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Laser-Induced Force for Bubble-Trapping in Liquids

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Abstract. The laser-induced thermal force that traps a bubble in an absorbing liquid is studied theoretically and experimentally. The force origins from the thermal gradients of the surface tension induced by a laser beam over the bubble surface. It is shown that this force is proportional to the square of the bubble radius and to the thermal gradient of the surface tension. A simple experimental method based on comparison with the Archimedes' flotation force, is used for the measurement of this force. The experimental results, performed on ethanol solutions of iodine, confirm the theoretical predictions.

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When an intense beam of light impinges into an absorbing medium different nonlinear optical phenomena can be induced: thermal blooming [1, 2], optical cavitation [3], dielectric breakdown [4], photochemical reactions [5], and photocapillary effects [6, 7, 8]. Recently, an interesting phenomenon of bubble formation and laser bubble-trapping in weak absorbing liquids has been reported [9, 10]. The focusing of a cw light beam of relatively low power generates microbubbles inside the absorbing liquid. One of the generated bubbles is trapped by the spatial temperature distribution induced by the light beam in the medium. A beam of light with a Gaussian intensity profile induces a similar temperature distribution in the absorbing medium. If a bubble is formed or located in the vicinity of the light beam, variations of surface tension over the bubble surface cause tangential strains on it. This induces convective motion in the liquid phase, which moves the bubble toward the point of maximal temperature (Marangoni effect) [11]. Therefore, the bubble is trapped at the center of the light beam. It is possible to control the radius of the trapped bubble by changing the magnitude of the light power [10]. The effect is observed at relative low light-power levels and is easily reproducible for different liquids (water, ethanol, bencene). It is the purpose of this work to study the physical origin of the laser-induced force for bubble-trapping and its relation with the bubble radius and thermal parameters of the interphase liquid-gas such as the temperature dependence of the surface tension and the liquid thermal conductivity.

The magnitude of this force is estimated using the Laplace's formula for the equilibrium between the internal, external and surface tension pressures at the bubble surface. It is shown that this force is proportional to the square of the bubble radius and to the thermal gradient of the surface tension. The force is equal to zero at the beam center and has a maximum value at a given point off the beam direction. A simple method for the experimental measurement of the maximum value of this force is proposed via its comparison with the Archimedes' flotation force. A good agreement between theory and experiment is obtained. From the dependence of the laser-driven force for bubble-trapping from the bubble radius we estimate the value of the thermal gradient of the surface tension for ethanol.

Different authors have studied the movement of gas bubbles in a vertical linear thermal gradient in the presence of gravity [12–14]. They show that thermal gradients lead to forces that act on the bubble, moving it to the place of higher temperature. They also show theoretically and experimentally that the magnitude of this force if proportional to the square of the bubble radius and to the thermal gradient of the surface tension. We show that similar dependences are observed when the heating is due to a light beam. When a laser beam propagates in an absorbing liquid, a thermal gradient of axial symmetry is induced. If the spatial intensity profile of the incoming beam is Gaussian, the point of maximal temperature coincides with the beam center. For this particular geometry of the experiment, we expect results similar to those obtained for linear temperature gradients.

Suppose that there is a bubble located at the vicinity of a light beam in a stationary situation (no bubble movement). From Laplace's condition for the hydrodynamic equilibrium we obtain [11]:

$$P_0 = P + \frac{2\sigma}{R}, \tag{1}$$

where P_0 is the hydrodynamic pressure inside the bubble, P is the hydrodynamic pressure outside the bubble, σ is the surface tension coefficient, and R is the bubble radius. The resulting force which the liquid phase applies on the bubble is given by

$$\mathbf{F} = \int_S P\mathbf{n}\,\mathrm{d}S\,, \tag{2}$$

where S is the bubble surface and $\mathbf{n}$ is the unit vector normal to the surface unit $\mathrm{d}S$. Equation (2) can be transformed to an integration over the bubble volume V using the Green's theorem. So, taking (1) into account we obtain,

$$\mathbf{F} = \int_V \operatorname{grad}\left(P_0 - \frac{2\sigma}{R}\right)\mathrm{d}V\,. \tag{3}$$

In (3) we suppose that the internal pressure P_0 does not vary substantially with the coordinate. This is true for small bubble radii, or, if we consider hydrodynamic equilibrium, this is always fullfilled inside the bubble. Considering the bubble radius small, from (3) we calculate

$$\mathbf{F} = -(8\pi/3R^2)\,\frac{\partial\sigma}{\partial T}\operatorname{grad}(T)\,. \tag{4}$$

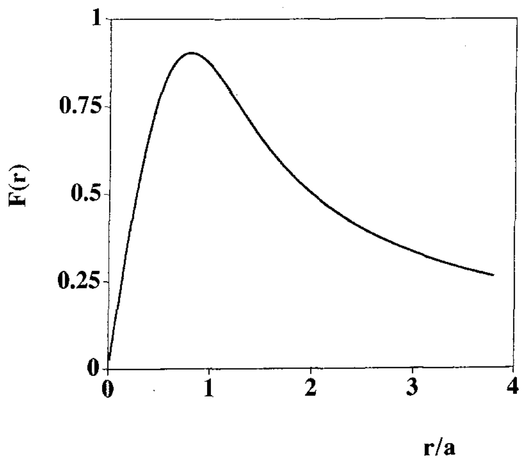

Fig. 1. The laser-induced bubble-trapping force in units of $(\beta/a)^{-1}$ as a function of the bubble position r in units of a

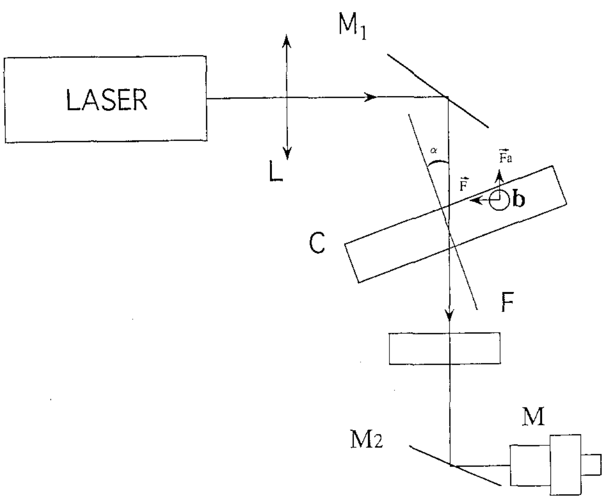

Fig. 2. The experimental setup for measuring the maximum value of the laser-induced bubble-trapping force, consisting in a cw argon laser, mirrors M_1 and M_2, a focusing lens L, a sample cell C, a filter F, and a microscope M

where $\mathrm{d}\sigma/\mathrm{d}T$ is the temperature gradient of the surface tension and T is the temperature. Usually, the surface tension decreases when the temperature decreases: $\mathrm{d}\sigma/\mathrm{d}T < 0$. Therefore, the force which the liquid imposes on the bubble is directed to the place of higher temperature.

Our following step is to calculate the temperature gradient induced by a laser beam in an absorbing liquid. We suppose that the light beam has a Gaussian spatial intensity distribution axial symmetry. The equation that rules the spatial temperature dependence at stationary conditions is

$$\kappa\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\frac{\partial T}{\partial r}\right)\right] = (\gamma 2P/\pi a^2)\exp(-2r^2/a^2)\,, \tag{5}$$

where κ is the thermal conductivity, γ is the absorption coefficient, P is the total light power, and a is the light-beam radius. From (5) we calculate the spatial temperature gradient,

$$\frac{\partial T}{\partial r} = \gamma P/(2\pi\kappa r)\,[1 - \exp(-2r^2/a^2)]\,. \tag{6}$$

Combining equations (4) and (6) we obtain

$$\mathbf{F} = -\beta[1 - \exp(-2r^2/a^2)]/r\mathbf{e}_r\,, \tag{7}$$

where $\beta = 4\gamma PR^2/(3\kappa)\,|\mathrm{d}\sigma/\mathrm{d}T|$. In Fig. 1 we have plotted the laser-driven force for bubble-trapping as a function of the position r. At $r = 0$, the force is zero. For small r, F is proportional to r. At $r = 0.77a$ the force reaches its maximum value. For $r > 0.77a$ the force decreases when r increases. The maximum value of the force is

$$|\mathbf{F}_{\max}| = 0.9\beta/a\,. \tag{8}$$

In the absence of external forces the bubble tends to the central position ($r = 0$), where the potential energy of the laser-driven force has a minimum. In a real experimental situation, besides the force induced by the laser, the bubble can be under the action of other forces such as gravity (Archimedes' flotation force). The bubble position results from the equilibrium of both forces. This fact is used in the experiments to measure the maximum value of the laser-induced force given by (8).

The experimental setup for the study of the laser-driven force for bubble-trapping is shown in Fig. 2. The light from a cw multiline argon laser is directed vertically downward to the sample using a 20 cm focal length lens L and the mirror M_1. When the light beam is focused inside the liquid sample, bubbles are generated in the focal point. One of the generated bubbles sticks to the upper face of the cell because of the Archimedes' force and because this is the place of maximal temperature. We used a microscope for bubble observation and measurement of the bubble radius. The light is directed to the microscope using the mirror M_2. For light-power attenuation we use the filter F. The sample is a 2 mm long glass cell filled with a 50 mM ethanol solution of iodine. The orientation of the cell can be changed, so the normal to the cell forms an angle α with respect to the light-beam direction. If the cell is horizontal ($\alpha = 0$), the projection of the Archimede's force over the bubble-trapping force vanishes and the bubble remains in the center of the laser beam. When increasing α, the Archimedes' force displaces the bubble from this position. For a given value

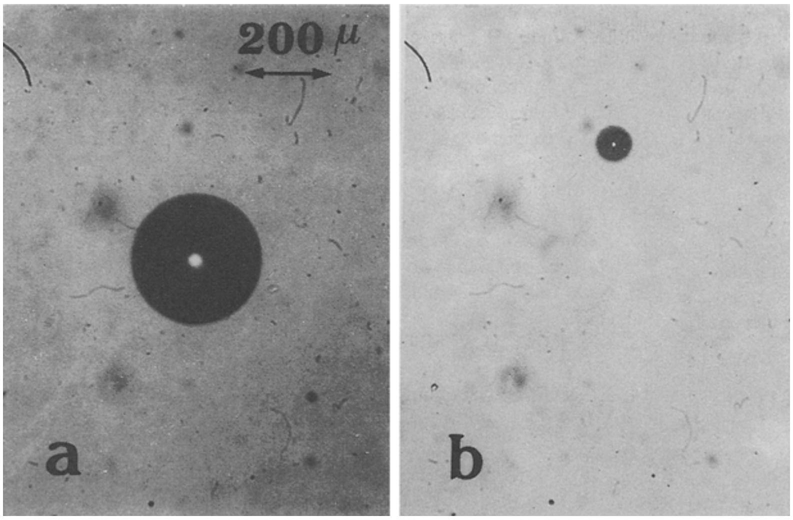

Fig. 3a, b. Photographs of two trapped bubbles of different radius: 150 μm (**a**) and 40 μm (**b**)

of $\alpha = \alpha_{max}$, this force projection becomes equal to the maximum value of the bubble-trapping force, and the bubble is freed. Under this condition, we calculate

$$|F_{max}| = F_a \tan(\alpha_{max}) . \tag{9}$$

where $F_a = 4\pi\delta g R^3/3$ is the Archimedes' force, δ is the liquid density and g the gravity. In the experiment we measure the angle α_{max} for different values of the bubble radius R. Calculating the Archimedes' force for each particular bubble we estimate the laser-induced bubble-trapping force by using (9).

Bubbles of different sizes can be generated by focusing the laser beam of different intensities. In Fig. 3 we show photographs of trapped bubbles of two different sizes. After creating the bubble, the light beam is defocused so its spot size becomes much larger than the radius of the generated bubble (several millimeters). Some changes of the bubble size occur during this beam defocusing, so the bubble radius is measured after the situation becomes stabilized, by using a micrometer that displaces the microscope. Then, we rotate the cell until the bubble is liberated from the thermal trap. In this situation, the rotation angle is equal to α_{max}. In Fig. 4 we have plotted the dependence of the laser-induced bubble-trapping force on the bubble radius R on logarithmic scale for light-power levels of 0.225 W and a beam diameter of 4 mm. Similar results were obtained for different light-power levels and beam diameters. The slope of this logarithmic dependence is equal to 2, consequently, the laser-induced bubble-trapping force is proportional to the square of the bubble radius. This kind of dependence demonstrates the surface origin of the bubble-trapping force. From the measured experimental values of this force and using the values for the light power ($P = 225$ mW), sample absorption ($\gamma = 12\,\text{cm}^{-1}$), beam radius ($a = 2$ mm), and the thermal conductivity of ethanol [$\kappa = 4\ 10^{-4}$ cal/(cm s° C)], we estimate the value of the thermal gradient of the surface tension coefficient between the interphase liquid–vapor inside the bubble. The result is

$$\frac{\partial\sigma}{\partial T} = -(7 \pm 1)\,10^{-4}\ \text{dyn}/(\text{cm}^\circ\ \text{C}) .$$

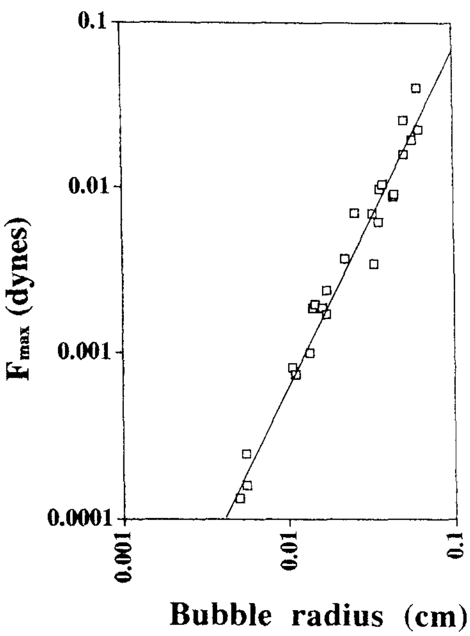

Fig. 4. Maximum value of the laser-induced bubble-trapping force as function of the bubble radius. The experiment was performed for a light power of 225 mW, a spot beam radius of 2 mm and a sample absorption coefficient of 12 cm^{-1}. The continuous line corresponds to a square dependence on the bubble radius

The results shown in Fig. 4 confirm the predictions of the theory and also previous studies of the dynamics of bubble movement in thermal gradients [12–14].

In conclusion, we have calculated the value of the laser-induced bubble-trapping force under stationary conditions. We also have measured the experimental value of this force for bubbles of different radii. In agreement with the theoretical predictions the laser-induced bubble-trapping force is proportional to the square of the bubble radius. From the measured values of this force we have estimated the value of the thermal gradient of the surface tension of the interface gas–liquid for ethanol.

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References

1. S.A. Akmanov, D.P. Krindach, A.P. Sukhorukov, R.V. Khokhlov: JETP Lett. **6**, 38–42 (1967)
2. J.P. Gordon, R.C. Leite, R.S. Moore, S.P. Porto, R. Whinnery: J. Appl. Phys. **36**, 3–8 (1965)
3. W. Lauterborn: Acustica **31**, 51–79 (1974)
4. P.A. Barnes, K.E. Riechkoff: Appl. Phys. Lett. **13**, 282–284 (1968)
5. K. Dareé: Opt. Commun. **4**, 238–240 (1971)
6. G. Gouesbet, M. Rhazi, M.E. Weil: Appl. Opt. **22**, 304–309 (1983)
7. R. Anthore, P. Flament, G. Gouesbet, M. Rhazi, M.E. Weill: Appl. Opt. **21**, 2–4 (1982)
8. V.Yu. Bazhenov, M.V. Vasnetsov, M.S. Soskin, V.B. Taranenko: JETP Lett. **49**, 377–379 (1989)
9. V.Yu. Bazhenov, M.V. Vastnetsov, M.S. Soskin, V.B. Taranenko: Appl. Phys. B **49**, 485–489 (1989)
10. A. Marcano O.: Appl. Opt. **31**, 2757–2764 (1992)
11. V.G. Levich: *Motion of drops and bubbles in fluid media*, In *Physicochemical Hydrodynamics* (Prentice-Hall, Englewood Cliffs, NJ 1962) pp. 385–471
12. N.O. Young, J.S. Goldstein, M.J. Block: J. Fluid Mech. **6**, 350–356 (1956)
13. J.F. Harper, D.W. Moore, J.R.A. Pearson: J. Fluid Mech. **27**, 361–366 (1967)
14. F. Durst, B. Schonung, K. Selanger, M. Winter: J. Fluid Mech. **170**, 53–82 (1986)