Separation of Solid Polymers by Magneto-Archimedes Levitation

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Solid polymers, including polystyrene, poly(ethylene terephthalate), poly(methyl methacrylate), and so forth, suspended in a paramagnetic aqueous solution were levitated in different vertical positions under a magnetic field gradient. This phenomenon will be used for separating solid polymers.

With recent advances in superconducting technology, high magnetic fields have become available to chemists and materials scientists. As a result, a number of new findings have been reported about magnetic effects on non-magnetic materials.[1] Among these, diamagnetic levitation has drawn attentions: diamagnetic materials, including a water droplet,[2] a piece of glass,[3] and even a frog,[4] can levitate under a high magnetic field gradient. However, it is usually necessary to use a very high magnetic field, B, typically ca. 20 T or over, in order to obtain the condition BdB/dz = 1400 T^2/m, for example, required for the levitation of a water droplet.

On the other hand, it has been demonstrated that the levitation of diamagnetic substance becomes possible with much moderate field strengths if the magneto-Archimedes effect[5] is used. This effect is described by the balance of the gravitational force and the magnetic force acting on the substance:[6]

$$-\Delta\rho\, g + \mu_0^{-1}\Delta\chi\, BdB/dz = 0 \qquad (1)$$

where $\Delta\rho = \rho_1 - \rho_2$ and $\Delta\chi = \chi_1 - \chi_2$ are the difference of the density and that of the magnetic susceptibility, respectively, between the substance (suffix 1) and the surrounding liquid (suffix 2); g and μ_0 are the acceleration of gravity and the magnetic permeability of the vacuum, respectively; B the magnetic flux density, and z, the vertical coordinate. The forces relating to suffix 1 are of volumetric forces acting directly on the substance, while the forces relating to suffix 2 are those acting on the substance through its surface. The levitation in the vacuum is described by equating ρ_2 and χ_2 to zero.

From equation (1), it is evident that a smaller value of BdB/dz is sufficient for the levitation if a larger $\Delta\chi$ and/or a smaller $\Delta\rho$ is chosen. Ikezoe et al.[6] used pressurized oxygen gas (paramagnetic) in order to obtain a larger $\Delta\chi$, which enabled them to levitate even paramagnetic substances. An alternative is to choose a surrounding medium so that its density becomes closer to the substance to be levitated. This idea is similar to that of the enhanced Moses effect.[7] In this report, the magneto-Archimedes effect is used to separate solid polymers suspended in a paramagnetic aqueous solution.

Polymer samples used in this study were pellets of atactic polystyrene (PS), poly(ethylene terephthalate) (PET), poly(methyl methacrylate) (PMMA), syndiotactic polypropylene (sPP), and styrene-butadiene block copolymer (SB). The densities ρ_1s of these polymer pellets were determined with a pycnometer at 25 °C. They were 1.044 (PS), 1.409 (PET), 1.180 (PMMA), 0.872 (sPP), and 1.003 g/cm^3 (SB). The densities ρ_2s of the manganese chloride ($MnCl_2$) aqueous solutions were also determined with a pycnometer at 25 °C. They were 1.064, 1.074, 1.082, 1.090, and 1.098 g/cm^3. The volumetric diamagnetic susceptibilities χ_2s of the solutions were determined by the levitation of the droplets of heptane, hexane, and toluene whose diamagnetic susceptibilities are available in literature.[8]

A Tamagawa TM-WTF6215C electromagnet was used, generating a horizontal magnetic field of 2.1 T. The profile of the field strength along the vertical direction was supplied by the manufacturer. This profile was curve-fitted by the summation of a number of Gaussian functions and hence the gradient was calculated analytically.

Figure 1a shows a schematic diagram of the electromagnet used, where z is the vertical coordinate with the origin being taken in the center of the magnet. Figure 1b shows the profile of the magnetic field B and the quantity BdB/dz, as a function of z. It should be noted that $BdB/dz < 0$ when $z > 0$ (above the center of the magnet) and $BdB/dz > 0$ when $z < 0$ (below the center of the magnet). In addition, $\Delta\chi < 0$ in the present study since the solution is paramagnetic ($\chi_2 > 0$) and the polymers are diamagnetic ($\chi_1 < 0$). Therefore, only two combinations regarding the sign of BdB/dz and $\Delta\rho$ are allowed in order to have a solution to equation (1), namely, (i) $BdB/dz < 0$ and $\Delta\rho > 0$ and (ii) $BdB/dz > 0$ and $\Delta\rho < 0$. In the case of (i), the pellets heavier than the liquid levitate, while in the case of (ii), the pellets lighter than the liquid are pushed downward into the liquid (anti-levitation).

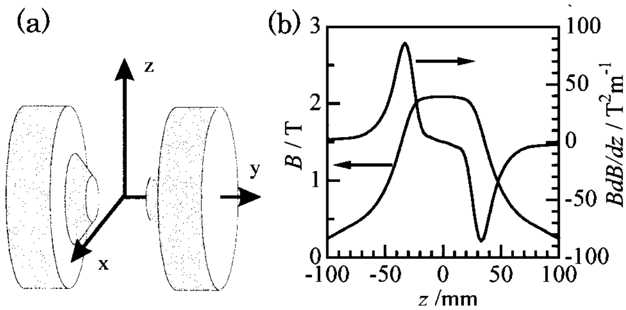

Figure 1. (a) Schematic picture of the electromagnet and the Cartesian coordinates used. The origin corresponds to the center between two pole pieces. The coordinate z is in the vertical direction. (b) The profile of B and BdB/dz plotted against z.

It should be noted that the strength profile of the magnetic field generated by the present configuration of the magnet has a minimum at $y = 0$ along the y-axis, while it has a maximum at $x = 0$ along the x-axis. This means that a diamagnetic substance on the z-axis receives a repelling force in the x direction, while it receives a centering force in the y direction. Therefore, a sta-

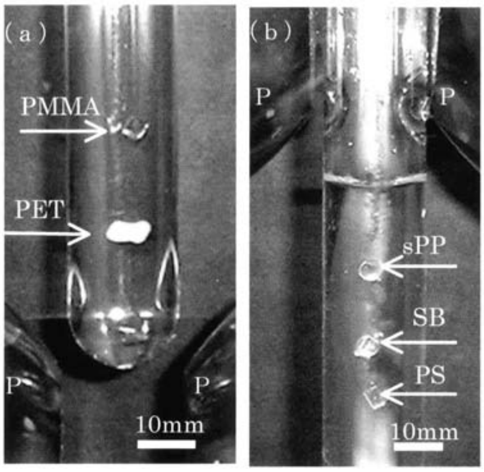

Figure 2. (a) Levitation of PET and PMMA in aqueous solution of $MnCl_2$ ($\rho_2 = 1.098$ g/cm^3, $\chi_2 = 1.7\times10^{-4}$) and (b) anti-levitation of sPP, SB, and PS in the same solution. In the photos, P indicates a pole piece of the electromagnet. Pellets are touching the wall of the sample tube in the direction of the *x* coordinate because the force is repelling in this direction.

ble levitation with respect to the *x* direction is impossible. The motion to this direction is prohibited by touching the wall of the sample tube. In the *z* direction, a repelling force is balanced with the gravitational force acting on the substance, enabling stable levitation at an off-center position.

The levitation of PMMA and PET is shown in Figure 2a. All these pellets were in the bottom of the sample tube in the beginning. Then, the tube was slowly moved from above the magnet toward the magnetic center. At a certain distance from the center, the pellets started to rise from the bottom and a stable levitation is attained as shown in the figure. Figure 2b shows the anti-levitation of sPP, SB, and PS. All these pellets were floating on the surface of the solution in the beginning. Then, the tube was moved from below the magnet toward the magnetic center. At a certain distance, the pellets left the surface and were pushed downward, each reaching a stable position as demonstrated in the figure. The value of *BdB*/*dz* necessary to achieve the levitation and anti-levitation is as small as 10 T^2/m.

The distance between the levitating positions of two different polymers is inversely proportional to *d*(*BdB*/*dz*)/*dz*. This means that a larger separation will be attained if the slope of *BdB*/*dz* is small. In the present case this value is about several hundreds (T^2/m^2). If we have a magnet which has the same value of *BdB*/*dz* but with the slope a hundred times smaller than the present one, the spatial separation would be improved a hundred times. The separation distance would become ca. 170 cm, for example, between PMMA and PET.

In Figure 3, the quantity $\mu_0\Delta\rho g/(BdB/dz)$ is plotted against χ_2. Although the data points are scattering, it is clear that the different polymers fall into different lines. According to equation (1), this plot should give a line with a slope of –1 and with an intercept giving the χ_1 value.

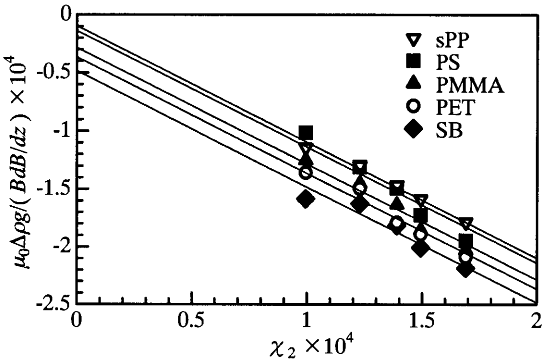

Figure 3. Plot of $\mu_0\Delta\rho g/(BdB/dz)$ against χ_2. The slope of the lines is -1. The intercepts with the ordinate give χ_1 values.

In conclusion, the magneto-Archimedes levitation or the anti-levitation of solid polymers was demonstrated. Polymers with different $\Delta\rho/\Delta\chi$ values levitate in different positions, and hence the separation of solid polymers is possible. Since the position of levitation uniquely depends on the $\Delta\rho/\Delta\chi$ value of the material, the phenomenon reported here could also be useful to characterize unknown materials in terms of $\Delta\rho/\Delta\chi$. The separation described here has a similarity to the separation by a density gradient column. A magnetic field gradient provides an effect similar to the density gradient. However, the magnetic method has an advantage since the field gradient is easily controlled in a flexible manner than the density gradient, enabling us even to design a separation process under a continuous flow system.

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References and Notes

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