Magnetic levitation experiments in Sendai

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Abstract. A levitating apple in a hybrid magnet implies the presence of microgravity conditions under gradient magnetic fields. However, several unique behaviors were found, the orientation of levitating rice grains, the alignment of levitating bismuth particles, and the thermal convection in water under the levitation conditions. These are unlikely under the microgravity conditions in the space and are characteristic of the magnetic levitation. On the basis of the understanding of such behaviors, the magnetic levitation was applied to containerless materials processing, and such an attempt resulted in the development of a magnetic levitation furnace.

1. A levitating apple in a hybrid magnet.
Diamagnetic materials receive a repulsive force in a magnetic field gradient. This force is too small to observe it under magnetic fields ~1 T generated by a conventional electromagnet or a permanent magnet. However, if an apple is placed in a hybrid magnet, the magnetic force could counterbalance the gravity, leading to a levitating state of the apple (Figure 1). This is a symbolic phenomenon implying the presence of microgravity conditions, even though it is not the “Newton apple”.

The first levitation experiment for various diamagnetic solids and liquids, water, wood, organic polymers, etc. was conducted by Beaugnon and Tournier using a hybrid magnet at the high magnetic field laboratory in Grenoble [1]. Then, several levitation experiments for many materials and living animals have been done in other high magnetic field laboratories in the world [2-6], and the applications to materials processing have been attempted at the high magnetic field laboratory at Tohoku University in Sendai [7-9].

Figure 1. An apple (a) lying on a dish and (b) magnetically levitating in the hybrid magnet.
When a diamagnetic material is placed in the vertical bore of a solenoidal electromagnet, the potential energy $U$ and magnetic force $F_m$ per unit mass of the material in the vertical direction is given by

$$U = -(1/2\mu_0)\chi_g B^2 + gz + C,$$

$$F_m = (1/\mu_0)\chi_g B(dB/dz),$$

where $\chi_g$ is the magnetic susceptibility per the unit mass, $\mu_0$ is the vacuum permeability, $B$ is the magnetic flux density and $C$ is a constant. The diamagnetic material has negative susceptibility, and thereby it receives an upward repulsive force if it is placed above the center of the magnet. The magnetic levitation can be realized when $F_m = g$, where $g$ is the gravity constant. To levitate an apple, the magnetic force field $B(dB/dz) = -1400$ T$^2$ m$^{-1}$ is required. Since a usual superconducting magnet with the maximum field of 10 T can produce magnetic force fields up to $\sim 400$ T$^2$ m$^{-1}$, a hybrid magnet must be used for the levitation of most diamagnetic materials.

The counterbalance between the magnetic force and the gravity holds for each molecule constituting the materials. It is hence noteworthy that the magnetic levitation provides a quasi-microgravity condition, allowing some similar experiments in a space shuttle. Strictly speaking, however, the magnetic levitation condition is not equivalent to the microgravity in the space. While no stable potential minimum exists in the space, the magnetically levitating materials lie in a “valley” of the potential energy. Moreover, the strong magnetic fields induce the other magnetic field effects on the levitating materials, e.g., magnetic orientation, dipole-dipole interaction, magnetic convection, etc.

For applications to materials synthesis, it is significant to understand the behaviors of diamagnetic materials under the levitation conditions. This is the first topic of this paper.

The magnetic levitation enables many novel techniques in materials synthesis, one of which is containerless synthesis of materials. A containerless technique provides clean environment, that is, free from contamination from a container. Heterogeneous nucleation is suppressed in the containerless

![Figure 2](image_url)

**Figure 2.** Levitating Bi particles in the hybrid magnet with (a) $B_z = 11.7$ T and (b) $B_z = 12.2$ T. Contour lines of the potential energy of Bi with (c) $B_z = 11.7$ T and (d) $B_z = 12.2$ T.
conditions, thus the liquid easily undergoes a supercooled or supersaturated state. Containerless technique has been applied to melt growth of levitating materials. Melting of levitating glasses was carried out without a crucible by using a hybrid magnet and a CO2 laser. This method was called “magnetic levitation furnace” [9]. The second topic is the development of the levitation furnace and thermal behavior of the levitating materials.

2. Levitating behaviors of diamagnetic materials

2.1. Alignment of levitating particles
It is difficult to control levitating materials under contactless conditions. In microgravity of the space, even weak forces such as wetness, which are usually negligible under the gravity condition, have strong effects on the behavior of materials. This is also the case under the magnetic levitation condition. While no stable potential minimum exists for the materials in the space, the magnetically levitating materials lie in a valley of the potential energy. Whether weak forces affect the behavior of these materials or not would thus depend on both the depth and width of the potential valley.

Figure 2(a) shows the magnetic levitation of bismuth particles in an optical cell placed in the hybrid magnet with the magnetic flux density at the magnet center $B_c = 11.7$ T [11]. The levitating particles align vertically around $z = 75$ mm. Figure 2(b) shows the magnetic levitation of bismuth particles at $B_c = 12.2$ T. The particles align horizontally around $z = 82$ mm, and it is noteworthy that they repel each other. Figures 2(c) and 2(d) show contours of the potential energy around the levitating positions in Figures 2(a) and 2(b), respectively. At $B_c = 12.2$ T, the potential valley lies horizontally around $z = 80 \sim 82$ mm (Figure 2(d)). As a result, the levitating particles align horizontally along the potential valley as shown in Figure 2(b). These particles then repel each other, because the diamagnetic moments in all of these particles are in the same direction. On the other hand, at $B_c = 11.7$ T, the potential energy has a local minimum around $z = 75$ mm, $r = 0$, as shown in Figure 2(c). The shape of the potential energy must likely cause the aggregation of the levitating particles in the local minimum. Nevertheless, the bismuth particles align vertically along the $z$-axis as shown in Figure 2(a). This indicates that the attractive force among the diamagnetic moments in the particles causes the vertical alignment.

2.2. Orientation of levitating rice
It is possible to apply the effect of the potential energy valley to the orientation of a levitating material, which has no anisotropy in magnetic susceptibility but has shape anisotropy such as a rotational ellipsoid [11]. Figure 3(a) shows the levitation of two grains of rice in the hybrid magnet at $B_c = 17.8$ T. The rice grains levitate vertically around $z = 76$ mm. On the other hand, they levitate horizontally at $z = 79$ mm with $B_c = 18.0$ T, as shown in Figure 3(b).

When a diamagnetic material without anisotropy in magnetic susceptibility is placed in a

Figure 3. Orientation of levitating rice grains in the hybrid magnet with (a) $B_c = 17.8$ T and (b) $B_c = 18.0$ T.
homogeneous magnetic field, the magnetic orientation depends on the shape anisotropy. For the case of a rotational ellipsoid, the long axis is liable to orient parallel to the magnetic field [12]. Under the magnetic levitation condition, however, the field is highly gradient, and the orientation also depends on the potential energy curve of the material. The calculated shape of the potential energy minimum at \( z = 76 \text{ mm} \) might preferably cause the horizontal orientation, as shown in Figure 2(c). Nevertheless, the orientation of the rice grains is vertical, namely, parallel to the magnetic field, as shown in Figure 3(a). The shape anisotropy is thus responsible for such vertical orientation. On the other hand, the horizontal valley of the potential energy exists around 80 mm, and this horizontal valley is responsible for the horizontal orientation of the rice grains in Figure 3(b).

These results demonstrate that the magnetic levitation allows control of alignment and orientation of diamagnetic materials even under the contactless condition.

2.3. Thermal convection under magnetic levitation conditions

Control of thermal convection is one of the most important factors for materials synthesis. The strong gradient magnetic fields causing the magnetic levitation provide a quasi-microgravity condition, and thus they are expected to suppress the thermal convection. To examine this, the heat transfer behavior in water was investigated in the hybrid magnet [13].

Water was put into a plastic optical cell, whose thickness was adjusted to 3 mm by inserting a spacer. A heater was placed horizontally in the middle of the fluid. The sample cell was placed in the magnet bore, and the position of the heater was adjusted to \( z = 76 \text{ mm} \). The behavior of heat transfer in water was visualized by a liquid-crystal sheet fixed on a spacer; the sheet changed its color from black to green only in the temperature range of 35-40°C or 40-45°C.

Figure 4 shows the heat transfer behaviors in water under the magnetic levitation condition \( B(dB/dz) = -1360 \text{T}^2 \text{m}^{-1} \) (Figure 4(a)) and a stronger force field \( B(dB/dz) = -2880 \text{T}^2 \text{m}^{-1} \) (Figures 4(b) and (c)). In the absence of a magnetic field, thermal convection rises up above the heater, and no convection appears below the heater. This is expected from the density decrease and the buoyancy for the hot water. On the contrary, no clear convection is seen around the heater under magnetic levitation conditions, as shown in Figure 4(a). This result demonstrates that thermal convection is significantly suppressed under levitation conditions, as expected under microgravity conditions. However, the heat transfer behavior is asymmetric on the upside and the downside. A slight convection seems to remain above the heater.

When the hot water with a temperature \( t_2 \) is surrounded by the cold water with a temperature \( t_1 \), the total force acting on the hot water is written by

\[
F = \left( \frac{1}{\mu_0} \right) \{ \chi_v(t_2) - \chi_v(t_1) \} B(dB/dz) - \{ \rho(t_2) - \rho(t_1) \} g, \quad (t_2 > t_1)
\]

\( (3) \)

Figure 4. Heat transfer in water (a) under a magnetic levitation condition \( B(dB/dz) = -1360 \text{T}^2 \text{m}^{-1} \) in temperature ranges of 35-40°C, and under a stronger magnetic force field of \( B(dB/dz) = -2880 \text{T}^2 \text{m}^{-1} \) in temperature ranges (b) 35-40°C and (c) 40-45°C.
where $\chi_v(t)$ and $\rho(t)$ are the magnetic susceptibility per unit volume and the density of water at temperature $t$, respectively. The first term is the magnetic force and the second term is the gravitational buoyancy. When $F = 0$, the buoyancy is cancelled out by the magnetic force, then the thermal convection is expected to disappear. If $\chi_g$ is independent of temperature, the magnetic levitation conditions provide the $F = 0$ state because $\chi_v(t) = \chi_g(t) \rho(t)$. The values of $\chi_g(t)$ and $\chi_v(t)$ are normalized by $\chi_g(20)$ and $\chi_v(20)$, respectively.

The magnetic force field for $F = 0$ decreases gradually with increasing temperature (Figure 6). Figure 4(c) shows the result in the higher temperature range 40-45°C under the same force field $B(dB/dz) = -2880 \, T^2 \, m^{-1}$. Downward convection is seen below the heater, indicating that the magnetic force predominates the buoyancy in this condition. Similar magnetic convection has been observed in a paramagnetic fluid [14], where the temperature dependence of $\chi_g$ (the Curie law $\chi_g \propto t^{-1}$) results in dominant effects of the magnetic force on the thermal behavior of the fluid. In the present case, it is surprising that the magnetic convection can be observed even in diamagnetic water.

3. Magnetic levitation furnace

3.1. Containerless melting and solidification

Containerless melting is one of the most practical and useful applications of magnetic levitation. The advantages of the containerless melting are (i) a clean processing free from contamination from a container, (ii) to produce a supercooled state easily due to the repression of heterogeneous nucleation and (iii) to reach higher temperatures than the melting point of a crucible. Furthermore, in the case of a
magnetic levitation furnace, high magnetic fields are expected to cause orientation of materials with anisotropic magnetic susceptibility.

The design of a magnetic levitation furnace requires several specific features, which are not seen in usual furnaces: The first is to heat samples in high magnetic fields. The second is to install the furnace in a confined narrow space in the hybrid magnet. The third is to observe the behavior of a levitating sample in the furnace. It is indispensable to check that the sample actually levitates in heating and cooling processes. If the magnetic susceptibility of the sample changes at melting or solidification, the sample falls or flies away.

A CO₂ laser furnace is one of heating methods satisfying above requirements. The laser beam is not affected by magnetic fields, and the local irradiation just on a sample allows use of a CCD camera near the sample. A horizontal laser beam from a CO₂ laser is reflected by a concave mirror and focused on the top of a levitating sample in the hybrid magnet.

The first experiment with this furnace was containerless melting of BK7 glass [9]. A cubic glass changed the shape into a perfect sphere after melting and solidification. In the case of the experiment with paraffin (Figure 7), the Marangoni convection was observed in the melting droplet [15]. A paraffin cube containing a few carbon particles was levitating in the hybrid magnet bore at \( B_c = 15.6 \) T (Figure 7(a)). When the laser irradiation melted it (Figure 7(b)), the vertical flow of carbon particles was observed along the droplet surface. Microgravity conditions including the magnetic levitation make it possible to ignore buoyant convection. The local heating from the upper side of the sample induces the inhomogeneity in the surface tension of the droplet, causing the Marangoni convection on the free interface. After turning off the laser, the droplet was solidified into a sphere (Figure 7(c)).

The appearance of the Marangoni convection exhibits that the magnetic levitation provides a quasi-microgravity condition, however, it reduces the effects of magnetic orientation, which is useful for synthesis of functional materials. In order to solve this problem, a homogeneous heating furnace with a YAG laser was designed [15]. The laser light is guided to the top of the furnace through a laser fiber and shaped to a ring by a cone mirror. The beam is then reflected by a concave ring mirror and focused on the levitating sample at the radial center of the furnace. Thereby, the sample can be

![Figure 7](image.png)

**Figure 7.** Containerless melting and solidification of paraffin in the magnetic levitation furnace: (a) before melting, (b) melt droplet, (c) solidification in the CO₂ laser furnace, and (d) falling down during the solidification in the YAG laser furnace.
irradiated homogeneously by the radial beam when its size is smaller than the beam width of 5 mm.

The experiment of paraffin melting was performed with the YAG laser furnace. A slight flow of carbon remained in the melting droplet, but the flow rate was approximately 1/10 as small as that in the CO₂ laser furnace. The homogeneous irradiation in the YAG laser furnace considerably reduced the Marangoni convection, leading to the magnetic orientation of paraffin. The levitating droplet fell at the solidification process, as shown in Figure 7(d), even though the applied magnetic field is kept constant. This indicates that the magnetic susceptibility along the magnetic field decreases due to the magnetic orientation of paraffin molecules. The orientation was confirmed by the measurements of magnetic susceptibility and X-ray diffraction.

The anisotropy in magnetic susceptibility of the falling sample \( \Delta \chi = \chi_\perp - \chi_\parallel \) was evaluated to be \(-0.095 \times 10^{-9} \text{ m}^3\text{ kg}^{-1}\), where \( \chi_\parallel \) and \( \chi_\perp \) are the magnetic susceptibility parallel and perpendicular to the magnetic field, respectively. This value is consistent with the estimation taking account of the magnetic orientation of a single C-C bond in the paraffin molecule [15]. On the contrary, falling of the sample was not observed in the case of the CO₂ laser furnace. Hence, the homogeneous heating in the magnetic levitation furnace reduces the convection, producing a spherical sample with the magnetic orientation. In addition, it is noted that the magnetic levitation condition is quite sensitive to a change in the magnetic susceptibility.

3.2. Thermal behavior of levitating materials

For practical use of the magnetic levitation furnace, it is necessary to understand the thermal behavior of diamagnetic materials in the magnetic levitation conditions. It is known that temperature dependence of magnetic susceptibility of diamagnetic materials is very small. A slight change of the susceptibility, however, affects the sample position in the magnetic levitation. In the experiment of paraffin melting in the magnetic levitation furnace, the sample moved upward by approximately 1 mm by the laser irradiation [15]. This means that \( |\chi_\parallel| \) of the paraffin increases with increasing temperature. From the potential energy profile, the change of \( |\chi_\parallel| \) can be estimated to be 0.5% for the 1 mm upward movement. If the increase of \( |\chi_\parallel| \) is larger than ~10%, the sample loses the horizontal stable position, then it moves to the wall. In order to keep such a sample at the horizontal center, the magnetic field must be adjusted successively during the heating process.

If a levitating sample is heated inhomogeneously and thermal conductivity of the sample is very small, the levitating behavior is complicated. Such an example is the motion of a piece of polymethylmethacrylate (PMMA) in the magnetic levitation furnace with a CO₂ laser, as shown in Figure 8. When the laser was switched on, the levitating sample began to rotate in horizontal plane. A period of the rotation was about 1~2 s, depending on the laser power. When the laser was switched off, the rotation became slower gradually and stopped finally. When the laser was switched on again, the sample started to rotate again.

The origin of the rotational motion is considered to be an inhomogeneous heating of the sample.

![Figure 8](image)

*Figure 8.* Rotational motion of a levitating sample of PMMA heated in the magnetic levitation furnace with a CO₂ laser: (a) and (b) are successive snapshots taken at 0.4 s interval. (c) Schematic illustration of the rotational motion.
When a part of the sample is irradiated by off-centered laser light beam, the increase of $|\chi_g|$ in the heated part causes magnetic force toward the horizontal center because the magnetic field is minimum at the horizontal center at the present height. However, the other part tends to stay on equipotential surface with a concentric circle shape. Consequently, a torque acts on the sample, leading to the rotational motion. The rotational mode depends on the irradiation manner. Actually, the rotation around a horizontal axis was observed in other irradiation. In these thermal motions, the thermal energy given by laser irradiation is transformed into the magnetic potential energy through the increase of $|\chi_g|$, and then transformed into the kinetic energy as a relaxation process.

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