# Laser-driven Marangoni flow and vortex formation in a liquid droplet

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## ABSTRACT

We present a systematic study of the laser-driven Marangoni flow and curvature induced vortex formation in a copper sulfate pentahydrate solution, visualized by dispersed carbon nanotube (CNT) bundles. The experiments are carried out using different objectives of numerical aperture (NA) in the range of 0.1–0.6 to investigate the effect of focusing on the flow dynamics. The flow velocities measured (for 0.1 NA) are in the range of 2 mm/s–5 mm/s depending on the size of CNTs. Both primary and secondary vortices are observed in our experiment. In the primary vortex, with a sixfold increase in NA, a tenfold increase in the angular velocity of CNTs is measured. We also discuss the important role played by the curvature of the droplet in the vortex formation. The numerical simulations carried out for flow velocity are in agreement with the experimental values.



Since its discovery more than three decades ago,[1] optical tweezers are widely utilized for trapping of micrometer and nanometer size particles. However, some applications demand the confinement of many particles. There have been previous attempts to circumvent this problem by focusing a continuous wave (CW) laser in an absorbing liquid to generate and trap bubbles,[2] wherein the trapped bubbles attract nearby particles.[3,4] The gradient of temperature is necessary for such a movement.[5,6] In the case of an absorbing liquid surface, because of laser heating, non-uniform surface tension is created, giving rise to the Marangoni flow[7] that depends on its gradients. The transition from an optical to thermal trapping has been observed for polystyrene beads in a weakly absorbing medium.[8] In the case of trapped bubbles in an absorbing dye, the simulated trap strength was found to be $>5 \times 10^{-9}$ N due to the Marangoni effect.[9] Apart from liquid absorbers, gold nanoparticle based resonant surface plasmon heating has been utilized to generate bubbles; the temperature change of ~3 K gave rise to a flow velocity of ~1000 $\mu$m/s.[10] Recently, using multiple laser spots, the direction of fluid flow was controlled in an absorbing film of gold nanoislands.[11] We have shown earlier a laser-based generation of gaseous, vaporous, and mixed bubbles using carbon nanotubes (CNTs) as an absorber at a low incident power of 5 mW.[12] Furthermore, with the use of a CW 1064 nm laser, dendritic patterns and accelerated crystal growth are observed in various solutions dispersed with CNTs.[13,14]

The Marangoni effect has widespread utility in microfluidic applications; flow velocities of magnitude higher than 1000 $\mu$m/s are reported using a sharp probe attached to a heater causing a temperature change of ~1 °C in water and oil.[15] Earlier, a massive movement of polystyrene beads was demonstrated with a maximum velocity of 8 mm/s, using an infrared (1.55 $\mu$m) laser-induced vortex flow in water.[16]

Namura and co-workers, using a gold nanoparticle film, created a bubble and then moved the laser beam in its vicinity and observed two circular flows that aided in the sorting of polystyrenes spheres.[17] In a subsequent work,[18] by balancing the horizontal and vertical temperature gradient controlled by the laser position around the bubble, a nearly collimated particle flow was demonstrated. Recently,[19] the collection of graphite oxide nanoplatelets dispersed