Magnetic Field Effects on Shape and Size of Pendent Water Drop

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The shape and size of a water pendent drop were affected by magnetic forces. Especially in pseudomicrogravity conditions, they changed considerably: the relative contribution of surface tension was increased by the magnetic field.

Microgravity experiments have been carried out and developed considerably with anticipation of interesting results. Recent experiments performed by Pettit in the space shuttle, *Endeavour*, demonstrated that a stable and large water film can be prepared without a surfactant.[1] The shape and volume of the water film depended only on surface tension for lack of gravity.

Since 1991 many groups have observed magnetic field effects on water behavior.[2–7] However, few studies on the surface tension were reported. We have studied magnetic field effects on the reaction at a solid–liquid state and showed that magnetic field effects are enhanced at nonequilibrium states at a solid–liquid interface.[8,9] So it is very interesting to know how a magnetic field influences the shape of liquid surface. In this letter, we report magnetic field effects on the pendent water drops' shape and mass, especially, under pseudomicrogravity conditions prepared by a magnetic field.

A superconducting magnet (JMTD-LH15T40; Japan Superconductor Technology Inc.) was used for our experiment. This magnet has a room-temperature vertical-bore tube of 40-mm diameter. Its maximum field and gradient field are 15 T and 1500 T^2/m, respectively. Details are described in previous papers.[8]

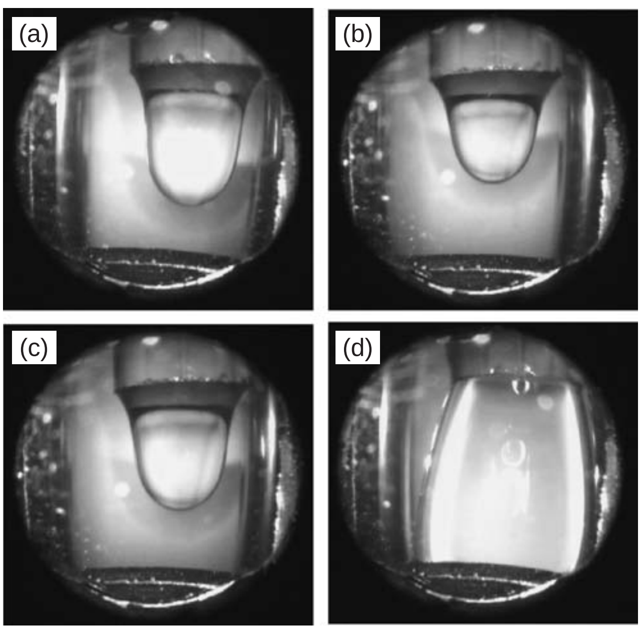

Figure 1. Photographs of water drops. (a) On the outside of the bore tube (control <0.0005 T), (b) in a 11.5 T, +1230 T^2/m magnetic field, (c) in a 15.0 T, +50 T^2/m magnetic field, (d) in a 9.87 T, −1500 T^2/m magnetic field.

All experiments were carried out at room temperature (23.7 ± 0.7 °C) using distilled water. A Pyrex glass capillary was installed at various magnetic field conditions. The contact face's capillary diameter was 8.3 mm; the water flow path diameter was 0.3 mm. Water drops fell from the capillary at a flow rate of 0.5 g/min with a flow pump. We confirmed that the shape and mass under ordinary gravity conditions were identical to those without the flow pump. The water droplet shape was observed using a CCD camera (OH-411; Olympus Co., Ltd.) attached to a bore scope (R100-095-090-50; Olympus Co., Ltd.).

Figure 1 shows photographs of the pendent water drops at various magnetic field conditions. The magnetic field caused drastic changes in the drop shape. The shape and size at 15 T and 50 T^2/m (Figure 1c) were nearly the same as those outside (Figure 1a). However, the radius of the drop decreased by about 0.8 times at the positive gradient (11.5 T, +1230 T^2/m, Figure 1b). In contrast, the radius was increased by about two times at the negative gradient (9.87 T, −1500 T^2/m, Figure 1d). These results indicate that the magnetic gradient, that is, the magnetic force, affected the water drop size.

Figure 2 shows dependence of the mass of one drop on the product of the magnetic field intensity and gradient. The mass of the drops decreased linearly with the increase of the product of

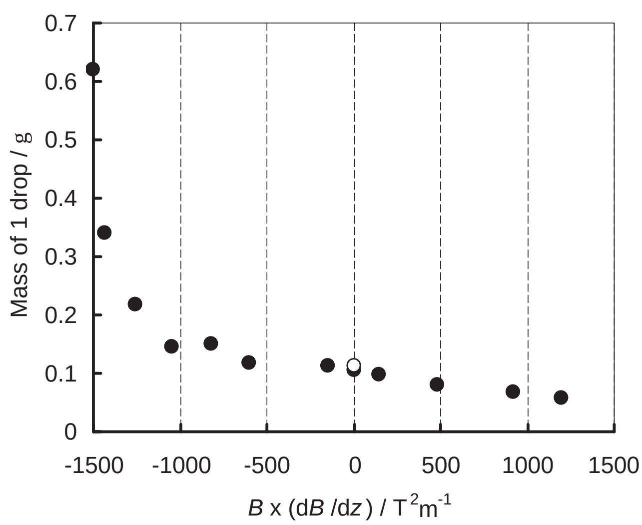

Figure 2. Plot of the mass of one drop vs $B(dB/dz)$: (●) in the magnetic field, (○) outside of the magnetic field. Experimental error is ±5%.

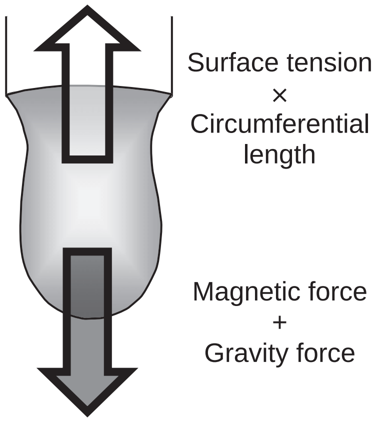

Figure 3. Sketch of the forces acting upon a pendent water drop formed at the end of a capillary.

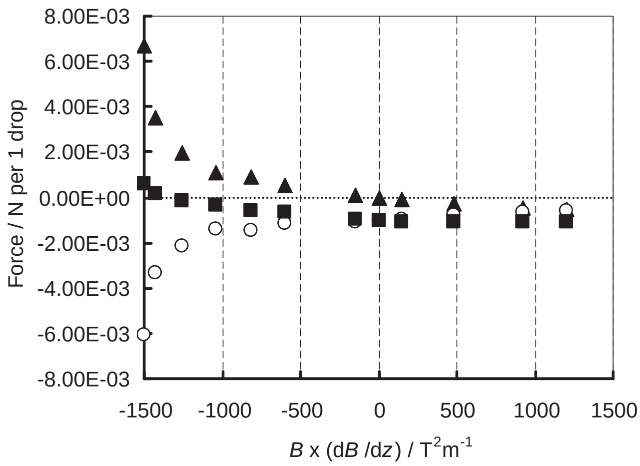

Figure 4. Plot of the magnetic forces, gravity forces, and total forces vs $B(\mathrm{d}B/\mathrm{d}z)$: (▲) the magnetic force, (○) the gravity force, (■) the sum of the magnetic force and the gravity force.

the magnetic field intensity and gradient in the region of -1300–$+1300\,\mathrm{T^2/m}$. However, for $<-1300\,\mathrm{T^2/m}$, the mass increased rapidly with a decrease in the gradient. The mass at $-1500\,\mathrm{T^2/m}$ was about six times larger than at $0\,\mathrm{T^2/m}$.

Forces that act upon the pendent water drop are magnetic force, gravity force, and surface tension, as schematically shown in Figure 3. When the drop just detaches itself, the downward force on the drop is equal to the force acting upward.

The magnetic force per mole ($\boldsymbol{F}_\mathrm{M}$) is given according to the following equation:

$$\boldsymbol{F}_\mathrm{M} = \chi \frac{1}{\mu_0} \frac{\mathrm{d}B}{\mathrm{d}z} B, \qquad (1)$$

where χ is the molar magnetic susceptibility, μ_0 is the magnetic permeability of vacuum, B is the magnetic field, and $\mathrm{d}B/\mathrm{d}z$ is the magnetic field gradient at position z apart from the center of the magnetic field along the bore. The molar magnetic susceptibility of water is $-4\pi \times 12.97 \times 10^{-12}\,\mathrm{m^3\,mol^{-1}}$ at 293 K.[10] We estimated the magnetic force per drop using eq 1. Dependence of gravity and magnetic forces acting on one drop on the product of the magnetic field intensity and the gradient is shown in Figure 4. The direction of the gravity force is always downward. However, its intensity changes, as the mass of the drop changes. In contrast, the direction of the magnetic force depends on the sign of the gradient. At $-1360\,\mathrm{T^2/m}$, the intensities of the magnetic force and the gravity force are equal. However, their directions are opposite. Consequently, the sum of these forces on a drop becomes zero. At this region, the drop system is in a pseudomicrogravity condition, so the shape and the mass of a pendent drop are determined almost entirely by surface tension. For that reason, the mass will increase rapidly in the region with $<-1300\,\mathrm{T^2/m}$. The sum of the magnetic and gravity forces is nearly constant at the positive gradient region. Because the sum of these forces is related to the surface tension times a circumferential length of the capillary, the result indicates that the surface tension will not be affected significantly by the magnetic field, if any. However, as the drop system goes into the pseudomicrogravity condition at the negative gradient region, the apparent surface tension increases with the concomitant decrease in the gravity force. It is clearly demonstrated that the apparent surface tension of a pendent water drop is controlled by magnetic forces. The magnetic field effects reported here will be important in some cases for interpreting the effects on a reaction at gas–liquid, liquid–liquid, and solid–liquid interfaces.

As one application, we succeeded to prepare a large, thin water layer without a surfactant in the pseudomicrogravity condition, indicating that high magnetic field is practically useful for mimicking microgravity. We continue our study of this phenomenon and expect to conduct various space-mimicking experiments in the magnetic field.

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