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Separation of a mixture of particles into its individual components with the aid of the magneto-Archimedes separation

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ABSTRACT

The magneto-Archimedes separation allows for separating mixtures of feeble magnetic materials into its components based on the difference of their densities and magnetic susceptibilities. So far, this technique was applied for the separation of relatively large particles of several millimeters in diameter. Here we apply this technique experimentally to the simultaneous quantitative analysis of multiple micrometer-sized particles in a fluid. It was confirmed that the magneto-Archimedes separation can be applied for the separation of mixture of microspheres larger than 20 μm. Further high performance separation efficiency is expected with the optimization of separation conditions including the control of the spatial distribution of the magnetic field.

1. Introduction

Magnetism is a property that all materials have. By applying a high magnetic flux density of more than 10 T, dynamic effects can be imparted even on diamagnetic or paramagnetic materials (feeble magnetic materials). Therefore, the behavior of all materials can be controlled without any direct contact utilizing high magnetic fields. The intensity of the magnetic force acting on feeble magnetic materials becomes large under high gradients of the magnetic field intensity. It is known that diamagnetic materials such as water can be levitated under such conditions called the diamagnetic levitation [1]. In addition, paramagnetic materials can be levitated if the differences of magnetic susceptibilities and densities of objects' materials and the surrounding medium are controlled by selecting surrounding media properly [2]. This method is called as the magneto-Archimedes levitation technique. When a mixture of different materials levitates in the field, the separation of materials can be attained because different substances have different equilibrium levitation positions under a certain magnetic field distribution due to their different materials' properties.

The magnetic ore concentration using magnetic fluids as the surrounding medium is known as a way of separation that based on the levitation of materials in fluid [3–5]. This will require a much lower intensity of magnetic field because of the superparamagnetic nature of magnetic fluids. However, the separation is attained based only on the difference of densities. Furthermore, it seems not suitable for the separation and analysis of biological materials.

So far, the principle of the magneto-Archimedes separation was provided and then, some demonstrations were carried out using relatively large particles of millimeters in size. Smaller micrometer-sized particles are affected heavily by the thermal energy, although it should nevertheless be possible to apply the magneto-Archimedes separation principle. This would allow to replace quantitative batch-run medical analyses (e.g., tests based on the antigen-antibody reaction) concurrently for multiple components. In this study, we experimentally evaluated whether the magneto-Archimedes separation technique can be applied on the separation of micrometer-sized particles in a fluid.

2. Magnetic levitation and magneto-Archimedes separation

To apply high magnetic field of more than 10 T, a superconducting magnet is generally used. The inside of the winding core, the bore, of the superconducting coil is used as the experimental space. The magnetic field in the bore is spatially distributed. Fig. 1(a) shows the spatial distribution of the magnetic flux density in the superconducting magnet bore used in this study, model JMTD13C100 manufactured by JASTEC Inc., as an example. This magnet has a room temperature bore of 100 mm in

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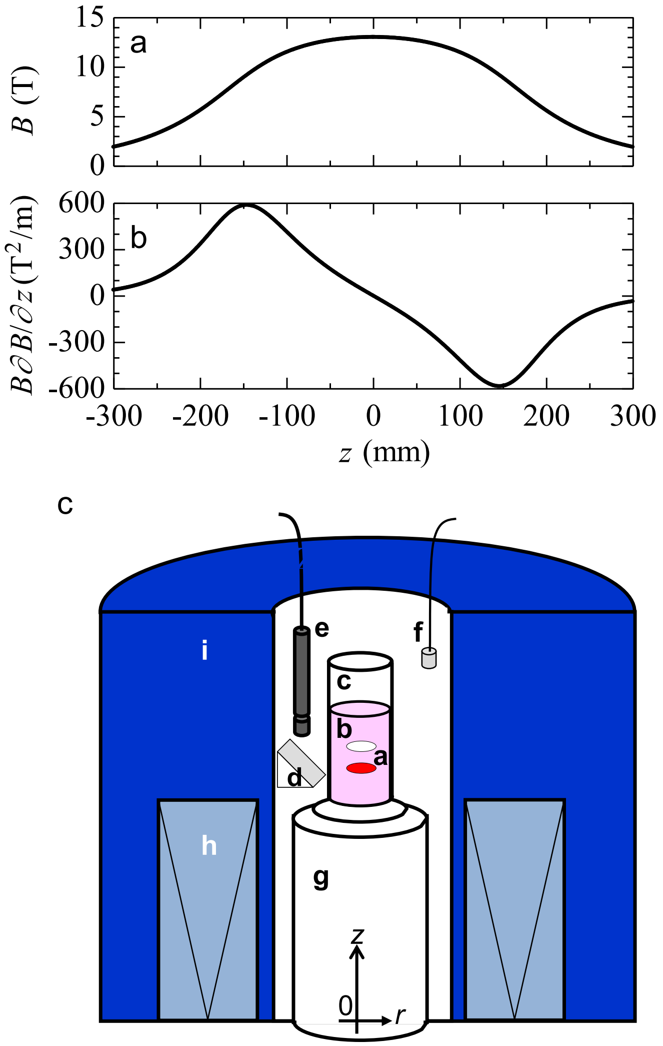

Fig. 1. Distributions of the magnetic flux density (a), the product of the flux density and its gradient (b) along the bore axis of the superconducting magnet used in this study and a schematic figure of the experimental set up (c), where a: samples, b: surrounding media, c: sample container, d: mirror, e: CCD camera, f: LED, g: stage, h: superconducting coil, i: superconducting magnet. The bottom of sample container was fixed at $z=140$ mm.

diameter and can generate up to 13 T along the bore axis. The horizontal axis in Fig. 1, z, is the position on the bore axis. The magnetic field is maximized at the center of the coil and gradually decreases towards both ends of the bore. Fig. 1(b) shows the product of the magnetic flux density and its gradient that is related to the intensity of the magnetic force acting on materials, along the bore axis. The maximum magnetic force is acting on materials at the off-centered position where gradients are high.

As described above, the levitation of diamagnetic materials can be obtained by exerting large upward magnetic force in vertical direction with applying high gradient magnetic fields. Diamagnetic levitation such as water was reported by Beaugnon and Tournier [1]. In the magneto-Archimedes levitation that takes into account the magnetic contribution of surrounding medium, the condition to attain the levitation becomes easier and even paramagnetic materials can be levitated [2]. By considering the contribution of the effect of surroundings, the condition for magneto-Archimedes levitation is expressed as follows,

$$-\rho_1 g + \frac{\chi_1}{\mu_0} B \frac{\partial B}{\partial z} + \rho_2 g - \frac{\chi_2}{\mu_0} B \frac{\partial B}{\partial z} = 0 \quad (1)$$

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 around it, g is the acceleration of gravity, μ_0 is the permeability of vacuum, B is the flux density, and z is the position along bore axis.

Since the magnetic susceptibility of diamagnetic materials is very small as 10^{-5} and negative, high and steep gradient magnetic fields are required to attain the magnetic levitation. Even in the case of water, which can be levitated more easily due to its relatively low density and large diamagnetic susceptibility, the value of $B \cdot \partial B/\partial z$ required for levitation is 1400 T^2/m, while typical superconducting magnets with a flux density of 10 T and a room temperature bore of 100 mm can commonly achieve only about 500 T^2/m. This value is approximately proportional to the square of B. As a result, diamagnetic levitation requires a very high field magnet. On the other hand, the magnetic field condition required for the levitation can be decreased by considering the magnetic contribution from surrounding media. For example, by using pressurized oxygen gas of 1 MPa, water can be levitated by ordinal superconducting magnet with a flux density of 10 T [2]. When materials levitate by the magnetic force, there is a stable levitation position. Even if the materials displaced from their stable levitation position, a restoring force will arise and return the material to the original position. Stable levitation position in magneto-Archimedes levitation is determined by the difference in volume magnetic susceptibilities and densities between the material and its surroundings. Therefore, different substances levitated in the field have different equilibrium positions. Even if, some materials levitated accidentally in the same position under certain conditions, it is possible to change the stable point by changing the property of the surrounding medium. So, it seems to be a potential way of separation. Indeed, several trials have been made to apply this separation technique to practical separation processes of feeble magnetic materials [6–8].

Microspheres that have antigens on their surfaces with magnetic or fluorescent materials are often used for medical analyses such as immunodiagnosis. To evaluate several different antibodies using such system, batch manner analysis is sometimes applied which requires a long time to analyze many antibodies. If different kind of microspheres with different antigens on their surfaces are introduced into the test sample and then, carried out the magneto-Archimedes separation, different microspheres are expected to levitate into different positions. Each component in the test sample can be analyzed quickly with optical methods in levitated condition or by analysis after collection from the fluid. Such a method might thus be a potential way to analyze multicomponent objects included in a fluid, simultaneously. To test the possibility of magneto-Archimedes separation as a way of simultaneous multicomponent analysis, the separation of a mixture of different microspheres was carried out in this study.

3. Experimental

The schematic of the experimental set up is illustrated in Fig. 1(c). Four kinds of glass microspheres listed in Table 1 were used. The soda-lime glass spheres, Model UB-23L made by Union Co., and the borosilicate glass spheres, UB-23MF made by Union Co., were particles of 50 μm size in diameter. For 20 μm size particles, two kinds of silica spheres, Sicastar produced by micromod, were used. To distinguish the difference of them easily when they were separated, two different colored silica particles, red, Sicastar-red (40-00-204), and white, Sicastar (43-00-204), were chosen. Densities and magnetic susceptibilities of particles were measured with the micromeritics Accupyc 1330 pycnometer and Quantum design MPMS XL magnetometer, respectively, and given in Table 1. Table 1 also contains densities and magnetic susceptibilities of