# Forward and backward laser-guided motion of an oil droplet

Department of Physics, Graduate School of Science, Kyoto University
Sergei RYBALKO [1]

It has been well established that laser exerts two different kinds of force on objects; one is optical pressure and the other is attraction toward the focus, i.e., laser trapping (see, e.g. [1, 2]). As for the object floating in gas phase, it is found that some type of object can move toward the source of the laser beam, which has been described in terms of radiometric force (see, e.g. [3] and Refs. therein). However, as far as we know, there has been no report on the controlled directed motion of an object forward and backward solely by changing the position of the illumination of the laser on the object. In the present work we describe a new phenomenon of directed motion of an oil droplet in an aqueous solution that is generated by a laser beam. Significantly, the direction of the droplet motion can be switched forward/backward depending on the optical path of the laser through the droplet. The controlled motion can be explained by photomechanical energy conversion based on a mechanism not mentioned above s, i.e.: The oil droplet is locally heated with a narrow laser beam, then this local heating evokes convection inside the droplet, and in succession the convective motion, thus generated, produces the translational directed motion of the droplet.

Convection in fluids has been a fruitful system for the study of nonlinear, nonequilibrium patterns for almost 100 years. [4, 5, 6]. Many years passed before it was conclusively shown that surface tension gradients, or Marangoni, forces were crucial. [7, 8]. At present, local very strong heating of a surface can be easy achieved by high-power lasers and therefore induce effect of thermocapillary convection compared with gravitational one.

In the present study, we report experiments on a nitrobenzene oil droplet in a water solution under a strong laser irradiation. The macroscopic motion of the oil droplet induced by laser was observed. Decreasing the surface tension between oil and water solution by adding the SDS (soduim dodecyl sulfate, 0.5 mM) allows us make the droplet to take hemi-sphere-like shape and to float just under the surface of the water and air. The floating droplet is approximately 5 mm in diameter and 5 mm thick. The laser heating the droplet is a diode laser pumped cw Nd:YAG laser, 532 nm wavelength. The power of the laser can be varied from 0.5 W to 2.0 W. To run up to maximum effect in local heating we focus the laser beam by a lens ($f = 50$ mm)

[1]E-mail: rybalko@chem.scphys.kyoto-u.ac.jp

up to 0.6 mm in diameter. Moreover to achieve very high absorbance of the light inside the oil we change the color of the oil by dissolving the $I_2$ (5 mM) and KI (until saturation at the room temperature). The tint of the droplet becomes brown or red. For comparison we have measured an absorbance of transparent oil as well as colored one. The increasing the absorption coefficient from 0.1 (transparent oil) up to 3.7 (brown oil) at 532 nm wavelength is registered.

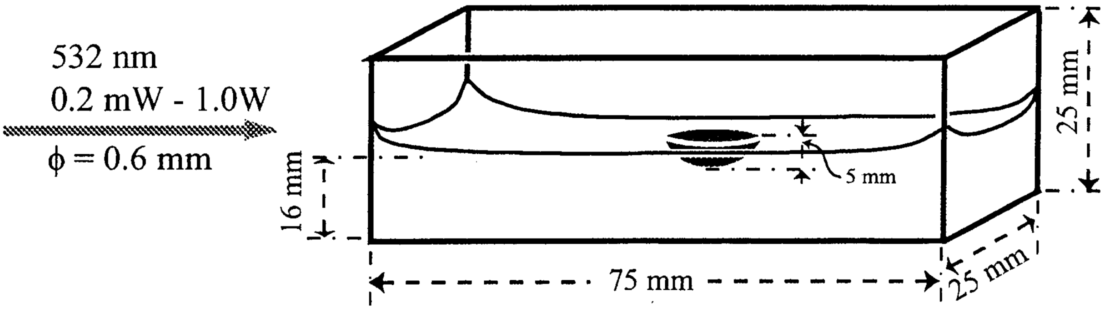


Figure 1: Schematic geometry of the experiment: Laser beam (532 nm) irradiates the droplet (5 mm in diameter approx.) from the left side of the pictures. The droplet moves from left to right or visa versa depending on a position of the laser. The power and the radius of the laser are shown on the arrow.

Figure 1 shows the droplet floating geometry implemented in a elongated rectangular glass vessel. The all walls of the container are made of Plexiglas with 2 mm average thickness. The laser beam aims to the oil droplet from the left-hand side. The oil moves from the left to right or visa versa depending on the laser position: backward motion can be seen if the laser is near the interface water-air and forward one if the laser is at the bottom of the droplet. For more details in Fig. 2 we show spatio-temporal plot of the oil droplet movement through out of whole long-time experiment.

If the laser is at the surface (see Fig. 2, white ranges on time scale) the most part of light energy is absorbed at transmission of a laser beam through the droplet of oil. In this case a layer of oil local heating is a diameter of a droplet connecting extreme left and extreme right its points. Strong absorption of energy is caused by an iodine brown tint of oil in the droplet. Strong local heating of oil results in a complex convection inside of the droplet and forces it finally to move aside the laser (backward motion). In the second case - an irradiation of a bottom of the oil droplet (see Fig. 2, gray ranges on time scale) – the beam of the laser refracts on an interface between water and oil and the most part of light energy is absorbed in the refracted laser beam. In turns it causes a complex convective flow in a bulk of oil. As a result the droplet moves in opposite to laser direction (forward motion).

We quantify the variation in velocity of the resulting droplet movement as a function of laser power $P$. We have conducted many experiments documenting the movements of oil droplet measuring the resulting velocity and the maximal temperature depending on the laser power,

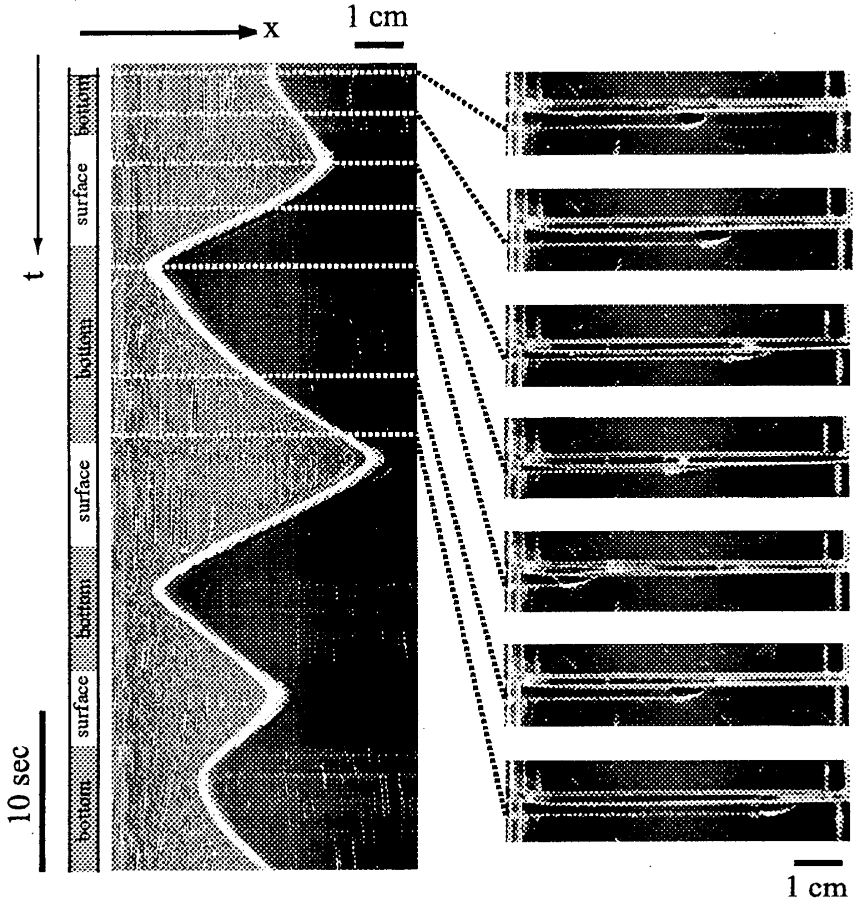


Figure 2: Experimental spatio-temporal images of the droplet motion extracted from the recorded movie. The irradiate position of the laser is indicate on the left time-bar. The right pictures are the actual snapshots.

which was varied from 0.1 W up to 1.0 W with 0.1 W steps. The velocity of the droplet was measured by analyzing recoded data. The maximal temperature was taken from the thermal IR camera image. The plot of velocity has the horizontal asymptotes for the forward motion (positive values) as well as backward motion (negative values). The dependence of temperature on the laser power can be well fitted by a linear function.

The key point of the our experiments on capture of the oil droplet by a laser beam is local oil heating that leads the system far from equilibrium and as a result to a complex convection inside of a droplet. For the detailed analysis of the convective flows in oil we have conducted some experiments on irradiating the droplet put in a narrow cylindrical vessel (test-tube). Such geometry of experiment does not allow the droplet to move and simplifies convective currents treatment studying. Analyzing this convection in more details we can assert that it is a result of two main components. First a strong local heating certainly causes a gravitational or free convection in the oil driven by density gradient that leads to appearance of buoyancy forces. The well-known phenomenon induces a vertical circular movement. From the other hand the most important effect in the experiment is occurrence a thermocapillary (or Marangoni) convection driven surface tension gradient. Convective currents near the surface between oil and water have mainly one direction. As a result, total interfacial force between oil and water is essentially higher than force on the surface oil-air. It leads to movement of a drop in the certain direction. Changing a position of the laser we change a layer of local heating of oil. It results in a changing of complex convection geometry and in succession in reversing direction of the oil droplet movement.

In summary, we have developed an experimental fluids system that demonstrates photomechanical conversion of energy. The system is nitrobenzene oil droplet (about 5 mm in diameter) in water solution. Changing a color of oil droplet adding the iodine we irradiate it by a diode laser focused by a lens. We have shown the macroscopic droplet motion which direction depends only on a position of the laser. This experimental system is easy to implement (see Fig. 1) and observed phenomenon is very well reproduced. Conducting many experiments in a longitude vessels as well as narrow test-tube we have demonstrated that the main reason of such energy transformation is complex 3D convective motion inside oil droplet, or coupled thermocapillary and gravitational convection, caused by strong local heating of oil-water interface. Presence of viscosity between oil and water leads to occurrence of inter-facial forces between oil and water and as a result to macroscopic oil droplet motion. We expect that this complex photomechanical phenomenon can be very well described by Navier-Stokes equations in Boussinesq approximation.

## References

[1] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, Opt. Lett., 11, no 5, 1986, p. 288

[2] S. Chu, Science, 253, no. 5022, 1991, p. 861

[3] P. C. Ke, M. Gu, Appl. Opt., 38, no. 1, 1999, p. 160 1. H. Monjoshiro, M. Tanaka, and H. Watarai, Chem. Lett., 32, no 3, 2003, p. 254

[4] H. B'enard, Rev. Gen. Sci. Pure Appl., 11, 1261 (1900).

[5] C. Normand and Y. Pomeau, Rev. Mod. Phys., 49, 581 (1977)

[6] M.C. Cross and P.C. Hohenberg, Rev. Mod. Phys., 65, 851 (1993).

[7] M.J. Block, Nature, 178, 650 (1956).

[8] J.R.A. Pearson, J. Fluid Mech., 4, 489 (1958). 8-1. K. Yoshikawa and N. Magome, Bull.Chem. Soc. Jpn, 66, no 11, 3352 (1993).