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Non-contact Mesoscale Manipulation Using Laser Induced Convection Flows

Emir Vela, Cécile Pacoret, Sylvain Bouchigny, Stéphane Régnier, Klaus Rink and Arvid Bergander

***Abstract*— Laser induced convection flows is a new and promising method to achieve better manipulation of mesoscale objects (above 1 μm and below 500 μm) in a liquid medium. The temperature gradient created by laser absorption generates natural and thermocapillary (or Marangoni) convection flows. These flows are used to perform the manipulation itself. In this paper, we demonstrate for the first time that large and heavy particles can be dragged using the Marangoni convection flows. Experiments based on these phenomena show that fast and accurate underwater micromanipulation of particles up to 280 μm is possible using only a convergent 1 480 nm laser beam.**

I. INTRODUCTION

Today the challenge for micromanipulation are to design highly flexible and effective systems which could control particles of large variety of sizes, shapes, materials and weights. Many devices exist and are dedicated to one type of object and applications either with direct contact like grippers [1] and cantilevers [2], or without contact like electrophoresis [3], magnetic [4], optical tweezers [5], [6] and microfluidic systems [7]. Many different tools are needed because of scale effects: objects from a few nm to a few mm undergo different interactions. Inertia and gravity effects become negligible, while adhesive, capillary and surface forces arise at the μm-scale [8].

Under the frame of the GOLEM European project, the need for a system capable of driving mesoscale particles (1 μm to 1 mm) was critical. The aim is to study the assembly of bio-functionalised components for which, the platform should be able to safely manipulate objects of many sizes and kinds e.g. MEMS, μ-tools and biological parts. For such an application, non-contact techniques provide the most interesting characteristics. Especially, it has been shown [9], [10] that individual and group movements can be easily achieved with temperature control and a large workspace.

A common approach in non-contact micromanipulation, that we first considered for the GOLEM project, is to use laser light radiation pressure to trap small particles of good refractive index in the focal point of a convergent laser beam. This setup is called "optical tweezers" and it was first demonstrated by Ashkin [11]. Since then, optical tweezers have routinely achieved piconewton forces and nanometric precision in the fields of natural sciences. Also, holographic systems allow manipulation of hundreds of particles at the same time [12]. And lately, optical vortices have also generated group movements, and present original rotating capacities [13]. However, this technology has some limitations regarding the size (dimensions less than 20 μm), shape (spherical) and refractive index of the particles. Specifications of the GOLEM project do not fit in this technology. The energy required to displace the particles is much higher than radiation pressure can achieve (a few pN).

We propose in the following section a novel laser micromanipulation approach closer to microfluidic methods and we will prove the feasibility of the strategy adopted. With convection flows, large and heavy particles can be dragged and we can exploit the fact that forces rise with the particle sizes. In section III, simulations are presented. Setup and experiments will be detailed in section IV. A brief summary of our first exploration results will be proposed in section V, followed by our conclusions on the potential of this technique and the outlook for new developments for micromanipulation in section VI.

II. CONVECTION FLOW MANIPULATION PRINCIPLE

The basic principle of convection flow micromanipulation is shown in Fig. 1. A convergent laser beam is shot on the bottom of a Petri dish, increasing the temperature locally. A convection column rises and drags particles toward the laser beam at the bottom of the Petri dish. An opposite effect appears at the free surface: when the convection column reaches the surface, floating particles are dragged away from the laser beam.

Two phenomena actually drive this current: natural convection flow and Marangoni convection flow. The first one results from the Archimedes lift force as water density decreases with temperature. The second occurs when a temperature gradient is created on the free surface. This gradient may be generated by the flow of hot liquid coming from the bottom by natural convection or directly by the laser radiation if it is not fully absorbed in the liquid before reaching the surface.

The flows at the microscale are highly laminar, as

E. Vela is with the sensory interfaces laboratory (LIS) at the French Atomic Energy Commission (CEA), Fontenay-aux-Roses, FRANCE (www-list.cea.fr) emir.vela-saavedra@cea.fr

C. Pacoret is with the sensory interfaces laboratory (CEA), Fontenay-aux-Roses, FRANCE and with the Institute of Intelligent and Robotic systems (ISIR), Université Pierre et Marie Curie, FRANCE (www.isir.fr) cecile.pacoret@cea.fr

S. Bouchigny is with the sensory interfaces laboratory (CEA), Fontenay-aux-Roses, FRANCE sylvain.bouchigny@cea.fr

S. Régnier is a professor at ISIR, Université Pierre et Marie Curie, FRANCE stephane.regnier@upmc.fr

Klaus Rink and Arvid Bergander are with OCTAX Microscience GmbH, GERMANY klaus.rink@octax.de, a.bergander@ieee.org

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Reynolds number is very small:

$$Re = \frac{\rho U L}{\eta} \approx 1,$$

where, U and L are the speed and the length of the flow. In our case, maximum speed is 600 μm s^{-1}, the water thickness is 1 650 μm, ρ is the density of water (1 000 kg m^{-3} at 20 °C) and η is the dynamic viscosity (10^{-3} Pa s).

In order to have an idea of velocity, drag force profiles and temperature gradients, we conducted simulations in parallel with velocimetry experiments (section IV.B).

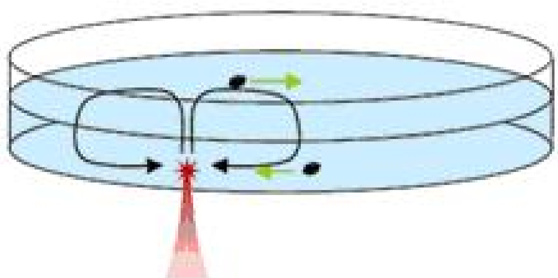

Fig. 1. Concept of micromanipulation using natural convection flows.

III. SIMULATIONS

We simulated the natural convection flows using COMSOL multiphysic modelling software. A 2D axisymmetric geometry model was accurate in our case, as the Petri dish was very big compared to the laser spot: Petri dish radius is 1 cm and spot radius is 100 μm. Therefore, we considered the laser spot to be at the centre of the Petri dish and assumed that during our experimentations we had negligible eccentricity. The geometrical model was meshed to process finite element methods; refinements of the mesh size were applied to critical zones such as walls, interface and laser spot.

The software provided us with two different interesting elements of information in the permanent state: thermal distributions and velocity field. For a laser power of 65 mW at the optical output, the thermal profile confirmed the localized heating around the laser spot, where the temperature was around 96 °C which is close to boiling point. Where as 200 μm, it was already 46 °C, (see Fig. 2).

The velocity field showed the presence of a significant boundary layer, in other words the viscosity of water at the bottom of the Petri dish introduced a layer of decreasing velocity. Using the equilibrium viscosity and distance to the laser spot, we can determine the boundary layer which, in our case is the height of maximum radial velocity (see Fig. 3). At 200 μm from the laser spot centre, the height was 100 μm for the maximum velocity (500 μm s^{-1}). As we can see, this boundary layer was above small particles (1-50μm), the fastest flows pass over them.

Having the speed profile (solid line in Fig. 3), we can estimate the drag force on the particles, and so evaluate the efficiency of this flow. Fluid viscosity introduces a surface stress on the surface of a particle in the fluid. This stress could be expressed on a sphere by [14]:

$$\frac{dF}{dS} = \frac{3}{2}\frac{\eta U}{R},$$

where dF is the surface force, dS a small surface element of the sphere, R is the radius, η is the dynamic viscosity and U the local flow speed. Fitting the speed profile, and integrating over the surface of the sphere, we express the action of a fluid on our particle. For example, the drag force on an 100 μm-sphere is maximal at 200 μm from the laser spot and is around 0.2 nN (as in Fig. 4).

Drag force rises with an increase of the radius of the particles or the power of the laser. For large and heavy particles, inertial and adhesion effects start to be significant, as shown in the experiments, see section IV.

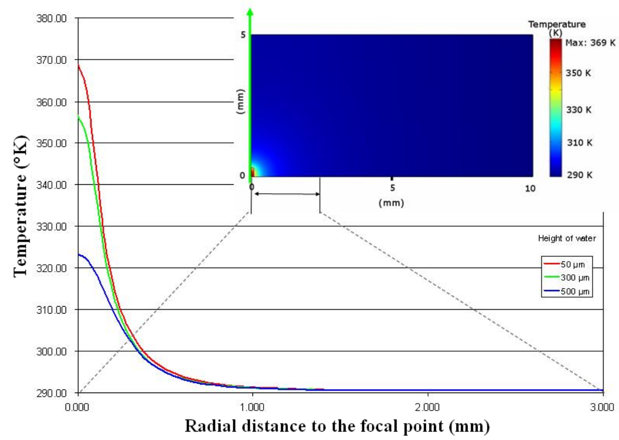

Fig. 2. a. Temperature profile resulting from a volumetric power transfer for a laser power of 66 mW at permanent state.The total Petri dish system is represented in axisymmetric geometry (green arrow is the symmetry rotation axis). Maximum temperature is on the laser spot : 369 °K or 96 °C. The detailed zone is marked by a double arrow. b. Detailed zone of 2 mm radius from the laser spot shows different temperature distributions along radius and height.

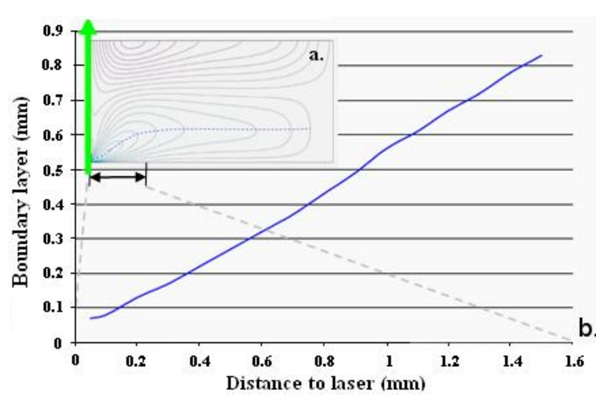

Fig. 3. a. Radial velocity profile shows the boundary layer or height of the maximum radial velocity. The detailed zone is marked by a double arrow. b. Detailed zone of 1.6 mm distance from the laser spot, the boundary layer is represented as a function of the distance to laser.

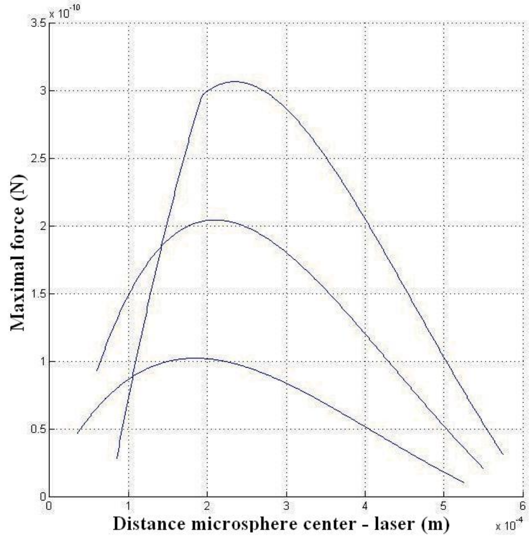

Fig. 4. Expected force profiles of three different sized particles (R=50, 100, 150 μm). The maximum force is drawn as a function of the distance from the centre of the sphere to the laser spot.

With a little power (65 mW), natural convection flow results are comparable with optical tweezers on small particles; but for bigger ones, we managed to produce a constant acceleration of the particles which was 10 times bigger. Simulations results prove the feasibility of our method. These results can be greatly improved if one makes use of Marangoni convection by irradiating the free surface with the laser. This is what we will confirm with the following experiments.

IV. SETUP AND EXPERIMENTS

A. Setup

The optical system is composed of an inverted Olympus IX71 microscope which is equipped with a 4x objective and a CMOS OCTAX Eye ^{TM} camera (1/2", 1.3M pixel, 30 fps) to monitor the displacements of micro-objects. An infra red laser (CW 1 480nm, max. power of 120 mW, from OCTAX Microscience GmbH) is included at the rear port of the microscope (cf. Fig. 5).

To scan the laser at the focal plane in a 2D configuration, a 2DOF scanner controlled with a labVIEW computer interface is under development. This scanner (actuated by 4 electromagnets), called Viflex, was designed at CEA-LIST [15]. The Viflex scanner is easily mounted onto an inverted Olympus microscope thanks to its small dimensions: height and length of 50 mm, width of 25 mm and weight of 90 g excluding electronics and power supply.

Some interesting facts about the scanner are that it has a single dichroic mirror to deflect the laser into the microscope objective and let light into the camera through the inner microscope optics (cf. Fig. 5). In the following experiments, the mirror scanner was in a fixed position at an angle of 45° to the incident laser beam. In order to drag particles in different directions, we have used the XY manual microscope stage to demonstrate the feasibility of our micro-manipulation setup. In further experimental works, we plan to drag the micro-objects with the laser scanner.

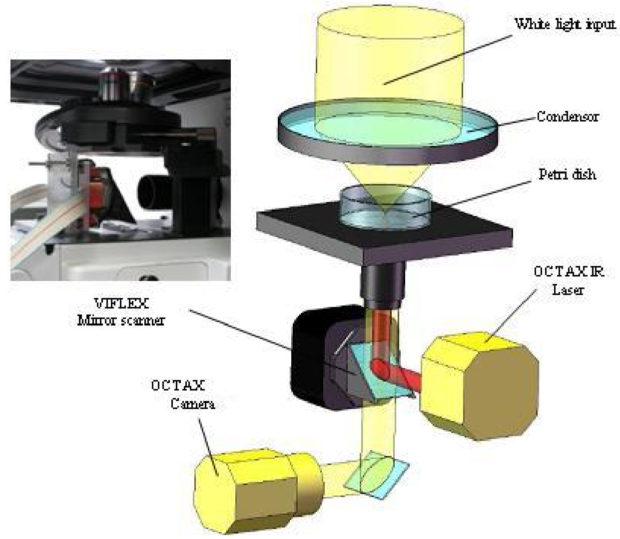

Fig. 5. Setup arrangement and photo of Viflex mirror scanner.

The micromanipulation experiments are performed in a Petri dish (60 mm diameter) filled with water (from 0.15 up to 3 mm depth). Several sizes of glass beads ranging from 50 μm up to 100 μm in diameter and solder beads in the range 180 up to 280 μm were used.

B. Natural convection flows experiments

With a needle, we have placed a small quantity of hollow glass microspheres $8-12$ μm in diameter in a Petri dish of 6 cm in diameter. It was filled with distilled water, the depth was then measured and readjusted if needed. For the first experiments, the water thickness was over a millimeter. Fig. 6 shows the convergence of the flow at 600 μm, from the bottom surface of the petri dish, toward the laser spot.

The first velocimetry experiments confirmed the simulation results. The speed profiles have similar shapes but speed values had been slightly over evaluated (Fig. 7).

Speed rises rapidly as the water thickness decreases. Below 800 μm of water thickness, as the laser starts to reach the free surface of the liquid, we observed that the current velocity starts to deviate slowly from our simulations. We start to enter the Marangoni convection regime. Moreover, our standard CMOS video camera is already too slow for velocimetry measurements in 600 μm of water thickness. In the next section, we will discuss the spectacular effect of Marangoni flows and their encouraging capability to drag large and heavy particles.

C. Marangoni convection flows experiments

In the situation described above, the water thickness is too great for the laser to reach the surface. At a wavelength of

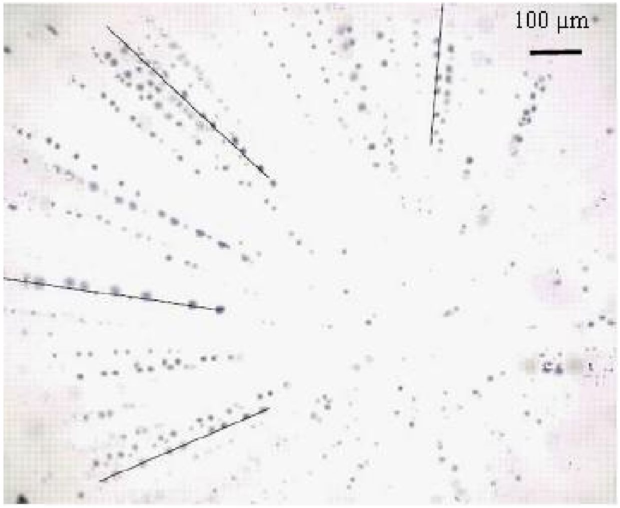

Fig. 6. Superposition of 15 images of the CMOS camera, picture shows microspheres from 2 to 20 μm converging on the laser spot. Four example trajectories are marked by a segment. Water thickness is 1.65 mm and images have been taken in 0.6 mm height of water.

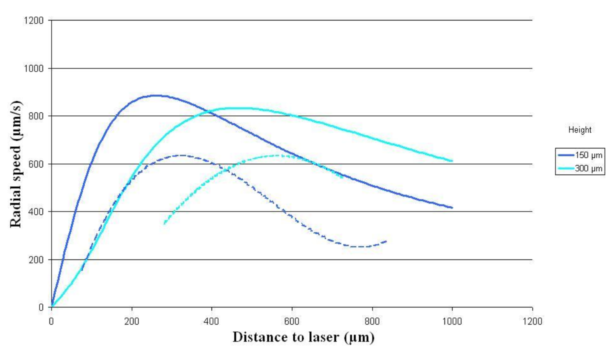

Fig. 7. Speed profiles of hollow glass microspheres (diameter 5 μm) for different heights ($150-300$ μm). Water thickness = 1.65 mm. Solid line represent simulation results, dash lines are experimental measurements.

1 480 nm, the laser power is absorbed within one millimetre of water thickness (absorption coefficient is 21 cm^{-1} [16], [17]). However, below 600 μm of water thickness, a significant amount of laser power starts to illuminate the free surface of the liquid. A surface tension gradient appears due to the thermal potential gradient induced by the laser in the surrounding fluid. The interface exhibits a shear stress in the direction of higher surface tension leading to an external flow which is usually called thermo-capillary flow or Marangoni effect. A strong current appears from the hot regions around the laser (lower surface tension) toward the cold zones (higher surface tension), and the liquid motion is maintained by subsurface flows which create a recirculation zone [18], [19], [20]. It has been demonstrated that with this phenomena it is possible to manipulate particles and droplets in oil and water mediums [21], [22], [23].

In [22], weed pollen (25 μm in diameter) and micro-droplets of water (in the range of $2-50$ μm in diameter) have been trapped and manipulated in the toroidal convection flows generated by micromachined heat sources. These heat sources are suspended from 5 to 250 μm above the liquid free surface. The liquid medium used is mineral and olive oil (thickness ranging $80-400$ μm) for weed pollen and water droplets respectively. Flow velocities of up to 1 700 μm s^{-1} have been reached. In the case of [23], a droplet immersed in a non-volatile liquid layer is moved in accordance to the Marangoni regime. An IR laser 1 550 nm is focalised from below at the edge of the droplet to generate a surface tension gradient. With these surface tension forces, droplets ranging from 14 pl to 1,7 μl in volume at speeds of around 3 mm s^{-1} were dragged.

In our case the flow exhibits a fast toroidal recirculation zone with a current going upward in the center and downward on the side of the torus. The size of this torus depends on water thickness in the Petri dish [22].

Two snapshots (microscope 4x) of this phenomenon are shown in Fig. 8 for 300 μm and 150 μm water thicknesses in the Petri dish. The particles used to reveal the flow are the same $8-12$ μm hollow glass beads used for velocimetry measurements.

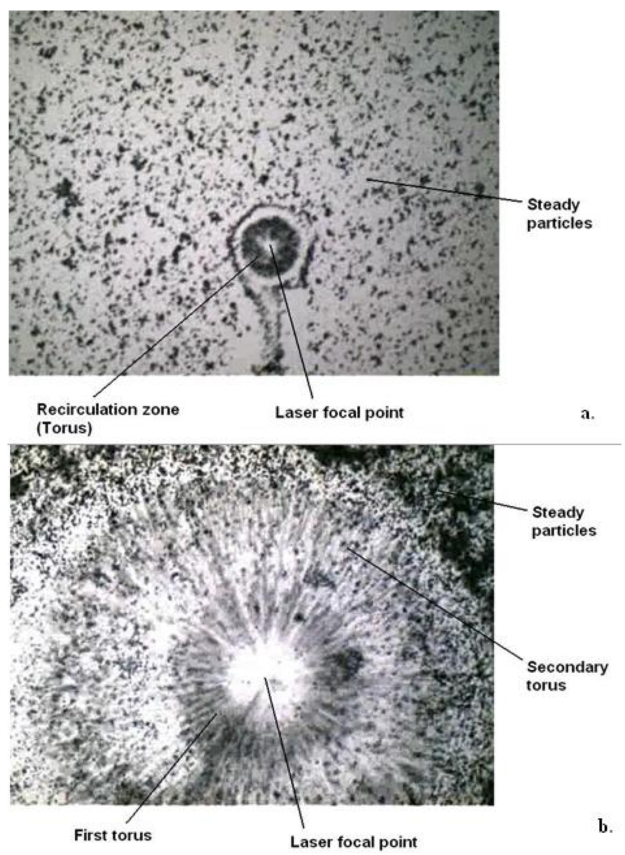

Fig. 8. Marangoni convection flows experiments, size of the image window is 1.5 x 1.1 mm^2. Particles are $8-12$ μm hollow glass beads. Laser: about 45 mW irradiating from below. a. 300 μm water thickness. b. 150 μm water thickness.

The microscope working area (size of the window) is 1.5 mm x 1.1 mm and laser is shot from underneath the petri dish in continuous mode providing a power of about 80 mW. In Fig. 8a, a small torus (200 μm in diameter) takes shape around the laser focal point. A circle of particles delimits the recirculation zone. Outside this circle, no currents are observed. The trail below the torus is comprised of particle deposition due to an intentional movement of the microscope's XY plane along the Y-axis during the experiment. In Fig. 8b, the level of water in the Petri dish is reduced by a factor of 2 (from 300 μm to 150 μm). We see a much larger torus reaching 600 μm in diameter. A secondary recirculation zone is also observed which is built around the first, with the current going in the same direction. Particles outside this second torus are not moving.

These flows are not turbulent and stop instantaneously when the laser is turned off. There is very little inertial effect at this scale as the Reynolds number is very small (< 1).

V. RESULTS

Some initial experiments have been performed to demonstrate the capability of this method for micromanipulation. Till now, we have proved the feasibility but we did not optimise all the Marangoni flows parameters and further investigations are needed to study current velocity, recirculation zone diameter, water thickness and son on. Consequently, this method's full potential has not yet been reached. Here, we will sum up our initial results in terms of size and speed for both natural and marangoni convection flows.

With natural convection flows, we are limited to small sized beads: 10 μm hollow glass beads reach 600 $\mu\mathrm{m\,s^{-1}}$ for water thickness of 1.65 mm. Observing the influence of the water thickness on the flow velocity, we quickly chose to work with smaller thickness within the Marangoni regime.

Our experiments take place in a 6 cm diameter Petri dish containing 150, 300 or 600 μm of water thickness. The surface (Duroplan glass) has been cleaned with distilled water but no other treatment has been performed, with suitable surface treatment we would expect to decrease the adhesion forces.

The laser light comes from an OCTAX Lasers Shot ^{TM} system installed on the microscope (1 480 nm and 80 mW on the focal plane). The 4x objective is used and produces a focal point of 100 μm in diameter. We studied the manipulation of $10-100$ μm glass beads and $180-280$ μm solder beads. The laser is shot in continuous mode for 10 ms or more.

The pictures in Fig. 9 show the displacement of an 85 μm diameter glass bead. The laser is shot in continuous mode and the bead is immersed in 300 μm of water depth. The particle speed is close to 400 $\mu\mathrm{m\,s^{-1}}$ (One image every 160 ms), flow speed is much higher than our measurement capabilities.

It is also possible to move larger objects with a Marangoni convection flow as the force increases with particle size. We have tried with 180 and 280 μm lead-tin solder beads. Because of the size and weight of these beads, we need to suppress the adhesion forces. By shaking the sample with ultrasonic waves, the beads could be moved at a pace of about 50 $\mu\mathrm{m\,s^{-1}}$. It is to be noted that the beads were not spherical and therefore were not rolling but dragged in the current.

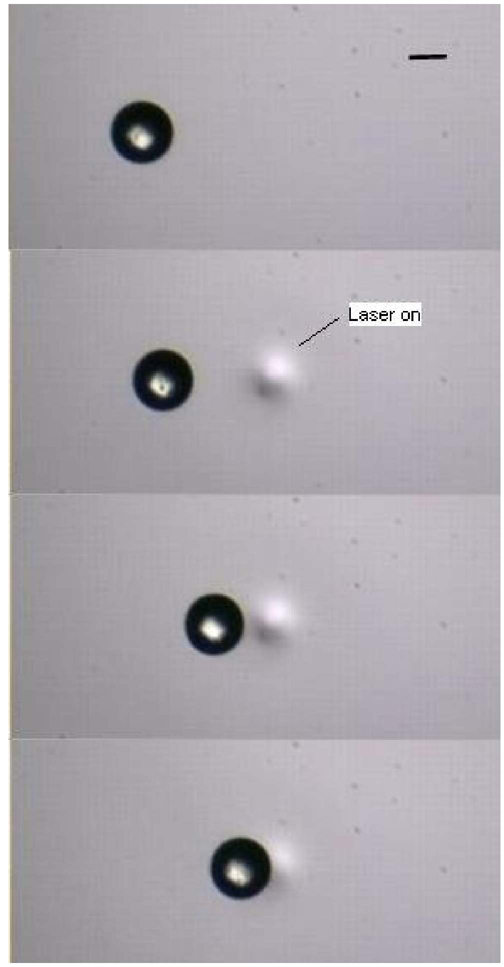

Fig. 9. Displacement of a 85 μm glass bead in 300 μm of water thickness using a CW IR laser, time between images 160 ms. Scale bar 50 μm.

In summary, we have moved glass beads in the range of 1 up to 100 μm and solder beads in the range of 180 up to 280 μm. A speed of 400 $\mu\mathrm{m\,s^{-1}}$ was obtained for an 85 μm glass bead in 300 μm water thickness using continuous laser mode, and a speed of 50 $\mu\mathrm{m\,s^{-1}}$ for a 180 μm irregular solder bead (7 310 $\mathrm{kg\,m^3}$) in 300 μm of water thickness.

VI. CONCLUSIONS AND PERSPECTIVES

A. Conclusions

We have studied micromanipulation of particles of variable sizes using two different types of flow regime by finite element simulation, velocimetry measurements and actual experimentation. We conclude that it is possible to move objects from 1 up to 100 μm by using natural convection flows but for larger particles (> 100 μm), we achieves the manipulation with smaller water thickness using Marangoni effect.

Indeed, the very fast currents in this regime increase the interaction forces of the flow on the particles. The surface-tension-driven flow micromanipulation (or Marangoni manipulation) is very promising. However, for solder bead displacements we have used ultrasonic waves to detach these beads and suppress adhesion forces.

We still need to improve our understanding of the phenomenon involved, and further investigation will be performed in the next few months.

B. Perspectives

In order to better exploit this novel method, we will first characterize the different parameters involved in the Marangoni convection flow, namely temperature, water thickness, speed and optimal driving distance between the laser focal point and the objects. Since there is a high temperature (96 °C at the laser focal point), we have to take into account a security distance (a hundred of μm) to protect objects which are sensitive to high temperatures, such as biological cells.

As a result, the trajectory and speed of the laser has to be controlled. For example, it is necessary to perform fast laser scanning, if we want to use a strategy such as a circle pattern to avoid thermal damage. In this way, the security distance is guaranteed: the particles go into the centre of the heating circle. By scanning, we can also deposit the required energy to move multiple particles without reaching the boiling point.

If we can suppress the adhesion effects, we will be able to move larger particles. We are investigating suitable surface treatment.

The method and setup proposed in this work are based on our preliminary study phase, however they have very promising outcomes and they can contribute significantly to the microtechnology industry.

VII. ACKNOWLEDGMENTS

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