INDIRECT MANIPULATION OF PARTICLES USING A SCANNING OPTOFLUIDIC TWEEZER

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ABSTRACT

Optofluidic tweezers (OFT), described previously by our group, can trap and manipulate oil-in-water (O/W) droplets using thermocapillary forces generated by a focused laser. Holding forces are in the µN range, 5 orders of magnitude larger than optical tweezers; however, thus far OFT has been limited to liquid droplets. This paper demonstrates the indirect manipulation of particles using the oil droplets as force transducers. The trapped droplets interact with the particles in one of two modes, engulfment and attachment. Using a wide field of view laser scanner, we demonstrate the manipulation of 50 µm glass beads using 400 µm oleic acid-in-water droplets. This approach extends the capabilities of optical manipulation to larger and heavier particles compared to current tools.

KEYWORDS

droplets, optical tweezer, particle manipulation, laser, assembly

INTRODUCTION

The dynamic manipulation of particles and droplets via light has been a long standing interest in the physical and life sciences, due to its numerous applications in microfluidics, cell manipulation, force measurements, micro-scale assembly, and other areas. Optical tweezers are widely used in the manipulation of dielectric particles [1]; however, their relatively small force (pN) limits their application to µm and sub-µm particles; and when used for manipulating water-in-oil (W/O) droplets, the forces are generally repulsive [2]. Optoelectronic tweezers rely on dielectrophoretic forces, which are larger (nN), but require on-chip electric fields [3], which may be undesirable in many cases. In this paper, we demonstrate the indirect manipulation of particles using optofluidic tweezers (OFT), an optical trapping technique previously shown by our group [4], [5], which enables the 2 dimensional manipulation of O/W droplets. Using a scanning laser, we use the droplets as optically controlled force transducers to indirectly manipulate particles (Fig. 1).

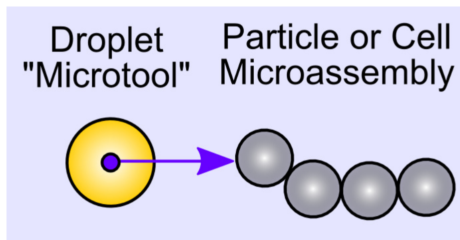

Fig. 1: *General concept*. Droplets trapped using optofluidic tweezers can serve as a force transducer for indirectly manipulating solid particles.

CONCEPT

The operational principle of OFT is shown in Fig. 2. OFT relies on thermocapillary forces generated by a focused laser at a liquid liquid interface. It has been shown previously that thermocapillarity can exert µN forces on a water-in-oil droplet, however, these forces were shown to be repulsive [6]. We recently demonstrated the concept of OFT, where a focused laser can be used to trap oil-in-water (O/W) droplets with an attractive force [4], [5]. The laser is focused on the surface of an oil droplet containing an absorbent dye. Local heating creates surface temperature gradients, resulting in interfacial Marangoni flow which takes the form of spherical microvortices. The resulting shear stress exerts a lateral force on the droplet, pulling it toward the axis of the laser. When the droplet is aligned to the laser, the vortices become symmetric and the droplet is trapped. The principle of balanced lateral restoring forces is similar to the conceptual model for optical tweezers (Fig. 1A), except in OFT the restoring force is due to thermocapillarity. Using OFT, we demonstrated the manipulation of oleic-acid-in-water droplets with diameters up to 1 mm at velocities of up to 10 mm/s [4], [5]. OFT works well on O/W droplets because the low thermal conductivity (1/6[th] of water) facilitates the formation of sharp temperature gradients. The advantage of OFT is that its holding forces are in the µN range, 5 orders of magnitude larger than optical tweezers. However, thus far OFT is limited to liquid droplets because it relies on thermocapillary flow at a liquid-liquid interface. In this paper, we utilize the droplet as an optically controlled force transducer for manipulating particles (Fig 1). We show that relatively large particles (50-100 µm glass beads) can be manipulated in one of two modes: attachment and engulfment.

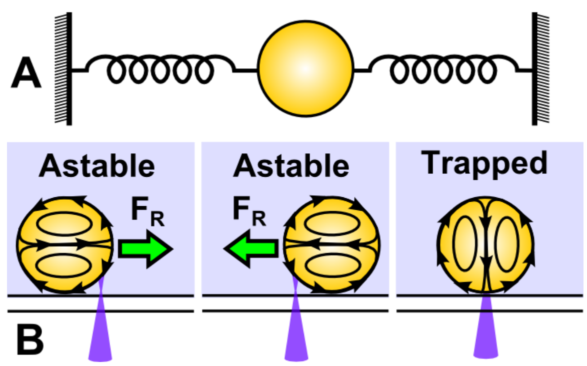

Fig. 2: *OFT Operational Principle*. (A) Conceptual model of an optical trap, which requires a restoring force. (B) Model of OFT, where the restoring force is provided by thermocapillary flows.

EXPERIMENTAL SETUP

The experimental setup (Fig. 3) is designed to provide both a small laser spot size over a large field of view (FOV). An F-theta scanning lens (Rodenstock, Germany) and a galvanometric scanner is chosen instead of the conventional optical setup used in optical tweezers [7]. The F-theta lens provides a linear relation between scan angle and focal length, and can therefore maintain a uniform, focused spot size (<20 µm) over the entire 3x3 cm field of view. Empirical studies with OFT [4], [5] indicate that the laser spot size should be a small fraction <20% of the droplet size. The F-theta lens is combined with a 200 mW, 405 nm diode laser mounted on a 2-axis galvanometric scanner. The laser intensity (and corresponding holding forces) are controlled over 2 orders of magnitude using pulse width modulation (PWM) at 100 KHz. The modulation period is much smaller than the thermal time constant of the system (around 10's of milliseconds), thus minimizing temperature ripple. The 20 Kilopixel/second galvanometric scanner provides scan speeds of several m/s, and is controlled via Labview (National Instruments). The sample holder is a glass slide placed at the back focal plane of the lens (~6.5cm). A layer of water is spread on the glass slide to a thickness of several mm. In some cases, a second glass cover slide, separated by a spacer, is added to constrain the buoyancy of the oil droplets. Oleic acid droplets with diameters of several hundred µm are generated by pipetting and manual agitation. The oil is dyed with Sudan IV, which absorbs 405 nm light. For imaging, we include a wide field of view stereomicroscope with a digital camera and a 450 nm long pass filter to block the 405 nm light. Hydrophobic green fluorescent iron oxide particles (Magnaflux) and hydrophilic green fluorescent polystyrene particles (Polysciences) are added to the droplet and continuous phases, respectively, for flow visualization.

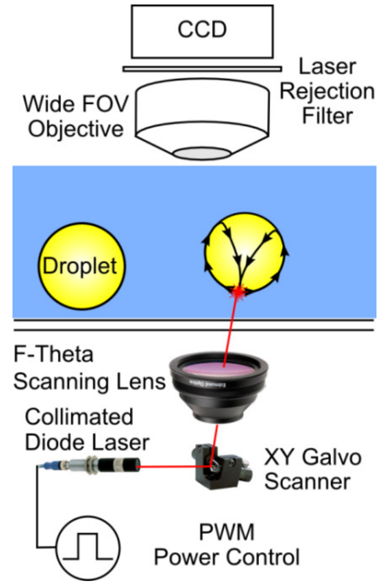

Fig. 3: Experimental setup for OFT using a laser scanning system with a wide field of view.

RESULTS AND DISCUSSION

Flow visualization. Fig. 4 shows the top view of the internal (yellow) and external (blue) flow patterns as a trapped droplet is translated in the horizontal plane. In this image the laser is at the edge of the droplet. Here the polystyrene tracers (10 µm) and the fluorescent iron oxide particles (10-20 µm) are used to visualize flow in the two phases. In the horizontal plane, two pairs of vertically symmetric vortices can be seen. Heating from the focused laser locally reduces the interfacial tension, resulting in Marangoni interfacial flow directed away from the focal point. The interfacial flow generates sympathetic microvortices within and external to the droplet. The flows exert an asymmetric body force which moves the droplet toward the laser's focal point.

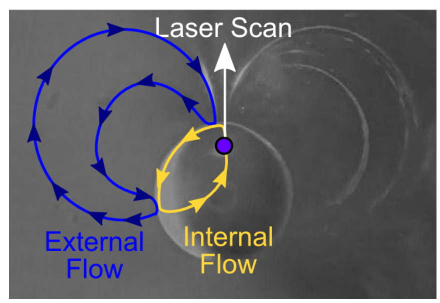

Fig. 4: Visualization of internal and external flows during droplet translation. The position of the laser is shown with the purple dot.

Translation of Droplets using a Scanning OFT. The translation of oil droplets using the scanning system is shown in Fig. 5. Several droplet diameters and dye concentrations are tested by first trapping the droplet, then increasing the scanning rate of the laser until the droplet can no longer follow it. Larger dye concentration increases the absorbed optical power, resulting in larger temperature gradients, larger thermocapillary force, and therefore larger scan speeds. This trend is consistent with conventional models for thermocapillary migration [8], which predict that migration velocities are directly proportional to the temperature gradient and radius. Conversely, experimental data shows that increasing drop diameter decreases migration velocity. This is likely due to increased drag forces, and also the larger thermal energy requirement to achieve the same temperature profile across the droplet.

Particle Manipulation in Engulfment Mode. OFT can be used to manipulate particles in one of two modes. In the engulfment mode (Fig. 6), the particle enters the interior of a trapped oil droplet. While the precise mechanism is still under investigation, it is believed that the microvortices play a key role in engulfing the particle because of two reasons: (1) Without active flow fields, a hydrophilic bead would not be likely to enter an oil droplet; and (2) the particle is released

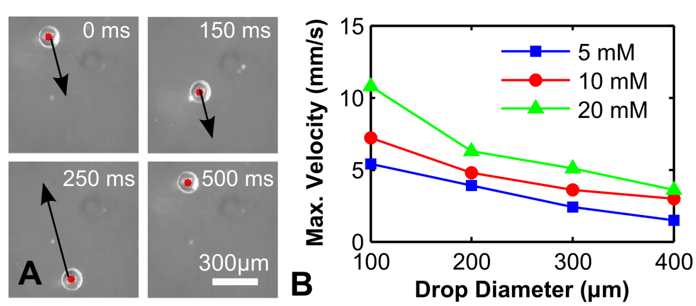

Fig. 5: Droplet translation using a scanning laser. A) A 150 µm O/W droplet moves in a linear pattern at ~2mm/s. (B) Maximum translation velocity vs. drop diameter and dye concentration.

when the laser power is removed. Fig. 6B the manipulation of 50 µm silica beads (Cospheric) with a 200 µm oleic acid droplet. The purple dot indicates the position of the laser, which is operating at 100% duty cycle. The trapped oil droplet is moved adjacent to the bead, at which point the bead disappears underneath the droplet, indicating that it has been trapped. The combined bead/droplet can then be translated in the horizontal plane at speeds of several hundred µm/s. In this case, the bead is moved ~1 mm in 0.5 s. When the laser power is removed, the bead releases from the droplet. Other experiments have shown this effect occurs with droplets ranging from 200-500 µm and silica beads from ~10-100 µm.

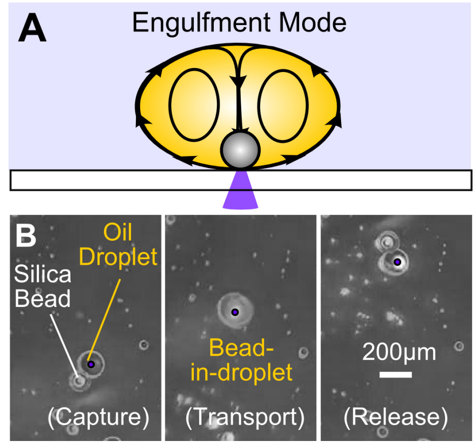

Fig. 6: *Particle Manipulation in Engulfment Mode.* (A) Schematic. (B) Experimental manipulation of a 50 µm glass bead by engulfment in a 200 µm droplet.

Particle Manipulation in Attachment Mode. In this mode (Fig. 7), the particles attach themselves to the surface of trapped oil droplet, and can be manipulated in this manner. Analysis of video frames shows that the particles are pulled adjacent to the oil droplet by the microvortices in the external phase (Fig. 4). The recirculating vortices exert sufficient drag force to pull the particles laterally toward the droplet, but have insufficient force to lift the particle away from the droplet. As a result, the particle remains trapped adjacent to the droplet boundary. As shown in Fig. 6B, a single droplet can attach multiple particles. In some cases, the particles oscillate tangentially along the interface due to the Marangoni flows. The particles remain attached as the laser is scanned at velocities of several 100 µm/s, and can be released by turning off the laser.

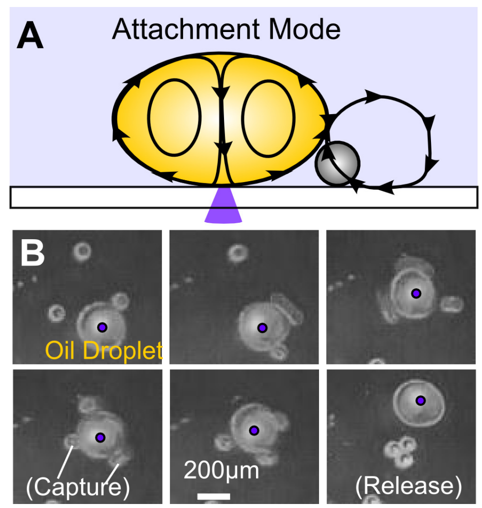

Fig. 7: *Particle manipulation in attachment mode.* (A) Schematic. (B) Experimental manipulation of three 50 µm glass beads with a 200 µm droplet.

CONCLUSIONS

This paper demonstrates a scanning laser system for manipulating O/W droplets using OFT, and also the indirect manipulation of particles using the droplets as force transducers. The manipulation of 50 µm beads at several 100 µm/s suggests a significantly larger force than other optical techniques for particle manipulation. The mechanisms of the engulfment and attachment modes will be further explored in subsequent works.

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