Light Moves Macro-objects

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Abstract— Photons energy can be conventionally converted into mechanical work through a series of energy expensive steps. It has been shown how some of these steps can be bypassed obtaining a direct conversion of photons energy into mechanical work. The most common way consists of using light in the visible or near infrared to move small objects floating on fluid surfaces exploiting the Marangoni effect. In this work we use a low power visible light source to induce a thermal surface tension gradient thus moving a floating object on a fluid surface. By real time tracking of the object trajectory we can determine some physical properties related to the floating object and to the supporting fluid. Moreover from the experimental data fitting we can evaluate the applied driving force due to light irradiation and object heating. In addition we show how even transparent object can be moved by light when the supporting fluid is properly doped.

In order to study the light induced motion of small objects on fluids [1–5] we performed a series of experiments by using an experimental setup based on an Argon Ion cw laser impinging on a small cork disc floating on three different fluids: water, ethanol and a solution of ethanol and an azo-dye whose absorption spectrum is centered around the blue wavelength of $\lambda = 476.5\,\text{nm}$ used to irradiate the cork. Fig. 1 shows the steps of the irradiation process at different time intervals when a small cork disk, whose diameter is 5 mm thickness 2 mm and mass $m = 0.058\,\text{g}$, floats on ethanol. As it is shown in Fig. 1(a), at the beginning of irradiation the cork disc is partially heated by light in order to induce the thermal gradient necessary to its motion. Indeed, with a uniform irradiation the object will not move along any particular direction because a thermal gradient cannot be established. After 1.5 seconds of irradiation (corresponding to Fig. 1(b)), the object motion starts along the direction defined by the induced gradient. The effect of irradiation becomes negligible when the object moves outside the light beam; after that a deceleration process occurs until the motion stops in about 6 seconds from the beginning of the irradiation. A typical object's displacement vs. time is shown in Fig. 2.

The object motion along the x direction can be described by the following equation:

$$\left(\frac{d^2x}{dt^2}\right) + \frac{D}{m}\left(\frac{dx}{dt}\right)^2 - \frac{\langle F\rangle}{m} = 0 \tag{1}$$

where $\langle F\rangle$ is the average force due to light irradiation and D is defined by $D = 1/2\rho S C_D$, being ρ the density of the solution, S the displaced area and C_D the drag coefficient. When the heating effect prevails on the dissipative term the object velocity increases until a maximum value is reached. At this location the acceleration is zero and there is an equilibrium between the two forces. After that the motion slows down and stops. By neglecting the driving force when the object is out of the light beam we can drop this term for the second part of motion and write:

$$\left(\frac{d^2x}{dt^2}\right) + \frac{D}{m}\left(\frac{dx}{dt}\right)^2 = 0 \tag{2}$$

Which can be easily solved and gives:

$$x = x_0 + \frac{m}{D}\ln\left(1 + \frac{Dv_0}{m}(t - t_0)\right) \tag{3}$$

Equation (3) can be successfully used to fit the experimental data concerning the deceleration process. As an example in Fig. 2 it is reported as dashed line the data fit made by using $D =$

0.04 g/cm and $v = 0.5$ cm/s. Once D is known the drag coefficient or the density of the solution can be easily calculated. Also the value of D derived from the experimental data fit can be used in Eq. (1) to determine the average value of F_l by fitting the first part of the curve using the solution of Eq. (1):

$$x = x_0 + \frac{m}{D}\log\left(\cosh\left(\sqrt{\frac{\langle F_l\rangle D}{m}}\,(t - t_0)\right)\right) \tag{4}$$

The fit reported in the inset of Fig. 2 allows evaluating $\langle F_l\rangle = 0.5$ mN. This value is compatible with an induced temperature gradient of about 1.5°C, see Fig. 3, measured when the cork sample is replaced by a PT100 resistance temperature detector.

As can be seen from the Fig. 3, after the start of irradiation the temperature change in ethanol reaches quickly the maximum value of $\Delta T = 1.5$°C where as in other fluids such as water it takes

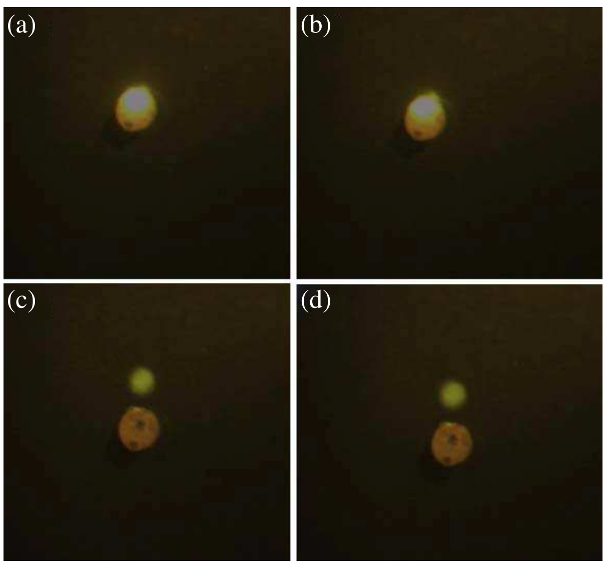

Figure 1: Position of a cork disc floating on ethanol after (a) 1.0, (b) 1.5, (c) 5.0 and (d) 6.0 seconds from the start of laser irradiation (power $P = 300$ mW, $\lambda = 476.5$ nm, spot diameter $d = 3$ mm).

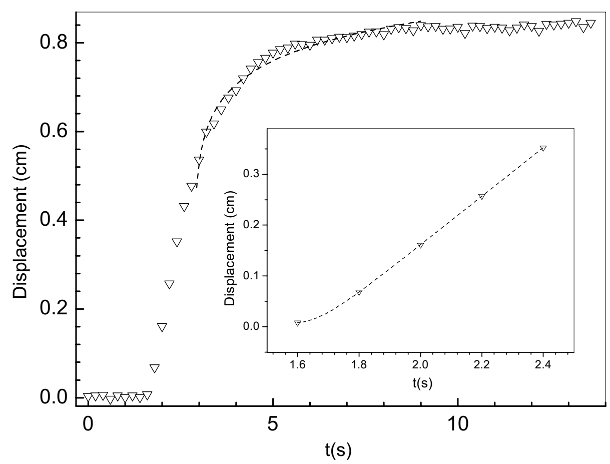

Figure 2: Typical object's displacement vs time. The dashed line represents the data fit of the deceleration process using $D = 0.04$ and $v = 0.5$ cm/s. The inset shows the data fit related to the initial part of motion using Eq. (4).

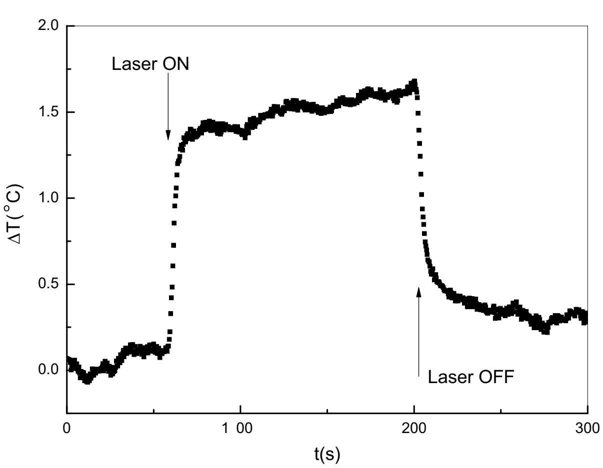

Figure 3: Induced temperature change in ethanol as function of the irradiation time measured using a PT100 thermocouple placed near the upper liquid surfaces. The irradiation power is 300 mW at $\lambda = 476.5$ nm.

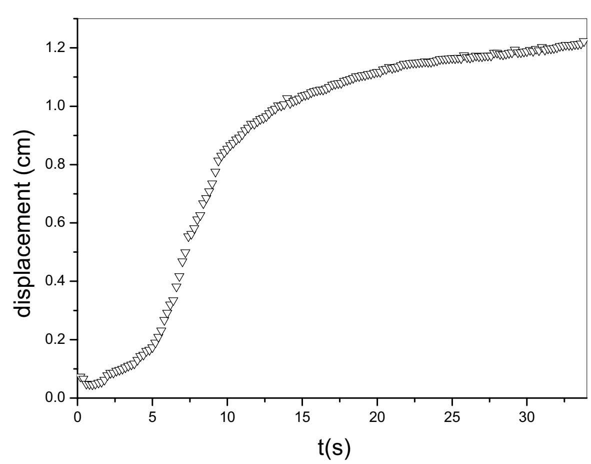

Figure 4: Sample displacement in ethanol doped with an azo-dye. The laser spot is 2 mm far from the cork disc.

a much longer time to geta comparable change. These results can be explained taking into account the different specific heat capacities of the two fluids. How this different physical behavior reflects on the motion of the floating object is still under investigation. It is worth remarking how by doping the ethanol with a proper azo-dye able to absorb part of the irradiated energy the object can be slowly moved even in a no contact mode. Acting this way transparent objects can be moved on floating liquids as shown in the preliminary results in Fig. 4.

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