Transactions of the Materials Research Society of Japan 27 [1] 21-25 (2002)

Non-magnetic Gases, Liquids and Granular Particles under High Magnetic Fields -Possible application to materials processing-

H. Uetake*, N. Hirota*,**, Y. Ikezoe*, T. Kaihatsu*, T. Takayama*and K. Kitazawa*,**

*Dept. of Appl. Chem., School of Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Fax: +81-3-5841-7205, e-mail: tt07214@mail.ecc.u-tokyo.ac.jp

**SORST, Japan Science and Technology Corp., 4-1-8 Hon-cho, Kawaguchi, Saitama 332-0012, Japan
Fax: +81-48-226-5651, e-mail: kitazawa@k.u-tokyo.ac.jp

Magnetic field effects recently observed in various processes involving non-magnetic substances such as air, water, organic liquids, and granular particles are discussed in terms of a possible application of the field effects to materials processing. Although magnetic fields are thought to have a very weak effect on non-magnetic or non-ferromagnetic substances, it has been found that increased magnetic fields in the range of 10 T can create various significant changes in the equilibrium of the interfacial morphology between liquids, in the movement of liquids, gases, or particles in these media, and in the orientation of granules. Furthermore, the recently observed interaction between two or more non-magnetic particles under strong magnetic fields has a potential to be utilized in materials processing.

Key words: High magnetic fields, non-magnetic substances, magnetic energy, magnetic force and materials processing

1. INTRODUCTION

The possible application of magnetic fields to materials processing has recently attracted much attention. The use of magnetic fields is characteristic for its non-contact manner, i.e., magnetic fields can have an effect on materials processing without any direct contact with the matter. The types of influence include the controls of 1) gravitational force and positions, 2) convections, and 3) magnetic orientations, among others. These are explained in terms of the magnetic energy or magnetic forces. The magnetic energy on a unit volume of a substance is expressed as

$$E = -\frac{\chi}{2\mu_0}B^2 \qquad (1),$$

where μ_0 is the permeability of vacuum, χ is the volume magnetic susceptibility, and B is the magnetic flux density. The magnetic force per unit volume is written as follows with the function of x, the position of the substance:

$$F = \frac{\chi}{\mu_0}B\frac{\partial B}{\partial x} \qquad (2)$$

The magnetic field distribution and the index of the magnetic force $B\partial B/\partial x$ produced by a typical solenoid coil are shown in Fig. 1. The magnetic field takes its maximum at the center of the coil and attenuates gradually with distance from the center; on the other hand, the magnetic force does not exert at the center while it works at off-centered position. The most striking field effect of gravitational force control was the diamagnetic levitation made by Beaugnon and Tournier.[1] Moreover, the morphological relationships among different phases and even in a single phase may be modified by the application of strong enough magnetic fields. The convection controls have been made in fluids such as liquids[2] or gases.[3] The magnetic orientation energy of a substance is expressed in terms of magnetic anisotropy as

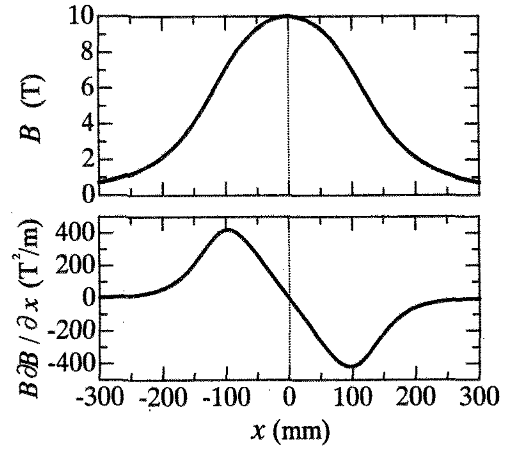

Fig. 1 Magnetic field distribution and index of the magnetic force of the superconducting magnet mainly used in the series of experiments presented in this paper.

$$\Delta U = U_a - U_b = -\frac{\chi_a - \chi_b}{2\mu_0} B^2 \times V \quad (3),$$

where V is the volume and a and b are the directions of a specific axis in an anisotropic substance. The magnetic orientation is observed in a typical ceramic powder particle of a size of 1μm or less when the energy exceeds the thermal agitation energy only under a magnetic field higher than the tesla range.[4] Above-stated equations indicate that the field effect on non-magnetic substances can be intensified with the square of field strength B^2 and that the use of a superconducting magnet provides the means to boost up the magnetic field effect. Therefore the facts presented above indicate that various new processes can be controlled by the presence of magnetic fields. In this paper, we will examine several cases along this line and discuss their possible applications.

2. VARIOUS CASES IN WHICH MAGNETIC FIELD EFFECTS ARE OBSERVABLE

2.1 Moses effect[5),6)]

The surface of water is suppressed when magnetic fields are applied on a part of the water surface, as shown in Fig. 2. This effect is known as the "Moses effect." The surface height difference of water between the positions of x_1 and x_2 was formulated as follows considering the competition between the gravitational potential energy and the magnetic energy:

$$\Delta h(x) = \frac{\chi}{2\mu_0 \rho g}\left\{B(x_1)^2 - B(x_2)^2\right\} \quad (4),$$

where h is the vertical height of the surface and g is the acceleration due to gravity. The total height difference was 39 mm between the positions in the 10 T field and the zero field, as was expected from Equation (4).

2.2 Enhanced Moses effect[7)]

By overlaying another liquid on top of the initial one, the interface profile $\Delta h(x)$ was significantly enhanced, as shown in Fig. 3, and can be described quantitatively as

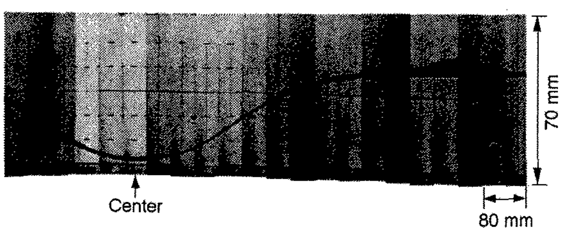

Fig. 2 Moses effect on water. The surface profile of water in a rectangular glass vessel was changed under the magnetic field. The glass vessel was placed in a horizontal bore of a solenoid superconducting magnet that can produce 10T at the center.

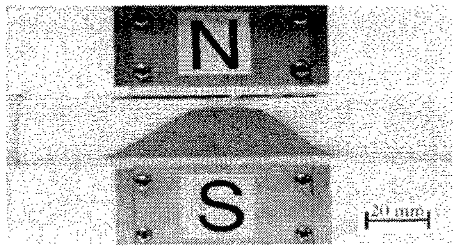

Fig. 3 Enhanced Moses effect: An organic liquid (Benzene-chloro-benzene mixture: transparent) is overlaid on an aqueous solution of $CuSO_4$ (blue). The layered liquids were placed in a gap of permanent magnet ($\chi_{upper} < \chi_{lower}$).

$$\Delta h(x) = \frac{\chi_A - \chi_B}{2\mu_0(\rho_A - \rho_B)g}\left\{B(x_1)^2 - B(x_2)^2\right\} \quad (5).$$

Here, the magnetic field at the center was 0.56 T. And it is to be noted that the same height difference as that shown in Fig. 2 has been observed under much lower fields.

2.3 Magneto-Archimedes levitation[8)]

The idea of enhancing an effective magnetic force on a certain substance by considering the atmosphere can also be applied to diamagnetic levitation.[1)] A liquid ball or solid substance was levitated in a gaseous medium mostly by the buoyancy force of the medium. Considering the effect of the medium, the condition for Magneto-Archimedes levitation is expressed as

$$-\rho_1 g + \frac{\chi_1}{\mu_0} B\frac{\partial B}{\partial z} + \rho_2 g - \frac{\chi_2}{\mu_0} B\frac{\partial B}{\partial z} = 0 \quad (6).$$

The effective weight of the gas must be heavier than that of the liquid, which is attained by the magnetic field gradient. An ordinary

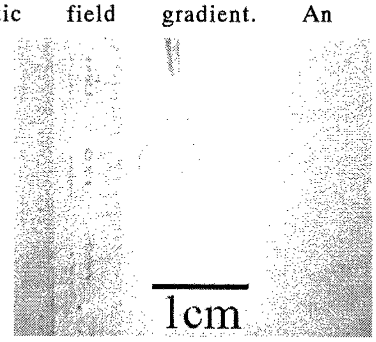

Fig. 4 A levitated ball of a para-magnetic $CuSO_4$ aqueous solution in oxygen gas at 18 atm. in a 10T magnet with a maximum $B\partial B/\partial z$ of $420T^2/m$.

Fig. 5 NaCl and KCl powders levitated at different positions by the Magneto-Archimedes separation. The pressure of oxygen gas is 32 atm.

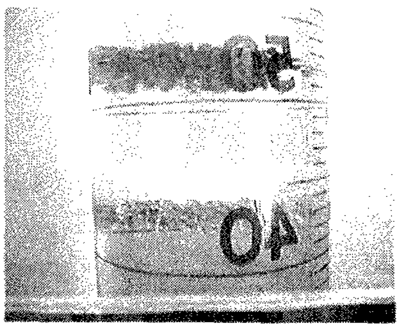

Fig. 6 Glasses of different colors levitated in $MnCl_{2aq}$.

superconducting magnet with a much smaller field-field gradient product, $B\partial B/\partial z$, than that needed for the dia-magnetic levitation of water, which is ca.1400 T^2/m, can levitate water and even heavier substances. It is also noted that the levitated substance does not necessarily have to be diamagnetic, which apparently contradicts Earnshaw's theorem,[9] according to which a para-magnetic substance can never be stably levitated by magnetic fields according to one of the Maxwell equations, i.e., div$B$=0. Figure 4 shows a levitated ball of a para-magnetic $CuSO_4$ aqueous solution.

2.4 Magnetic separation by the Magneto-Archimedes principle[10)~12)]

If different substances with different values of magnetic susceptibility and density are levitated, they find different stable positions for levitation, as shown in Fig. 5. Previously mixed KCl and NaCl powders were separated from the top to the bottom by Magneto-Archimedes separation. When an aqueous solution can be used as a medium, it is easier to separate glasses of various colors because the aqueous solution can have larger susceptibility. The Magneto-Archimedes separation in a liquid is shown in Fig. 6. As seen in the figure, the glass particles with the same color were levitated together to their stable positions.

2.5 Enhancement of the water vaporization rate[13)]

The rate of water vaporization was significantly enhanced under a strong magnetic field created by a superconducting magnet. The examination of how the magnetic field gradient is related with the enhancement allowed us to propose the following mechanism. Near the water surface, the partial pressure of the water vapor becomes higher than in the bulk, resulting in smaller volume susceptibility of the atmosphere near the surface. Consequently, the atmosphere in the bulk is more strongly attracted towards the field center than that near the water surface, creating a quasi-steady state convection flow in the atmosphere. Hence, a fresh atmosphere is constantly brought onto the water surface to enhance the vaporization rate, as illustrated in Fig. 7. The rate of airflow becomes as fast as 1 m/s, and the enhancement easily reaches 4-5 times.

2.6 Kinetic Enhancement of Oxygen Gas Dissolution into Water[14)]

When we examined the process of oxygen dissolution into water, we found that the magnetic field did not have a significant effect on the equilibrium but that it enhanced its kinetics. This mechanism was elucidated in terms of the induced convection of water during the process of oxygen dissolution. The gradient of oxygen content creates the susceptibility gradient. This gradient under a gradient magnetic field can cause convection, as shown in Fig. 8. This convection in a whole body of water can accelerate the oxygen gas dissolution into water, while the equilibrium remains unchanged.

2.7 Magnetic Wind Tunnel[15),16)]

On the basis of the preceding findings, we devised a wind tunnel that can generate wind through a tube placed in a magnet but without any moving mechanical parts in it. This is based on the following generalized observations. The volume magnetic susceptibility of the heated air

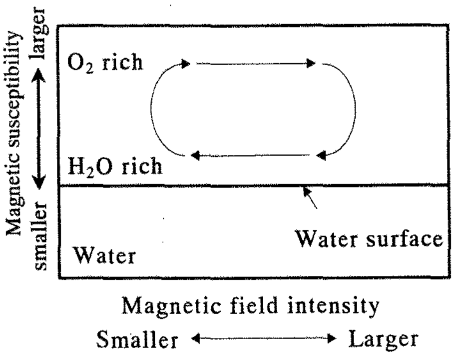

Fig. 7 The mechanism proposed for the magneto-enhancement of water vaporization. The susceptibility of gas near the surface becomes slightly smaller due to the higher concentration of slightly diamagnetic water vapor.

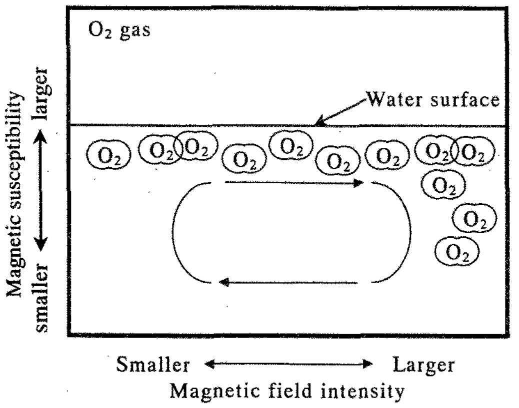

Fig. 8 The mechanism proposed for the magneto-enhancement of the dissolution rate of oxygen into water. The susceptibility of water near the surface becomes slightly larger compared with that at the bottom due to the higher concentration of oxygen, which is slightly paramagnetic.

decreases with T as $1/T^2$. The neighboring colder air in the tube tends to replace the heated air, pushing it out of the strong field region in order to maximize the total magnetization of the air, thereby minimizing the magnetic energy. Figure 9 shows the magneto-thermal wind created under a magnetic field of 8 T.

This phenomenon can be applied to control the thermal convection in a vertical furnace, in which thermal convection always occurs upward. The use of the magnetic field can even reverse the direction of the thermal convection of the air in a vertical furnace.[16)]

3. DISCUSSION: THE APPLICATION OF MAGNETIC FIELDS TO MATERIALS PROCESSING

As demonstrated by the experiments described above, many of the magnetic field effects on non-magnetic substances become barely observable at a field intensity of 10 T. The effects in the range of 10 tesla become comparable in strength with the gravity-induced effects and become more significant as the field is further increased. The manners in which the magnetic field effects manifest themselves are varied, but they may be categorized as follows from the viewpoint of practical applications:

1) All the effects observed above are motivated by the magnetic force exerted on different substances with specific magnetic susceptibility values. Therefore, the substances tend to change their shape so as to minimize the magnetic energy of the material system as a whole, e.g., Moses effect.

2) Then, the tendency to minimize the magnetic energy in the vertical direction makes a liquid or particles levitate. The levitation of a liquid results in a nearly spherical shape in a non-contact manner with the vessel.

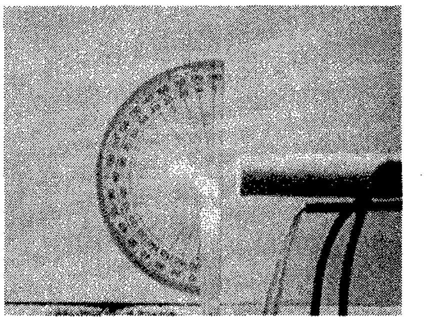

Fig. 9 Out of a ceramic tube, a wind of 1 m/s is generated (8 T). The ceramic tube is inserted in a superconducting magnet on the right (not shown) and is wound with a heater so that the tube is heated externally at an off-centered position from the maximum field position.

This can be used for materials processing without any containers such as melt-solidification of a glass,[17)] polymerization of a resin into a spherical shape,[18)] or crystal growth in a spherically shaped droplet by means of diamagnetic levitation or Magneto-Archimedes levitation.

3) While the gravity does not change with the position in a small system, the magnetic field intensity changes rapidly with the position. This makes the control of the material's position possible since a substance has its stable position in the magnetic field. If a powder of different densities and magnetic susceptibility is subjected to "magnetic position control," it will be differentially separated, e.g., magnetic separation by the Magneto-Archimedes levitation.

4) When mobile fluids are placed under a magnetic field, they rearrange their distribution so that the one with the larger magnetic susceptibility comes to the higher field position. Even in a single phase of a substance such as a liquid or gas, the inhomogeneous distribution of solutes gives rise to the gradient of magnetic susceptibility in the phase. Then, a magnetically induced motion is created so as to redistribute the mobile medium, attracting the part with the highest susceptibility towards the field center. Examples are the magnetically induced convections that brought the enhancement of the oxygen dissolution rate and the water vaporization rate.

5) If a liquid or gas is heated in a manner with different symmetry from the magnetic field distribution, a magneto-thermal convection can be created. This should provide a means to control the direction and the intensity of a thermal convection, or, more drastically, it can be used for a magnetic wind tunnel.

6) Magnetically induced dipole interaction has recently been observed in high magnetic fields.[19)] This indicates the possibility of arranging even "non-magnetic" substances in a chain-like structure along the magnetic fields.

7) Magnetic orientation effects are not dealt with in this study; however, they can be combined with various other processes under magnetic fields.

The considerations presented above indicate that various new processes can be controlled by the presence of magnetic fields. Since the effects are proportional to the square of the field strength B^2, making use of a superconducting magnet is essential to boost up the magnetic field effect. Consequently, magnetic fields have a great potential to be applied to materials processing in accordance with the future development of further higher fields.

REFERENCES

[1] E. Beaugnon and R. Tournier: *Nature*, **349**, 470 (1991).
[2] D.Braithwaite, E. Beaugnon, and R. Tournier: *Nature*, **354**, 134 (1991).
[3] N. I. Wakayama: *J. Appl. Phys.*, **69**, 2734-2736 (1991).
[4] T. Suzuki, H. Ohtsuka, Y. Sakka, K. Hiraga, and K. Kitazawa: *J. Jpn. Soc. Powder and Powder Metal.* **47**, 1010-1014 (2000).
[5] S. Ueno and M. Iwasaka: *J. Appl. Phys.*, **75**, 7177-7179 (1994).
[6] N. Hirota, T. Homma, H. Sugawara, K. Kitazawa, M. Iwasaka, S. Ueno, H. Yokoi, Y. Kakudate, S. Fujihara, and M. Kawamura: *Jpn. J. Appl. Phys.*, **34**, L991-L993 (1995).
[7] H. Sugawara, N. Hirota, T. Homma, M. Ohta, K. Kitazawa, H. Yokoi, Y. Kakudate, S. Fujihara, and M. Kawamura, M. Iwasaka, and S. Ueno: *J. Appl. Phys.*, **79**, 4721-4723 (1996).
[8] Y. Ikezoe, N. Hirota, J. Nakagawa, and K. Kitazawa: *Nature*, **393**, 749-750 (1998).
[9] S. Earnshaw: *Trans. Camb. Phil. Soc.*, **7**, 97-112 (1842).
[10] Y. Ikezoe, T. Kaihatsu, T. Suetsuna, H. Uetake, N. Hirota, and K. Kitazawa: *Proc. Inter. Symp. New Magneto-Science '99*, 400-404 (1999).
[11] T. Kimura, S. Mamada and M. Yamato: *Chem. Lett.* **11**, 1294-1295 (2000).
[12] Y. Ikezoe, T. Kaihatsu, S. Sakae, H. Uetake, N. Hirota, and K. Kitazawa: *Energy Conversion and Management* **43**, 417-425 (2002).
[13] J.Nakagawa, N. Hirota, K. Kitazawa, and M. Shoda: *J. Appl. Phys.*, **85**, 2923-2925 (1999).
[14] N. Hirota, Y. Ikezoe, H. Uetake, and K. Kitazawa: *Mater. Trans., JIM,* **41**, 976-980 (2000).
[15] H. Uetake, J. Nakagawa, N. Hirota, and K. Kitazawa: *J. Appl. Phys.*, **85**, 5735-5737 (1999).
[16] H. Uetake, J. Nakagawa, N. Hirota, Y. Ikezoe, and K. Kitazawa: *J. Appl. Phys.*, **87**, 6310-6312 (2000).
[17] N. Kitamura, M. Makihara, M. Hamai, T. Sato, I. Mogi, S. Awaji, K. Watanabe, and M. Motokawa: *Jpn. J. Appl. Phys.*, **39**, L324-L326 (2000).
[18] See:http://kunugi.indchem.metro-u.ac.jp/polychem E/themes/file6/file6.htm
[19] Y. Ikezoe, T. Kaihatsu, K. Ujimine, H, Uetake, N. Hirota, and K. Kitazawa: Magneto-Archimedes Separation of Feeble Magnetic Particles and Interaction between Magnetically Induced Dipoles, *Abstracts of Fourth Symposium on New-Magneto Science*, Omiya, Japan, November, 2000 (in Japanese), Y. Ikezoe, T. Takayama, H. Uetake, N. Hirota and K. Kitazawa: submitted to *Nature*, T. Takayama, Y. Ikezoe, T. Kaihatsu, H, Uetake, N. Hirota, and K. Kitazawa: submitted to *Trans. Mater. Res. Soc. Jpn.*

(Received December 21, 2001; Accepted January 30, 2002)