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Magnetically inspired deformation of the liquid/vapor interface drives soap bubbles

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The possibility of driving millimetrically scaled, soap and glycerol bubbles floating on a liquid, using a steady magnetic field of *c.* 0.5 T, is demonstrated. The bubbles are repelled by the magnet, starting from a threshold initial lateral distance of $L_0^{\text{cr}} = 4$ mm from the vertical axis of the magnet, and are attracted to the magnet when the initial lateral distance $L_0 < L_0^{\text{cr}}$. The displacement of bubbles is due to the deformation of the liquid/vapor interface by the magnetic field, known as the Moses effect. This deformation gives rise to the change in apparent contact angles driving the bubble. Switching of repulsion to attraction is explained in terms of a model of an interaction between two capillary charges, one of which represents the bubble and the second represents the well, produced by the magnet on the liquid/vapor interface. The experiments with bubbles demonstrate that the role of gravity in the displacement of floating diamagnetic objects driven by steady magnetic fields may be negligible. The mathematical model of the process is suggested. The experimental data are well explained by the proposed model.

Notation

B_z	vertical component of the magnetic field
F_{dr}	driving force
F_{visc}	viscous force
h	separation of the magnet from the liquid surface
L_0	initial lateral distance
L_0^{cr}	threshold initial lateral distance
l	perimeter of the triple line
R	radius of the triple line
r	coordinate of the radial distribution of the magnetic field
r_{cm}	lateral distance between the center mass of the bubble and the axis <i>z</i> of the magnet
t	time
v_{cm}	velocity of the center mass of the bubble
γ	surface tension
$\Delta\theta$	contact angle hysteresis
η	dynamic viscosity
θ	interfacial angle
$\tilde{\theta}$	maximal contact angle hysteresis
λ	characteristic length, describing the spatial attenuation of B_z
$\hat{\rho}$	specific resistivity

1. Introduction

Applying electrical and magnetic fields at interfaces gives rise to numerous physicochemical events, including the magnetic actuation of foams,¹ self-assembly^{2–6} and magnetocapillary

valving.⁷ Magnetocapillary effects are usually obtained by the introduction of nano- or microferromagnetic particles to the interfaces.^{1–6} However, the authors demonstrated recently^{8,9} that floating diamagnetic objects (polymer rafts) could be directly actuated with moderate magnetic fields (*c.* 0.1 T). The authors related the effect to the driving force arising from the difference of the contact angle on both sides of the drop. This force in turn results^{10–16} from the deformation of the water/vapor interface by the magnetic field.^{8,9} The effect of deformation of liquid interfaces by magnetic fields is also called the Moses effect.^{17–19} However, the role of gravity (buoyancy) remained obscure. Indeed, the floating body may be displaced by the driving force arising from the difference of the contact angle on both sides of the drop, as suggested by den Dulk *et al.*,⁷ and also by gravity diminishing the potential of a body in the course of its motion.

The present paper sheds light on the role of gravity in the displacement of floating diamagnetic objects driven by steady magnetic fields. The authors studied the motion of floating soap bubbles driven by a magnetic field of *c.* 0.5 T (at the surface of the magnet ($h = 0$), $B_{z0} = 0.52 \pm 0.01$ T; for $h = 1$ mm, $B_z = 0.33 \pm 0.01$ T; for $h = 2$ mm, $B_z = 0.26 \pm 0.01$ T; and for $h = 3$ mm, $B_z = 0.18 \pm 0.01$ T). The radial distribution of the magnetic field is well fitted by the exponential approximation – that is, $B_z(r) = B_{z0} \exp(-r/\lambda)$, with $\lambda = 2.5 \pm 0.2$ mm. The suggested exponential decrease law of the magnetic field is justified by the fact that the stack of magnets used has a rather complicated internal structure.⁹

Figure 1. Scheme of the experimental unit used for the study of magnetically inspired displacement of bubbles is depicted

2. Experimental

The scheme of the experiment is depicted in Figure 1. The distance between the magnet and the water/vapor interface was $h = 1\text{--}3$ mm. Two kinds of bubbles were investigated, namely, glycerol and soap bubbles. The glycerol dynamic viscosity η was $(934 \pm 1) \times 10^{-3}$ Pa s, and the surface tension γ was $(72.0 \pm 0.5) \times 10^{-3}$ N/m.²⁰

The soap bubbles were prepared as follows: air bubbles with a diameter of about 3 ± 0.2 mm and a volume of 15 μl were inflated with a precise microsyringe on a 20% surfactant aqueous solution surface, placed in a petri dish with a diameter of 195 mm. The surfactant used in the experiments was prepared as follows: 30 cm^3 of oleic acid was mixed with 50 cm^3 of distilled water; 73 cm^3 of a 10% solution of triethanolamine, 164 cm^3 of pure glycerin and 47 cm^3 of distilled water were added to the mixture.²¹ All of the chemicals were supplied by Sigma-Aldrich.

The deionized water was prepared by using a Synergy ultraviolet water purification system from Millipore Sas (France), and its specific resistivity was $\hat{\rho} = 18.2$ M Ω cm at 25°C. The dynamic viscosity η and the surface tension γ of the solution were established as $\eta = 1.45 \pm 0.01 \times 10^{-3}$ Pa s and $\gamma = 26.2 \pm 0.1 \times 10^{-3}$ N/m. The surface tension of the solution was established with the pendant drop method using a ramé-Hart 500 goniometer. The viscosity was measured by using an Ostwald viscometer.

Bubbles, such as those shown in Figure 2, were blown with the precise microsyringe at various initial lateral distances $L_0 = 4\text{--}9$ mm taken from the axis of the magnet to the axis of a bubble (see Figure 1). The precise location of the permanent magnet was fixed with a laboratory-built accurate XYZ actuator adjusted from components supplied by CCM Automation Technology. The controller used in the experiments was an Arduino controller for step motors. The motion of the soap bubbles was registered from above with a rapid camera (Nikon 1 V3). The experiments were carried out under ambient conditions.

3. Results and discussion

Now consider the experimental observations obtained with glycerol bubbles. Glycerol bubbles were ‘repelled’ from the magnet (see Video 1 in the online supplementary material) when $L_0 > L_0^{\text{cr}} = 4$ mm took place (where L_0^{cr} is the ‘critical’ initial lateral distance) and attracted by the magnet for $L_0 < L_0^{\text{cr}}$ (see Video 2 in the online supplementary material). Soap bubbles were repelled from the magnet when $L_0 > L_0^{\text{cr}}$. It was technically impossible to place soap bubbles at smaller distances from the magnet, due to their relatively large hemispherical ‘cap’, which was already touching the rim of the magnet. The typical time dependencies of the velocity of the center of mass v_{cm} of the soap bubbles, repelled by the magnet, are presented in Figures 3(a) and 4.

The very question is, what is the physical mechanism of the repulsion of bubbles by the magnet? Consider first switching of the

(a)

(b)

Figure 2. (a) Floating soap and (b) glycerol bubbles are shown

Figure 3. Time dependencies of the velocity of the center of mass v_{cm} of glycerol bubbles (a) attracted and (b) repelled by the magnet are presented

Figure 4. Time dependencies of the velocity of the center of mass v_{cm} of soap bubbles repelled by the magnet are depicted, where $v_{cm0} = 0.93$ mm/s is the averaged maximal velocity of the center mass of a bubble; $t_0 = 2$ s is the averaged time, necessary for attaining the velocity of v_{cm0} . (a) The experimental results obtained for various separations of the magnet from the liquid surface h (●, $h = 1$ mm; ○, $h = 2$ mm) are presented. The diameter d of the bubble was 3.3 mm. (b) The double-logarithmic plots of the time dependence of the velocity of the center of mass of the bubble are depicted. The dashed line depicts the linear fitting of the experimental data. The water–magnet separation and the diameter of the bubble were ●, $h = 1 \pm 0.1$ mm and $d = 3.3 \pm 0.1$ mm; ○, $h = 2 \pm 0.1$ mm and $d = 3.3 \pm 0.1$ mm; ■, $h = 3 \pm 0.1$ mm and $d = 3.5 \pm 0.1$ mm; □, $h = 1 \pm 0.1$ mm and $d = 4 \pm 0.1$ mm; and ▲, $h = 2 \pm 0.1$ mm and $d = 4 \pm 0.1$ mm

apparent repulsion of bubbles to their attraction to the magnet observed at L_0^{cr} . This effect was already considered by Frenkel *et al.*,⁹ and it is illustrated in Figure 5. The change in the apparent interaction of bubbles with the magnet is well explained by the model proposed by Kralchevsky and Nagayama^{22,23} and Kralchevsky *et al.*,²⁴ introducing the notion of the capillary charge $Q_i = R_i \sin \theta_i$, where R and θ are the radius of the triple line and the interfacial angle of a floating bubble (curved surface), respectively.^{22–25} The interaction of a bubble with a magnet is seen in this model as an interaction between two capillary charges, one of which represents the bubble and the second represents the well (punctum) produced by the magnet on the liquid/vapor interface. As shown by Kralchevsky and Nagayama^{22,23} and Kralchevsky *et al.*,²⁴ the interaction is attractive when $\sin \theta_1 \sin \theta_2 > 0$ and repulsive when $\sin \theta_1 \sin \theta_2 < 0$, where θ_1 and θ_2 are the interfacial angles²⁵ of the well and the bubble, respectively (consider for bubbles $\sin \theta_1 < 0$). When a bubble is located initially at the left from the liquid surface inflection point K, $\sin \theta_2 < 0$ takes place, and when it is placed at the right from the inflection point, $\sin \theta_2 > 0$ occurs (see Figure 5). Thus, switching of repulsion to attraction is explained. The qualitative analysis of the attraction of bubbles by the magnet is extremely challenging due to the proximity of characteristic lateral dimensions of a bubble and the well arising from the Moses effect (both of them are *c.* 5–10 mm).

Consider now the repulsion of pure glycerol and soap bubbles (in other words, the condition $L_0 > L_0^{\text{cr}}$ takes place). Note that bubbles present an extremely convenient object for clarifying this mechanism due to the fact that all of the bulk forces (namely, buoyancy, inertia force and magnetic force^{26,27}) are negligible (in other words, a bubble serves as a probe elucidating the role of interfacial effects, driving floating diamagnetic bodies^{8,9,22–25,28}). Thus, the displacement of the floating bubble by the steady

magnetic field is a pure interfacial effect inspired by the deformation of the liquid/vapor interface by the magnetic field.^{8,9}

The magnetic field deforms not only the liquid/vapor interface due to the Moses effect but also the shape of the bubble, as shown in Figure 6. This deformation, which is actually possible due to the contact angle hysteresis ($\Delta\theta = \theta_1 - \theta_2$; see the papers of Chen *et al.*¹⁶ and Sugawara *et al.*¹⁷), gives rise to the driving force, which may be roughly estimated according to the Fumidige equation²⁹

$$1. \quad F_{\text{dr}} \cong \gamma l (\cos \theta_2 - \cos \theta_1) \cong \gamma l \Delta\theta \sin \frac{\theta_1 + \theta_2}{2}$$

where l is the perimeter of the triple line. This driving force is balanced by the viscous force $F_{\text{visc}} \cong \eta l v_{\text{cm}}$. Consider that the triple line of floating bubbles is completely depinned.³⁰ Assume naively that the contact angle hysteresis $\Delta\theta$ exactly follows the magnetic field; in other words, Equation 2 takes place

$$2. \quad \Delta\theta = \tilde{\theta} \exp\left(-\frac{r_{\text{cm}}}{\lambda}\right) \quad \tilde{\theta} = \text{const}$$

where r_{cm} denotes the location of the center mass of the bubble. The balance of forces gives rise to the equation (consider that the soap bubbles are treated as zero mass particles)

$$3. \quad \alpha \frac{dr_{\text{cm}}(t)}{dt} - \beta \exp\left(-\frac{r_{\text{cm}}}{\lambda}\right) = 0$$

where $\alpha \cong \eta = \text{const}$ and $\beta \cong \gamma \tilde{\theta} = \text{const}$ (the numerical factors are omitted for the sake of simplicity). The routine integration of

Figure 5. Scheme of the interaction of bubbles with a magnet is shown. The interaction depends on the location of the bubbles on the surface of liquid curved by the magnet. Red arrows indicate the direction of the driving forces $\vec{F}_{\text{dr}}$

Figure 6. Scheme of the deformation of the soap bubble by the magnetic field is depicted. θ_0 denotes the interfacial contact angle of non-deformed liquid/vapor interface; θ_1 and θ_2 denote the interfacial contact angles of the same surface deformed by the magnet

Equation 3 yields the following scaling law for the velocity of the center mass of the bubbles

$$4. \quad v_{\text{cm}}(t) \cong \frac{\lambda}{t}$$

Fitting of the experimental data with the power function, shown in Figure 4(b), supplied the best possible approximation given by $v_{\text{cm}}(t) \cong 1.8 \times 10^{-3}/t^{1.014}$ [m/s], which is in more than satisfactory agreement with Equation 4. The numerical value of power (namely, 1.028 ± 0.01) was obtained by averaging over five experimental curves. It is recognized from Figure 4(b) that the experimental data obtained for various magnet/liquid separations and diameters of the bubbles are well fit by the same master line, thus validating the proposed model, summarized by Equation 3. Moreover, the value appearing in the numerator of the function fitting the experimental data (namely, 1.8×10^{-3} m) is on the order of magnitude of the characteristic length λ , describing the spatial attenuation of the vertical component of the magnetic field.

4. Conclusions

The authors conclude that the proposed qualitative model satisfactorily explains the observed repulsion of soap bubbles by a steady magnetic field, and it is reasonable to attribute the displacement of the bubbles, floating on diamagnetic liquids, to the magnetically inspired deformation of the liquid/vapor interface, known as the Moses effect. It is plausible to suggest that the impact of gravity on the motion of bubbles, seen as zero mass particles, is negligible.

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