Magneto-convection processes observed in non-magnetic liquid-gas system

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Magnetic fields up to 10 T have been applied on various substances composed of non-magnetic liquids and/or gases. It has turned out that the magnetic fields of this range do produce various visible effects on the equilibrium shape, relative distribution of the substances or kinetic processes of the systems. The phenomena observed are due to the magnetic force. The effects manifest themselves through the deformation of the equilibrium shape of the liquid interfaces and through the creation of convection in a non-uniform gas or liquid phase in terms of the magnetic susceptibility. Some of the processes seem to be utilized for practical purposes.

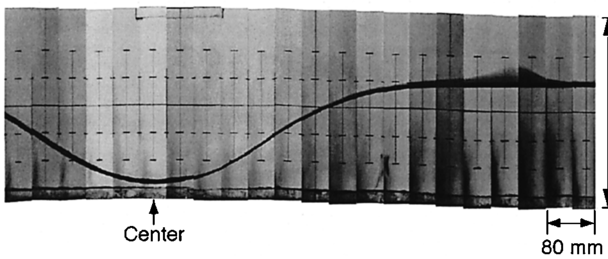
Introduction

It has been demonstrated in recent years that strong magnetic fields exert influence on the shape of candle flames and smokes in the air [1–3] and water can be levitated by a strong field, 20 T or over by the diamagnetic levitation,[4] water splits into two parts by the application of the field.[5] Utilizing a recently developed cryo-cooler-operated 10 T superconducting magnet (Sumitomo Heavy Industries, HF10-100VHT) which is compact sized and readily operated in an ordinary laboratory, we have examined the field effects on various liquids, gases and powders which are non-magnetic with either dia- or para-magnetic susceptibility. In this paper the observed effects are summarized and discussed in terms of the magnetic energy or magnetic force, which become significant in proportion with the square of field intensity B^2, and hence in the tesla range of the field the effects become visible even on non-magnetic substances.

Moses effect and enhanced Moses effect

In a horizontal solenoid coil, the surface profile of water deforms as shown in Fig. 1 (a), termed as “Moses effect”.[6] The Moses effect, defined as a deformation of the liquid surface profile by magnetic fields, can be quantitatively understood by considering the balance between magnetic and gravitational potentials.

In the Moses effect, however, the deformation Δh is as small as 39 mm under a 10 T field in Fig. 1 (a). Since the effect is proportional to the square of the field intensity B^2, Δh would be less than 0.1 mm in $B = 0.5$ T, explaining why the Moses effect is non-visible with a permanent magnet. By overlaying another liquid B on top of the heavier liquid A, the change of the interface profile $\Delta h(x)$ has been significantly enhanced as shown in Fig. 1 (b) and can be described quantitatively as;[7]



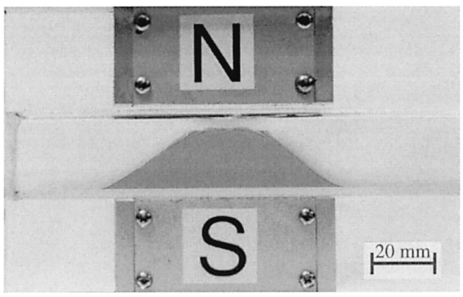


Fig. 1. (a) Moses effect on water. The magnetic field deforms the surface profile of water in a rectangular glass vessel placed in a horizontal bore of a solenoid superconducting magnet, 10 T at the center. (b) Enhanced Moses effect: An organic liquid of benzene-monochlorobenzene mixture (transparent and diamagnetic) was overlaid on a slightly paramagnetic aqueous solution of $CuSO_4$ (dark). The glass vessel is placed in a gap of Nd-Fe-B 0.56 T permanent magnet.

$$\Delta h\,(x) = \frac{\chi_{\mathrm{A}} - \chi_{\mathrm{B}}}{2\mu_0\,(\rho_{\mathrm{A}} - \rho_{\mathrm{B}})\,g}\left\{B\,(x)^2 - B\,(0)^2\right\}, \tag{1}$$

where χ is the volume magnetic susceptibility of the respective liquid, μ_0 is the permeability of vacuum, ρ is the density of liquid and g is the gravitational acceleration. This enhancement of Moses effect on the interface was attained by adjusting the density of the two liquids very close to each other.

Enhancement of water vaporization rate

It was noticed that the rate of water vaporization was enhanced significantly in a bore of superconducting magnet. Examining how the magnetic field gradient is related with the enhancement, the following mechanism has been proposed.[8] Near the water surface, the partial pressure of the water vapor becomes higher than in the bulk, resulting in the 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 and then, a quasi-steady state convection flow will take place in the atmosphere. Hence, a fresh atmosphere is constantly brought onto the water surface to enhance the vaporization rate as illustrated in Fig. 2. The rate of air flow becomes as fast as 1 m/s under the typical conditions in a superconducting magnet of 10 T, estimated according to the Navier-Stokes equation of viscous flow. The degree of enhancement was up to 4–5 times in a horizontal bore of a superconducting magnet in which the maximum $B \cdot \mathrm{d}B/\mathrm{d}x$ was $300\,\mathrm{T}^2/\mathrm{m}$. What it implies is that a living animal or plant may feel colder if placed in a field gradient due to the enhanced vaporization of water from the body and the consequently induced convection of the atmosphere. Therefore, an experiment to judge the magnetic field effects on living bodies must be carefully interpreted because the actual temperature, conditions of the environmental water may be different from that designed initially after they are subjected to the field.

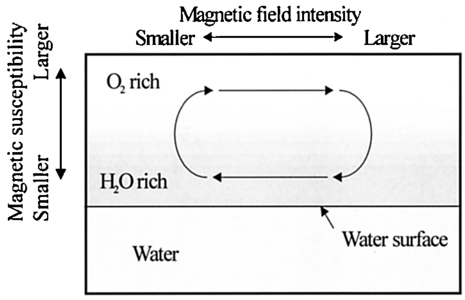


Fig. 2. The mechanism proposed for the magnetically enhanced water vaporization.

Enhancement of oxygen gas dissolution rate into water [9]

There have been a number of papers reported and patents applied, claiming that application of magnetic fields significantly enhances the oxygen concentration in water dissolved from gas phase to an extent typically several tens of percentage. The thermodynamics, however, predict that one may expect only a negligible increment of equilibrium oxygen concentration, considering the magnetic susceptibility of oxygen according to $RT\,\ln[P(B)/P(0)] = \chi B^2/2\mu_0$ where the ratio $P(B)/P(0)$ is the partial pressure ratio in the atmosphere or the concentration ratio of oxygen in water in equilibrium and χ is the molar susceptibility of oxygen. For example, the increment is calculated to be 0.07 % under a field intensity of 10 T, which should be less than the usual measurement error. Hence those reports have been disputed. In order to settle the problem, we have examined the oxygen dissolution process, paying special attention to the equilibrium and kinetic aspects. Our conclusions are twofold: (1) the enhancement of equilibrium content of oxygen in water is below the detection limit as thermodynamically expected; (2) the dissolution rate, however, can be significantly enhanced under the influence of magnetic fields. The discrepancies between the thermodynamic prediction and the previous reports should therefore be attributed to the erroneous interpretation of the measurement results. The kinetics and equilibrium must be clearly considered as two independent phenomena. It has turned out that the dissolution kinetics can be enhanced by several times by the application of the magnetic fields readily. The mechanism behind the enhancement has become clear by the observation of the relative degree of the enhancement as a function of the field intensity (Fig. 3). The enhancement is roughly proportional to the value of $B \cdot \mathrm{d}B/\mathrm{d}x$ rather than the field intensity itself. The mechanism was found to be based on the magnetically induced convection in water due to the non-uniformity of magnetic susceptibility created by the dissolution of oxygen into water phase. In a typical setup the convection rate of water is estimated to be as high as 10 mm/s for a vessel of size about a few centimeters in each direction.

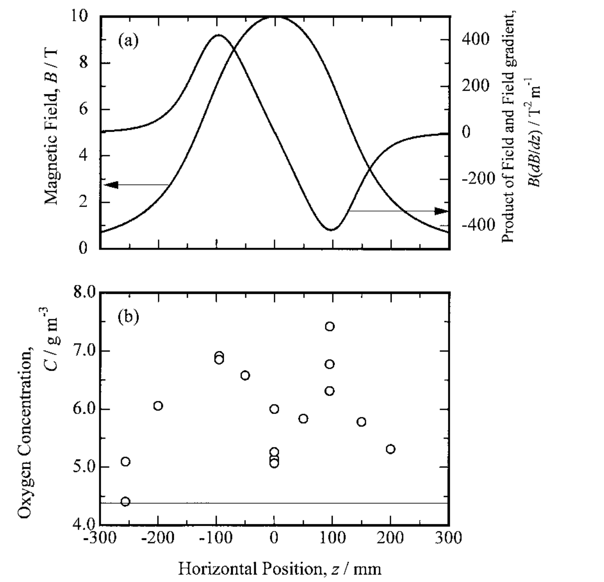


Fig. 3. (a) Distributions of the magnetic field, B, and the product of the magnetic field and its gradient, $B \cdot \mathrm{d}B/\mathrm{d}z$, along the bore axis. (b) Concentration of oxygen in water dissolved at various positions on the bore axis. Degassed water was touched with 2×10^4 Pa of oxygen for 30 minutes at 15.0°C. The solid line in the figure indicates the average value of dissolved oxygen concentration in the case of 0 T under the same condition. Note that the concentration of oxygen roughly scales with the absolute value of $B \cdot \mathrm{d}B/\mathrm{d}z$.

Magnetic wind tunnel [10, 11]

A wind tunnel has been made to generate a wind through a ceramic tube without having any mechanical moving parts in it (Fig. 4). The air is locally heated in a region of the tube just

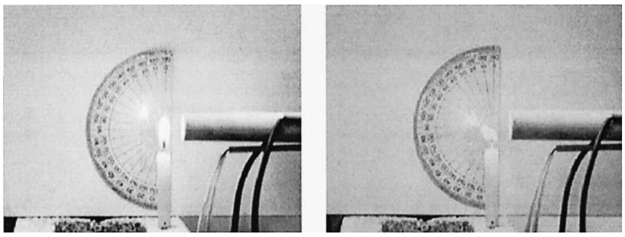


Fig. 4. Demonstration of magnetic wind tunnel. Out of a ceramic tube a wind of velocity 1 m/s is generated (right picture: 8 T) while no wind is detected (left) in the absence of the magnetic field. The ceramic tube is inserted in a superconducting magnet on the right (not shown) and is wound with a heater so that the tube is heated externally at a position off-centered from the maximum field position.

slightly off the field center. The volume magnetic susceptibility of the heated air decreases with the heating temperature T as $1/T^2$. Consequently, the neighboring colder air in the tube replaces the heated air, pushing it out of the strong field region in order to maximize the total magnetic energy of the air. A velocity of wind up to 1 m/s has been observed by this wind tunnel in a horizontal bore of a superconducting magnet of 9 T. A semi-quantitative analysis has been made according to the Navier-Stokes equation, which tells us that it is not difficult in a scaled-up system to generate a wind with velocity 10 m/s provided that a quick heating of the air is achieved. Furthermore, the acceleration or the suppression of thermal convection have been made possible by utilizing this method.[11)]

Conclusion

Utilizing a 10 T superconducting magnet near the room temperature, there have been several different types of phenomena observed in which the magnetic field effects are significant on the processes of "non-magnetic" substances. Although the appearances are different from one phenomenon to another, the mechanisms behind them are all based on the magnetic force due to the slight difference in the magnetic susceptibility of the component non-magnetic substances or due to the inhomogeneity created in the steady state process in the liquid or gas phase with the magnetic field gradient. The liquid/gas or liquid/liquid interfaces can be deformed under a gradient of magnetic field (Moses effect). The deformation can be amplified for the interface of the two liquids by adjusting the density of the two liquids (enhanced Moses effect). In a fluid system any non-equilibrium processes, such as vaporization or gas dissolution into water, create a concentration gradient. It then creates the gradient in the volume magnetic susceptibility in the fluid. If a magnetic field is applied with the intensity gradient perpendicular to thus created gradient of susceptibility, then a steady convection will take place in the phase in which the susceptibility gradient is present. In the case of water vaporization it occurs in the gas phase, while in the dissolution process of oxygen into water it occurs in the liquid phase. A local heating of the air also brings about the inhomogeneity of the magnetic susceptibility and hence provides a magnetic wind tunnel.

It should be noted that the size of the field effect of all the phenomena reported above is proportional to B^2, and hence most of the phenomena become observable only under strong magnetic fields above tesla range, the usage of which has become practically possible due to the recent development of the cryogen-free superconducting magnet. Consequently, the development of further stronger magnetic fields in the future will see more varieties of the field effects.

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