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Use of Vertical Magnetization Forces in Materials Processing

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This paper reports a new method for continuously controlling vertical acceleration, i.e., effective gravity from normal gravity to microgravity by applying an upward magnetization force on fluids. We verified this method by generating bubbles in the magnetic-gravitational complex field and observing their behavior. When magnetic forces counteract gravitational one, bubbles were observed to behave as if they were in microgravity environments. The change of vertical acceleration suggests it possible to control convection. We conducted the numerical simulation of thermal convection in an electrically nonconducting fluid and lowconducting fluid ($\sigma=21\Omega^{-1}m^{-1}$) when a vertical magnetic force acted on them. Numerical simulations show that the convection can be suppressed or enhanced by applying a vertical magnetic force. For lowconducting fluids, the effect of Lorenz force is not significant. The method to change vertical acceleration (effective gravity) will find many applications over a wide range of research, for example, in damping convection in nonconducting and lowconducting materials, the formation of high-quality crystals, and synthesis of new materials, and be useful in preliminary tests before aboard the Space Shuttle.

Key words: convection, gravity, magnetization force, control of convection

1. INTRODUCTION

There are many studies about magnetically controlled convection in electrically conducting fluid. Essentially, when an electrically conducting fluid such as metal and silicon melts moves in a magnetic field, a damping force due to the Lorentz force is exerted on the fluid motion. In particular, the application of magnetic fields have proven to be quite beneficial to control convection in a number of crystal growth processes.

However, this technique is not applicable to electrically nonconducting fluids, for example, the melt of inorganic oxides such as glasses and the supersaturated aqueous solution of proteins. There have been few studies about the control of convection in electrically nonconducting fluids. Recently, the effect of vertical magnetization forces caused by inhomogeneous magnetic fields on fluids have been reported [1-4]. Braithwaite et al. [1] observed the strong suppressing or enhancing effect of vertical magnetization forces on thermal transport in the solution of paramagnetic salt confined in a closed cylindrical cell heated from below. Furthermore, Wakayama et al. [2] found that when an upward magnetization force F_m and a downward force were applied to a supersaturated protein solution, the number of crystals segregated from it tended to decrease and increase, respectively, compared with the crystal number in the absence of the magnetic force. These observed phenomena suggest it possible to change the level of vertical acceleration (effective gravity) and control convection by using vertical magnetization force instead of centrifugal force, which is used in high-gravity experiments and in the Space Shuttle [3].

In this paper, first, we study the change of vertical acceleration (effective gravity) by applying an upward magnetic force on liquids and observing the behavior of bubbles therein. Gravitational fields affect every phenomenon on the earth, specially convection and precipitation. The decrease of vertical acceleration (effective gravity) suggests the possibility of quenching natural convection. Therefore, we conduct numerical simulations of thermal convection in lectrically and lowconducting fluids, focussing on the effect of vertical magnetic forces. Magnetization forces caused by inhomogeneous magnetic fields can exert on every material including paramagnetic and diamagnetic material. The present study will suggest a new method to change vertical acceleration and control convection.

2. CONTROL OF VERTICAL ACCELERATION (EFFECTIVE GRAVITY)

Generally, a unit volume of material in a one-dimensional magnetic field gradient as shown in Fig.1a experiences a magnetic force (F_m) defined

$$F_m = \chi \int H\left(dH/dy\right)dV = \rho \bullet \chi_g \int H\left(dH/dy\right)dV \quad (1)$$

where the integral is over the volume of the material specimen, H is magnetic field strength, y is a site-coordinate, and χ is volume magnetic susceptibility defined as the product of the material density (ρ) and mass magnetic susceptibility (χ_g). Specially when $H(dH/dy)$ is spatially uniform (Fig.1b), Eq.(1) is rewritten:

$$F_m = \rho \bullet \chi_g \bullet H(dH/dy) \bullet V_0 \tag{2}$$

V_0 is a unit volume. When an upward F_m is applied along with the gravitational force F_g, the total force F acting on the material is

$$F = F_g - F_m = \rho V_0 \left\{ g_0 - \left| \chi_g \bullet H(dH/dy) \right| \right\}$$
$$= \rho V_0 p g_0,$$
$$p = 1 - \left| (\chi_g / g_0) \bullet H(dH/dy) \right| \tag{3}$$

This equation indicates that the effective gravity, i.e., vertical acceleration p can be modified continuously by applying a magnetic field gradient of spatially uniform $H(dH/dy)$ and varying the strength of this magnetic field gradient. For diamagnetic material, its χ_g is independent of temperature. Therefore, F_m is linearly proportional to the density even in the presence of a temperature gradient. For example, when $\mu_0^2 H(dH/dy)$ is 700 T^2/m, an effective gravity of $0.5\, g_0$ is expected in pure water (χ_g=-0.716x10^{-6} cm^3g^{-1}). For paramagnetic materials exposed to a temperature gradient, p in Eq.(3) is not uniform because of Curie's law, $\chi_g \propto 1/T$.

3. BEHAVIOR OF BUBBLES WHEN AN UPWARD MAGNETIZATION FORCE ACTS ON LIQUIDS

3.1 Experimental procedure

We generated bubbles both in diamagnetic and paramagnetic liquids under a magnetic-gravitational complex field as shown in Fig. 1b and studied their behavior. The bubbles were generated by injecting N_2 gas through a plastic tube (0.1 cm inner diameter and 0.2 cm outer diameter) into liquid contained in a square plastic cell (Fig. 2a). A bubble is considered free from an end of the injection when the buoyancy force acting on the bubble, F_B exceeds the adhesive force between the bubble and the tube (F_A):

$$F_B = (\rho_L - \rho_G) \bullet V \bullet p g_0 > F_A \tag{4}$$

where V is the volume of the free bubble. The equation suggests that V increases when p is decreased. When the flow rate of the injection gas (q) is constant, the number of bubbles formed in a unit time (N_B) is:

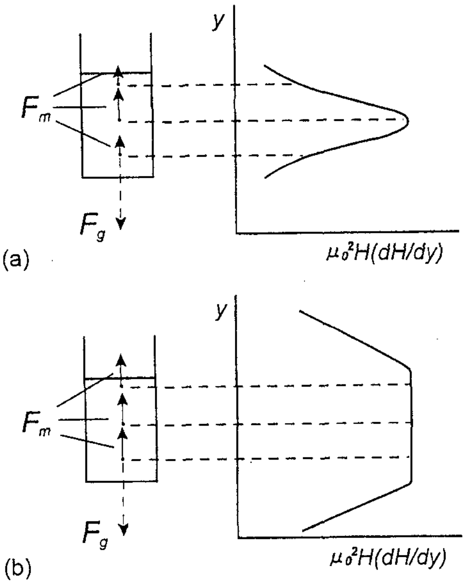

Fig.1 (a) F_m and F_g when H(dH/dy) is not uniform, (b) F_m and F_g when H(dH/dy) is uniform.

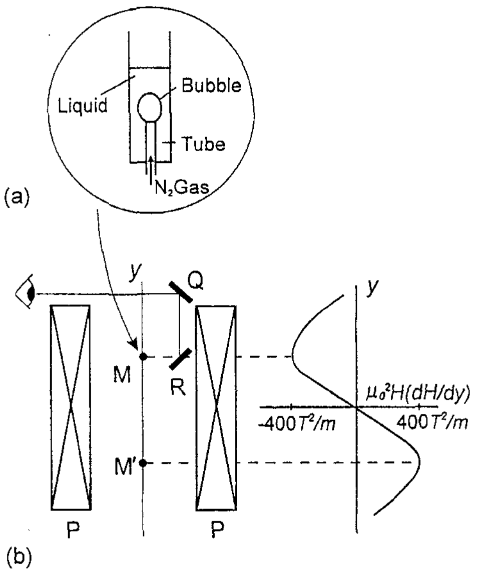

Fig.2 Experimental setup.

$$N_B = q/V = q(\rho_L - \rho_G)p \bullet g_0 / F_A \tag{5}$$

This equation suggests that N_B decreases as p is decreased.

We conducted the experiment by imposing an upward F_m generated by a superconducting magnet (Japan Magnet Technology Inc.) whose bore diameter was 10 cm. Fig.2b illustrates the experimental setup, and P is a cross section of the magnet. This magnet produced a maximum $\mu_0^2 H(dH/dy)$ of 400 T^2/m around the point M and M', and its variation inside the volume of 10mm ϕ (along a horizontal axis) x 10 mm (along a vertical axis) was within 0.6%. The bubble-generation apparatus (Fig. 2a) was set inside the magnet, with the end of the tube positioned inside the space of the maximum $\mu_0^2 H(dH/dy)$. In order to observe the behavior of N_2 bubbles, two mirrors were set at the points Q and R. The flow rate of the N_2 gas (q) was controlled by a flow controller (SEC-6400, Estec Co. Ltd.), and it was kept to be 3cm³/min.

3.2 Experimental results and discussion.

First, we did the experiments using a paramagnetic aqueous solution ($CoCl_2$: 7 weight %). Because χ_g of the solution has a positive large value, the solution experiences an attractive magnetic force and an F_m as large as F_g is easily obtained. The number of bubbles formed per minute, $N_B(p)$ decreases with increasing upward magnetic force and decreasing the level p (see Fig.3a). Fig.4 shows the bubbles which were going to be separated from the nozzle in 1 g_0 and 0.04 g_0. When $\mu_0^2H(dH/dy)$ was 209 T²/m, N_B was 3 and p was 0.04, the shape of bubble was quite different from the bubbles generated under normal gravity. Furthermore, the surface of the solution became concave in 0.04 g_0. Such behavior is generally observed for microgravity.

Similar results were obtained in the experiments involving diamagnetic materials, the aqueous solution of glycerol (81 %). $N_B(p)/N_B(p=1)$ decreased with increasing $\mu_0^2H(dH/dy)$ and decreasing p. p decreased to 0.7 when $\mu_0^2H(dH/dy)$ was 400 T²/m (Fig.3b). These results confirm that the level of vertical acceleration, p was changed from normal gravity (g_0) to near zero-gravity.

Control of vertical acceleration (effective gravity) will find many applications. For example, the change of vertical acceleration suggests the possibility of controlling convection. In the following section, as one example of the applications of the present method, we will show the numerical simulation of natural convection when a vertical magnetization force is applied.

4. NUMERICAL SIMULATION OF THERMAL CONVECTION WHEN VERTICAL FORCES ACT ON LIQUID

4.1 Mathematical model

We assume the vertical field-field gradient product: $|\mu_0^2H(dH/dy)|$ takes a spatially uniform value. We present numerical calculations in a two-dimensional rectangular cavity (L=0.025, h=0.01m) filled with lowconducting and nonconducting fluids as sketched in Fig.5. The fluid is heated from below and the temperatures at the top (T2) and bottom walls (T1) are kept at 20 and 22°C respectively. The two other walls are thermally insulated. No-slip condition is imposed at four walls of the cavity. For an incompressible, electrically nonconducting fluid

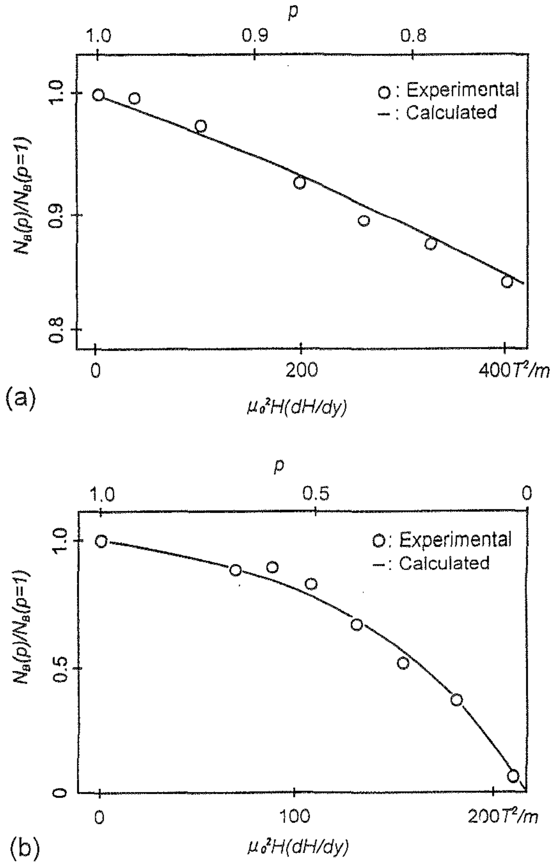

Fig.3 Dependence of $N_B(p)/N_B(p=1)$ on $\mu_0^2H(dH/dy)$ and p (a) in a paramagnetic aqueous solution (CoCl2: 7 weight %), and (b) glycerol aqueous solution (glycerol:80 weight %).

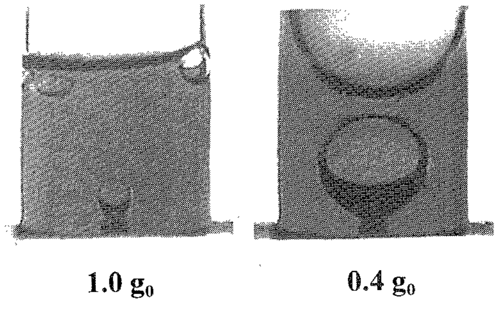

Fig.4 Bubbles at the moment of separation.

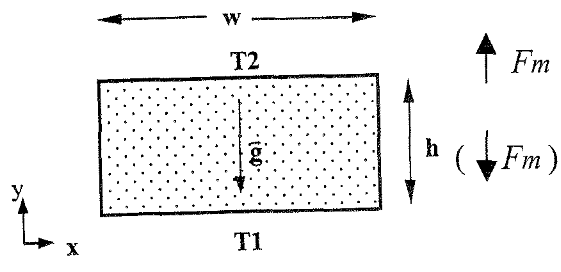

Fig.5 Schematic view for the physical system.

in the presence of an external inhomogeneous magnetic field, the basic equations used in the simulation of fluid flow are the Navier-Stokes equations including the magnetization F_m given by Eq. (2) and the gravity force F_g=ρg. When a fluid is lowconducting, Lorenz force is also added. When a uniform grid size of 101x41 is employed in the computations.

Two kinds of fluids, a paramagnetic gadolinium nitrate aqueous solution (lowconducting, $\sigma=21\Omega^{-1}m^{-1}$) [1] and pure water (diamagnetic and nonconducting) are considered. For paramagnetic liquids, we used the same parameters as the experiment. The mass magnetic susceptibility χ_g of the gadolinium nitrate solution and water are 1.63×10^{-4} and -9.0×10^{-9} m^3/kg, respectively at room temperature. We use the same values for parameters density $\rho=1000$ kg/m^3, thermal expansion coefficient $\beta=2.5\times10^{-4}K$, kinematic viscosity $\nu=10^{-6}$ m^2s, and $D=1.454\times10^{-7}m^2/s$ for both water and the gadolinium nitrate solution due to the lack of available values for the latter.

4.2 Simulation results

4.2.1 Paramagnetic solution heated (lowconducting).

Figure 6a shows the distributions of the velocity vectors (left) and the isothermals (right) without external magnetic field. Due to gravity, natural convection is generated in the cavity. When the upward magnetic force is applied [H(dH/dy)>0], natural convection will be gradually suppressed as shown in Fig.6b (4.86 T^2/m) and Fig.6c (5.5 T^2/m). Figure 7 shows that the Nusselt number and the maximum value of the velocity are decreasing with increasing H(dH/dy) and the convection is completely suppressed when μ_0^2H (dH/dy) > 4.9 T^2/m. In contrast, when the magnetic force is applied downward [H(dH/dy)<0], the convection is promoted. The Nusselt number and the maximum value of the velocity are increasing with ncreasing | H(dH/dy)|. These numerical results are consistent with the experimental observations [1]. We also numerically simulated the convection without Lorenz force, and obtained nearly the same results. Therefore, the contribution from magnetization becomes dominant in a low conducting fluid under weak magnetic fields. Lorenz force is considered to become dominant when the conductivity is high, for example, the melts of semiconductor, liquid Gallium ($\sigma=2.6\times10^6\Omega^{-1}m^{-1}$).

4.2.2 Water heated from below (nonconducting).

For diamagnetic fluids, such as water and the melt of inorganic oxide, they experience a weak repulsive force. For comparison with the paramagnetic fluids, the convection in pure water is investigated here. The effects of the vertical magnetization force on convection in pure water are given in Fig.8. The similar tendencies are obtained that convection in the diamagnetic fluid can be controlled via vertical magnetic force. In contrast to the paramagnetic fluid, the upward magnetic force in the diamagnetic fluid is produced by the negative field gradient (H(dH/dy)<0) due to the negative susceptibility of the diamagnetic fluid. Moreover, it need a large value of vertical field

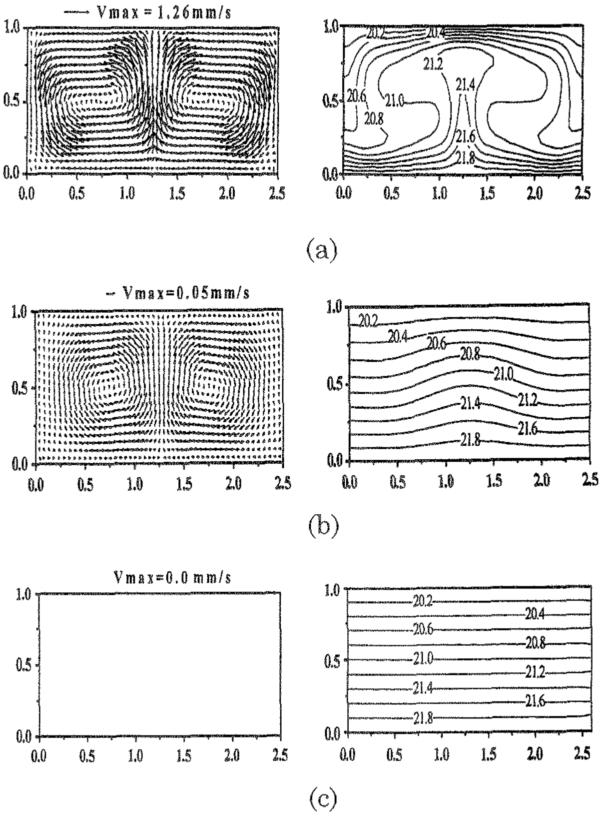

Fig.6 Velocity vectors (left) and temperature contours right) in paramagnetic fluids heated below when $\mu_0^2H(dH/dy)$ is (a) 0, (b) 4.86 and (c) 5.5 T^2/m.

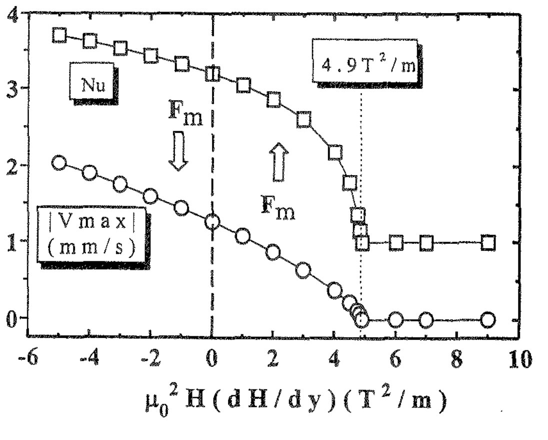

Fig.7 Influence of $\mu_0^2H(dH/dy)$ on the average Nussel number (☐) and maximum velocity (○) in a paramagnetic fluid.

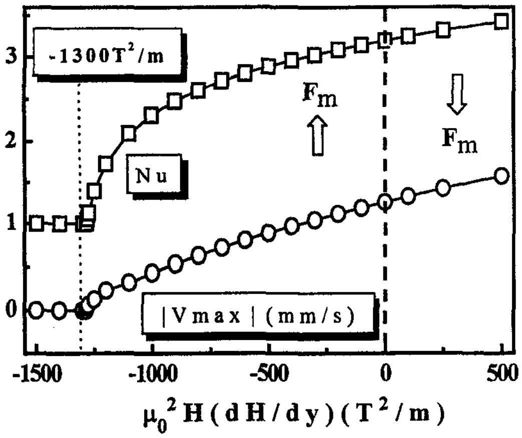

Fig.8 Influence of $\mu_0^2H(dH/dy)$ on the average Nussel number (□) and maximum velocity (○) in a diamagnetic fluid

gradient, $\mu_0^2H(dH/dy)$, to compete gravity in the diamagnetic fluid (above 1300-1400 T^2/m), which will be obtained only by a large superconducting magnet.

4.3 Discussion

In order to completely counteract gravitational acceleration on earth by the magnetic force shown in Eq. (2), it will require the value of $\mu_0^2H(dH/dy)$ equal to 75.6 T^2/m for the paramagnetic solution of gadolinium nitrate, and 1370 T^2/m for the diamagnetic solution of water, respectively. For the diamagnetic fluid, it is the nearly same as the value of 1300 T^2 /m to quench convection in Fig.8. However, it's only the value of about 5T^2/m to offset the effect of gravity on convection in the paramagnetic fluid (shown in Figs.6 and 7).

This big difference between 75.6 and 5T^2/m for paramagnetic fluid occur in the presence of the temperature gradient. A density difference ($\Delta\rho$) will produce the gravitational buoyancy force $\Delta F_g = \Delta\rho g$. Similarly, a susceptibility difference existing in the fluid can produce a magnetic buoyancy force in a uniform magnetic field gradient:

$$\Delta F_m = \Delta\chi H\left(dH/dy\right)$$
$$= \left(\chi_g \Delta\rho + \rho\Delta\chi_g\right) H\left(dH/dy\right) \qquad (6)$$

The magnetic buoyancy force is determined by both density and mass magnetic susceptibility differences ($\Delta\rho$ and $\Delta\chi_g$). For diamagnetic fluids, under temperature gradients, $\Delta\chi_g$ is zero. In contrast, for paramagnetic fluids, Curie's law, $\chi_g \propto 1/T$ exists. Due to $\Delta\chi_g$ / $\chi_g \propto \Delta T / T$ and $\Delta\rho$ / $\rho \propto \beta\Delta T$, the contribution of the magnetic buoyancy force caused by mass magnetic susceptibility difference is larger than that of density difference. For a paramagnetic solution of gadolinium nitrate, the buoyancy force caused by $\Delta\chi_g$ is above ten times larger than that of $\Delta\rho$. Therefore, the moderate value of $\mu_0^2H(dH/dy)$, i.e. 5T^2/m, can be applied to effectively control convection in paramagnetic fluids. At a scale of about one centimeter, we can achieve gradients of about 100 T^2/m with permanent magnets. Therefore, even in the absence of the temperature gradient, it is easy to control convection in paramagnetic fluids.

On the other hand, a field-field gradient product as high as 1400 T^2/m is required to control convection in water and diamagnetic fluids. Recently, commercial superconducting coils are now available which can produce a field-field gradient product as high as 400 T^2/m, which can damp or enhance convection in diamagnetic fluids on earth.

In order to control vertical acceleration, the magnet which provides spatially uniform H(dH/dy) is necessary. The group of National Research Institute for Metals did the research to construct this kind of magnets [5].

5. CONCLUSIONS

The key results of the present study are:

1. The experiment about the behavior of bubbles proves that an upward magnetization force acting on liquids decreases the vertical acceleration.
2. Numerical simulation proves that upward magnetization forces suppress thermal convection in nonconducting and lowconducting fluids, while downward forces enhance the convection.
3. In order to completely counteract gravitational acceleration, it will require the value of $\mu_0^2H(dH/dy)$ equal to 1370 T^2/m for diamagnetic fluids, and much smaller value for the paramagnetic fluids, respectively.
4. Our results indicate a new method for changing vertical acceleration (effective gravity) and controlling convection in electrically nonconducting and lowconducting fluids, for example, the melts of inorganic oxides, glasses. At present, there are few methods for damping convection for such materials.

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