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Stable Levitation of Water by Magneto-Archimedes Principle

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The new method discussed here, Magneto-Archimedes levitation that has been proposed recently by the authors, is a much easier way to levitate substances. In this method, not only the direct magnetic force on the substance but also magnetic force acting on the environmental gas is utilized in order to exert the Archimedes buoyant force on the substance. We have succeeded in levitating water with diamagnetic susceptibility in oxygen gas by using an ordinary superconducting magnet with the max. field of 10 T. Moreover, we have also succeeded in levitating a paramagnetic substance, which has been considered impossible according to Maxwell's equation, div$B$=0 (Earnshaw's theorem). Details of the levitation conditions are discussed.
Keywords: Magneto-Archimedes levitation, magnetic susceptibility, and buoyancy

1.INTRODUCTION

The microgravity environment can keep a free surface state of a liquid. Because the container-less crystal growth is posssible under the microgravity conditions, it has been payed a much attention from the materials science point of views, being due also to an additional factor that the gravitational convection in the liquid is expected to be small. However, it is quite costly to acquire the microgravity conditions in the space.

There have been some other methods to levitate a liquid on the earth; for instance, levitation of liquid metal in a radio-frequency field, a superconductor by a static magnetic field, and also a diamagnetic substance. The diamagnetic levitation is especially a promising technique because it is applicable for many kinds of diamagnetic materials in a wide range of temperature. However, the diamagnetic levitation requires an extremely strong magnet. The first demonstration of diamagnetic levitation was performed using a Bitter type hybrid magnet with the field of over 20 T on water, plastic, Bi metal, and wood chips. Since then the number of levitated substances increased such as a frog, egg, ice, etc, drawing a wide public attention.

The magneto-Archimedes levitation, discussed here, enables us to achieve the levitation more easily only with the use of normal superconducting magnet. In this paper, at first the principle of previous diamagnetic levitation is discussed, and then, the principle of magneto-Archimedes levitation is compared and the detailed conditions of levitation are described.

2.DIAMAGNETIC LEVITATION

The diamagnetic levitation is based on the balance between the magnetic force, which is a repulsive force from a field, and the gravitational force. The condition of stable levitation for a substance with the density of ρ and magnetic volume susceptibility of χ is

$$-\rho g + \frac{\chi}{\mu_0} B \frac{dB}{dz} = 0 \qquad (1)$$

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.

In order to realize the diamagnetic levitation, it is necessary to use an extraordinarily strong magnet with the field of ca. 20 T or over, because the value of diamagnetic susceptibility is very small. Even in the case of water, which can be levitated more easily due to the lower density and the larger diamagnetic susceptibility, the value of $B(dB/dz)$ should be as large as 1400 T^2/m, while it is only about 400 T^2/m for an ordinary superconducting magnet with the field of 10 T. This value is approximately proportional to the square of B. As the result, the diamagnetic levitation needs a very strong magnet.

3.PRINCIPLE OF MAGNETO-ARCHIMEDES LEVITATION

A stone becomes lighter in water than in air because the buoyancy acts on the stone according to the Archimedes principle. Magneto-Archimedes levitation applies this principle to the levitation in a magnetic field.

Figure 1 shows the balance of forces, considering the density and magnetic susceptibility of the medium gas. The condition for magneto-Archimedes levitation is

$$-\rho_1 g + \frac{\chi_1}{\mu_0} B\frac{dB}{dz} + \rho_2 g - \frac{\chi_2}{\mu_0} B\frac{dB}{dz} = 0 \quad (2)$$

where ρ_1 and χ_1 are the density and susceptibility of the levitating substance, respectively. ρ_2 and χ_2 are those of the medium gas around it. In the "diamagnetic levitation", latter 2 terms of left side in eq. (2) is neglected.

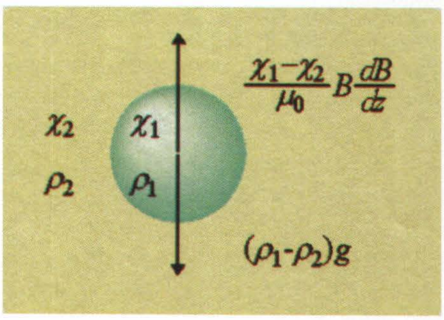

Figure 1; Magnetic and gravitational forces, including buoyancies from both fields, acting on the levitating object. ρ_1 and χ_1 are the density and susceptibility of the levitating substance, respectively. ρ_2 and χ_2 are those of the medium gas around it.

The susceptibility of air is slightly paramagnetic, contributed mainly by the presence of oxygen gas because those of other components of air are much smaller than oxygen. Therefore, the air in a magnetic field is drawn towards the field center although the attractive force is rather weak. The effective weight of air corresponds to about 2% of that of water in the magnet with the field ca. 10 T. But if the air is replaced by a pressurized oxygen gas, say to 10 atm, then the magnetic attraction force is intensified by about 50 times. That is, the atmosphere becomes as heavy effectively as water and hence water floats on the "heavy" oxygen gas.

4.LEVITATION OF PARAMAGNETIC SUBSTANCES

In addition to the balance of magnetic and gravitational forces, there is another requirement for stable levitation. The total of gravitational and magnetic potential energy should become minimum at the stable point. If the levitating object is moved to any direction, a restoration force should work. The condition is as follows,

$$\oint \boldsymbol{F}(\boldsymbol{r})\cdot d\boldsymbol{S} < 0, \quad (3)$$

where $\boldsymbol{F}$ is the force at the equilibrium point, $\boldsymbol{r}$, and the integral is over small closed surface surrounding the point. In order to satisfy this requirement, the sign of χ must be minus in the conventional magnetic levitation because of one of the Maxwell's relations, div$\boldsymbol{B}$=0, which means that there is no maximum field point in the free space. Hence, it has been considered that magnetic levitaion can be achieved only of diamagnetic but not of paramagnetic substances in the free space (Earnshaw's theorem). [2, 7, 8)]

However, in the "magneto-Archimedes levitation", the requirement for stablity is expressed by $(\chi_1 - \chi_2)<0$ rather than $\chi_1 <0$. In other words, even a paramagnetic substance can be levitated as long as it is less paramagnetic than the surrounding gas.

5.EXPERIMENTAL REQUIREMENTS FOR CONTACTLESS STABLE LEVITATION

The magnet used was a cryo-cooler-operated 10 T magnet of 100 mm bore diameter of room temperature (Sumitomo Heavy Industries; HF-10-100VHT). The maximum $B(dB/dz)$ was 420 T^2/m. The distribution of field, B, and product of field and field gradient, $B(dB/dz)$, along z axis is shown in Figure 2. z=0 is the position of the maximum field.

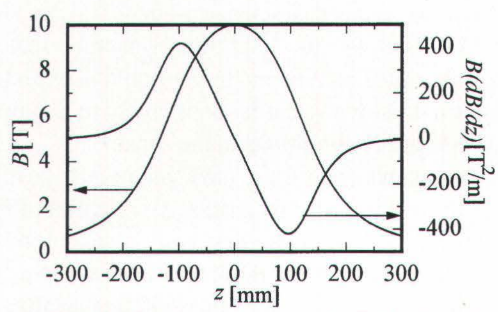

Figure. 2; Distributions of magnetic field, B, and the product of field and field gradient, $B(dB/dz)$, along z axis. z is the height from the field center.

The total of gravitational and magnetic potential energy per unit volume of water(1) in an environmental gas(2) is

$$E = (\rho_1 - \rho_2)gz - \frac{(\chi_1 - \chi_2)}{2\mu_0}B^2 \quad (4)$$

where the gravitational potential energy at z=0 is set zero. Figure 3 shows the total potential energy curves under various pressures of oxygen. A minimum point where water levitates appears at high pressure although there is no minimum point at low pressure. These energetic minimum points appear at the pressure of over 11 atm. The total of magnetic and gravitational force is also equal to zero at maximum point in a curve, but that is not a stable point as mentioned in the previous chapter.

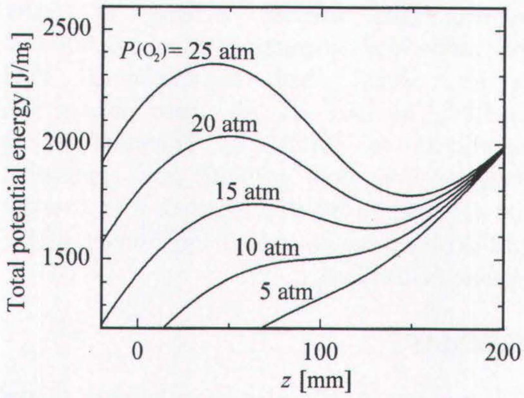

Figure. 3; The total potential energy curves for water in a pressurized oxygen gas in the superconducting magnet used in this study under 10 T maximum magnetic field.

Figure 4 shows the radial distribution of field at various height of z. The points of r=0 mm and r=50 mm are the center and the surface of the bore wall, respectively. In the region of $z \geqq 130$ mm, the field is larger at the radial center than on the wall. That is, the total potential energy of the levitating object is smaller towards the wall, so it is drawn to the wall surface. Therefore, it is impossible to achieve the contactless levitation in the region of $z \geqq 130$ mm.

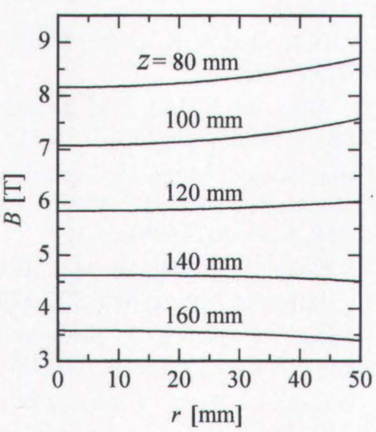

Figure. 4; Radial magnetic field distribution at various heights z.

On increasing the pressure of oxygen, its effective weight becomes larger. Consequently the water levitation can be attained at a lower $|B(dB/dz)|$. Moreover, since $|B(dB/dz)|$ decrease monotonously in the region of $z \geqq 96$ mm, the equilibrium point, z_e, gets higher with the increase of the pressure. But contactless levitation is possible only in the region of $z \leqq 130$ mm. Therefore, the contactless stable levitation can be realized within the range of 96 mm $\leqq z \leqq$ 130 mm with 11 to 16 atm oxygen gas.

6.MAGNETO-ARCHIMEDES LEVITATION

Demonstration of levitation was done both on dia- and para-magnetic liquids; water and an aqueous $CuSO_4$ solution whose magnetic susceptibility can be changed from diamagnetic to paramagnetic by adjusting the solute concentration. Figure 5 shows the pressure dependence of requirement of $B(dB/dz)$ for magneto-Archimedes levitation for water (χ=-9.03$\times 10^{-6}$[SI]) and the solution (χ=+0.30$\times 10^{-6}$[SI]). As the maximum $B(dB/dz)$ of our magnet was 420 T^2/m, the minimum oxygen pressure needed for levitation of water and $CuSO_4$ aq. was 11 and 18 atm, respectively. Moreover, note that the requirement of $|B(dB/dz)|$ for $CuSO_4$ aq. is diverged below a certain oxygen gas pressure. That is because (χ_1 - χ_2) decresases and changes its sign from plus to minus below this pressure. If (χ_1 - χ_2) becomes minus, the levitation of the paramagnetic substance becomes impossible.

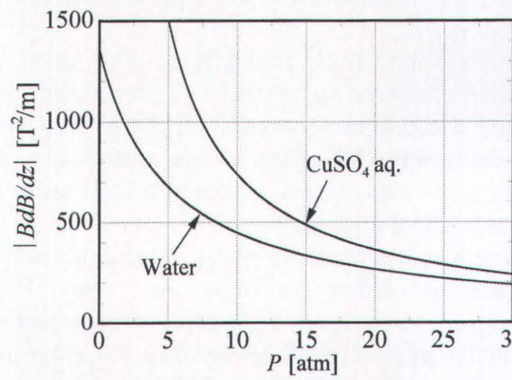

Figure. 5; Requirements of "Magneto-Archimedes levitation" for water with diamagnetic susceptibility, χ_w=-9.03$\times 10^{-6}$, and for aqueous $CuSO_4$ solution with paramagnetic susceptibility, χ_{Cu}=+0.30$\times 10^{-6}$.

Figure 6 is the set up used for the magneto-Archimedes levitation. This consisted essentially of a stainless vessel for water supply and a pressure-tight glass vessel as the levitation chamber. At first, pressurized oxygen gas is filled into the two vessels. But the pressure in the stainless vessel was about 5 atm larger than in the glass vessel. When a valve between the two vessels was opened, water was introduced through the capillary from the stainless vessel with the aid of the pressure difference, and a water droplet was formed at the lower tip of the capillary which was initially located at the height of maximum $|B(dB/dz)|$ point. The vessel system was retracted upwards as a whole, and then, the droplet was detached from the capillary and levitated. In the case of $CuSO_4$ aq. solution the procedure for levitation was the same except for the pressure of the oxygen gas.

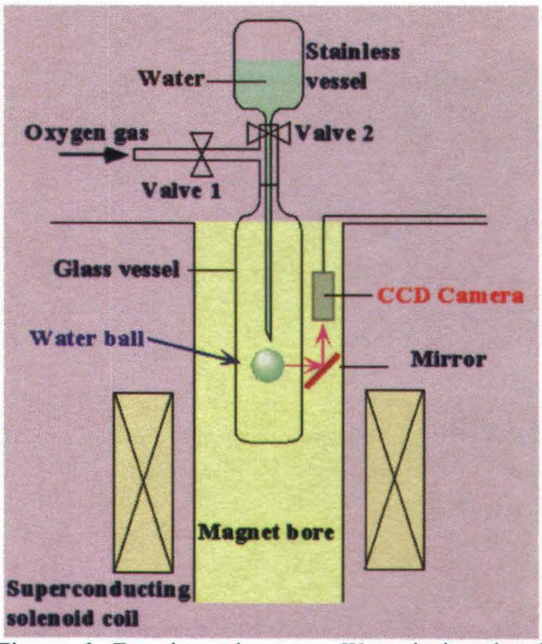

Figure. 6; Experimental set up. Water is introduced through the capillary from the upper stainless vessel.

The levitating water rested in air after about 1 minute of bouncing motion. Its size could be enlarged by dripping water from above onto the levitating water ball. Figure 7 are photographs of water and $CuSO_4$ aq. balls taken by a CCD camera with the aid of a mirror.

Generally, it is harder to levitate a solid substance because its density is larger than water. For example, the required $|B(dB/dz)|$ for diamagnetic levitation of NaCl with density of 2.164 g/cm^3 is calculated to be 1900 T^2/m which is much larger than for the case of water. But by the present "magneto-Archimedes levitation" it was possible in 27 atm oxygen gas. Figure 8 is the photograph of levitating NaCl grains.

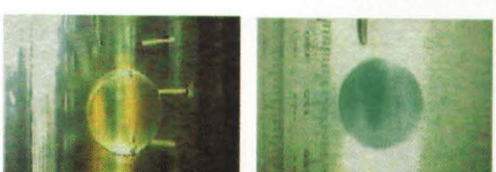

Figure. 7; Pictures of water and $CuSO_4$ aqueous solution levitating in a pressurized oxygen gas.

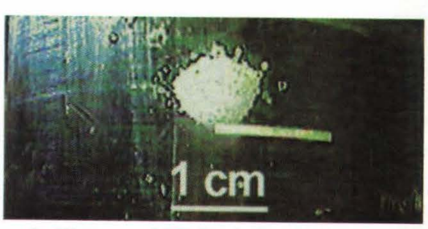

Figure. 8; Picture of NaCl grains levitating in 32 atm oxygen gas (χ_{NaCl}=-1.4$\times 10^{-5}$)

In addition, we recently found some other magnetic field effects: increase of water vaporization rate[9], increase of oxygen dissolution rate into water[10], and magnetothermal wind tunnel[11]. The size of all these effects are proportional to $|B(dB/dz)|$. Therefore it is interesting from both scientific and application point of views to develop magnets with stronger $|B(dB/dz)|$ in order to extend the frontier of the magnetic field effects.

7.SUMMARY

The magneto-Archimedes levitation was shown to be readily applied to substances using an ordinary superconducting magnet. And besides, it can also achieve the paramagnetic levitation that has been considered impossible according to Earnshaw's theorem. The levitation of paramagnetic $CuSO_4$ aq. solution was demonstrated. This was the first demonstration of levitation of a paramagnetic substance.

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