2 grams was put into a cylinder filled with a 6.0 wt% $\mathrm{MnCl_2}$ aqueous solution ($\chi = +81.4 \times 10^{-6}$, $\rho = 1.052 \times 10^3\ \mathrm{kg/m^3}$). The bottom of the cylinder was then set at the maximum point of $|B \cdot dB/dz|$. As the magnetic field was increased, the behavior of the glass particles was observed.

Results and discussion

Figure 1 is a photograph of levitated KCl and NaCl grains by magneto-Archimedes levitation. After introducing the glass tube that contains the mixture of KCl and NaCl into the bore, two clusters of powders immediately formed and were stably floated in mid-air. The upper and lower clusters consisted of KCl and NaCl, respectively. This figure clearly shows that the two diamagnetic substances were separated as expected.

Photographs of the magneto-Archimedes separation of colored glass particles taken under several magnetic fields are shown in Fig. 2. At the beginning, under a zero field, all the colored glass particles were in the bottom of the cylinder, as shown in Fig. 2 (a). With the increase of the field, the glass particles gradually floated in the solution. When the field in the center exceeded 8 T, the red particles floated (Fig. 2 (b)). After that, the yellow and blue particles floated in succession between 9.0 and 9.5 T (Fig. 2 (c)). Even under 12 T, the black particles did not levitate because their paramagnetic susceptibility was too large. The value $B \cdot dB/dz$ required for the levitation of red, yellow, and blue particles was 205, 298, and 325 $\mathrm{T^2/m}$, respectively. These values were in good agreement with the calculated ones. A comparison between (c) and (d) in Fig. 2 indicates that the distance between the glass flocks was different, i.e., the distance was larger in (c) than in (d). This is due to the difference of spatial distribution of $B \cdot dB/dz$. Around the maximum point of $B \cdot dB/dz$, $z = 113$ mm, $B \cdot dB/dz$ varied gently compared with a higher region. Therefore, the resolution of magneto-Archimedes separation became high in this area.

In the experiment of KCl and NaCl separation, the ratio of $\Delta\chi$ for KCl to that for NaCl was 1.00 : 1.02, and the ratio of $\Delta\rho$ for KCl to that for NaCl was 1.00 : 1.09. By considering this and the resulting position of levitation, it is possible to say that the difference in the equilibrium positions of the two substances is mainly the result of the difference in density rather than that in magnetic susceptibility. On the other hand, in the experiment involving the separation of colored glass, the order of the required absolute value of $B \cdot dB/dz$ corresponds to that of magnetic susceptibilities. Judging from the results in this case, we can say that the equilibrium position is mainly determined by the magnetic susceptibility. In magneto-Archimedes separation, the fac-

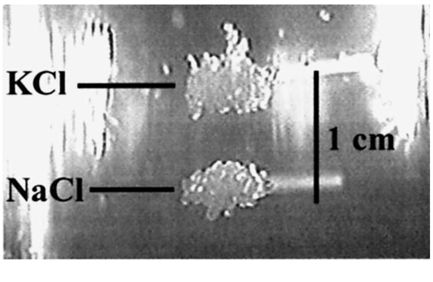

Fig. 1. Picture of NaCl and KCl powders levitated at different positions by magneto-Archimedes separation. The pressure of oxygen gas was 32 atm.

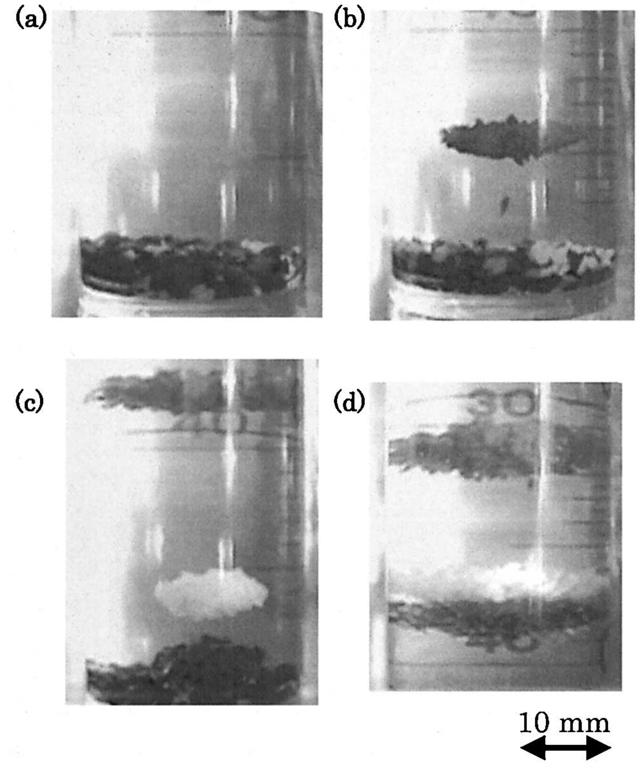

Fig. 2. Magneto-Archimedes separation of colored glass particles. (a) under a zero magnetic field; (b) under 8.0 T at the center of the field; (c) 9.5 T; (d) 12.0 T.

tor to be emphasized can be chosen, that is, the difference of magnetic susceptibilities or the difference of densities, by selecting the proper surroundings.

Conclusion

There are various techniques for magnetic separation. Two examples are picking out iron materials from metal scraps with the use of a magnet and attracting tiny ferromagnetic particles onto steel filter wires (high-gradient magnetic separation). In any case, these techniques can only be applied to ferromagnetic substances because they are based on whether or not a substance is attracted toward higher fields. Therefore, feeble magnetic substances are not attracted and not separated from each other. Another conventional method of magnetic separation is "gravity concentration," which has been well known for a few decades. However, this method is controlled solely by the density of solid materials, and those with an equal density cannot be separated.

The magnetic separation of feeble magnetic particles demonstrated in this study could be readily achieved with the aid of the magneto-Archimedes principle by using an ordinary superconducting magnet. This separation technique resulted from the difference in material density and volume magnetic susceptibility and should enable the fast separation of a powder mixture composed of more than one substance into separated clusters. We confirmed that this method is sensitive to both material density and magnetic susceptibility. This technique will be a powerful way for the practical separation of feeble magnetic materials. The separation of colored glass particles with the magneto-Archimedes technique seems to be an especially useful process for recycling.

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