HIGH SPEED MICROFLUIDIC DOUBLET FLOW IN OPEN POOLS DRIVEN BY NON-CONTACT MICROMACHINED THERMAL SOURCES

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ABSTRACT

We report a phenomenon in which a micromachined heat source placed less than 50 μm above the surface of a liquid drives a high-speed doublet flow pattern with linear velocities reaching nearly 5 mm/sec and rotational velocities up to 1200 rpm. Tests were performed on a 50-100 μm-thick layer of water containing 3 μm polystyrene beads for flow visualization. The thermal source is a polyimide cantilever with an integrated heater near the tip, operated with input powers ranging from 0-32 mW. It has no moving parts and does not contact the liquid. The speed of the doublet flow scales with input power as well as liquid temperature, and is inversely related to the air gap between the heater and liquid surface. The orientation of the doublet flow can be reversed by changing the angle of the cantilever. A one-dimensional array of probes used in the same manner generates a linear flow pattern.

I. INTRODUCTION

The ability to generate high speed micro-flow patterns plays a critical role in the mixing, pumping, and pre-concentration of particles, particularly for cellular and biomolecular manipulations. There have been several attempts in the past to generate vortex flow in microfluidic environments. An opto-electrostatically driven vortex pattern generated by a focused 50 mW laser spot in combination with a 2 kV/cm electric field was shown to have a maximum particle velocity of 120 μm/sec in conductive liquids [1]. Vortices driven electrokinetically in polymer channels with patterned surface charges [2] operate on less electric field (100 V/cm), but produce slower velocities and require ionic solutions. More recently, a laser cavitation pump was shown to generate flows up to 1 mm/s [3]. It required that an optical fiber to be immersed in the liquid and coupled to a high-power pulsed laser. Bubbles generated in cavitation pumps can pose challenges for a variety of applications. Approaches using moving parts include a 600 rpm magnetic micro-stirrer [4].

This effort reports a thermally driven phenomenon in which a micro-scale heat source suspended above water drives a high-speed doublet flow patterns at the liquid surface. Particle velocities of 5 mm/sec and rotational velocities of up to 1200 rpm have been achieved, making it potentially useful for high speed pumping and mixing of liquids and suspended particles. The heat source, a micromachined thermal probe, is separated from the liquid surface by a small air gap and has no moving parts, thus eliminating common problems of mechanical wear, electrode contamination, and bubble generation. Furthermore, the technique does not require ionic or conductive liquids. In addition to generating single doublet flow patterns, a linear array of probes is shown to generate a linear channel-like flow pattern that would be useful for pumping applications.

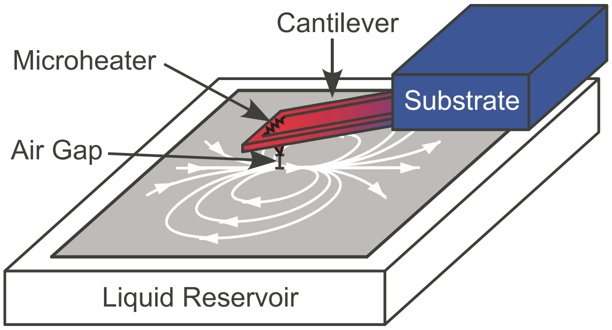

Fig 1: Schematic of device operation. A heated micro-cantilever suspended above a liquid induces a high-speed doublet flow pattern at the surface.

II. DEVICE CONCEPT

A fluidic doublet is a two-dimensional flow characterized by two adjacent vortices of opposing rotational directions, and resulting linear streamlines between them. The flow pattern for a single doublet located at (x_0, y_0) on a Cartesian plane is described by the following stream function [5]:

$$\Psi(x,y) = \frac{\mu}{2\pi}\frac{(y-y_0)}{(x-x_0)^2+(y-y_0)^2} \tag{1}$$

where μ is a constant reflecting the strength of the doublet. A contour plot (Fig. 2a) illustrates the streamlines resulting from a single doublet. The direction of flow can be inferred from the gradient of the ψ function, which in this case is left to right.

To determine more complex flow patterns resulting from multiple doublets, the stream equations for each doublet may be added up by applying the principle of superposition. The flow pattern generated by an array of 8 doublets with 85 μm spacing is shown in Fig. 2b. This particular geometry was chosen to model the structure of the multiprobe array. Flow patterns resulting from single and multiple doublets present a number of opportunities for flow manipulation; namely, the linear streamlines can be used to drive high speed particle flow, while the adjacent eddies can be used for mixing or particle trapping.

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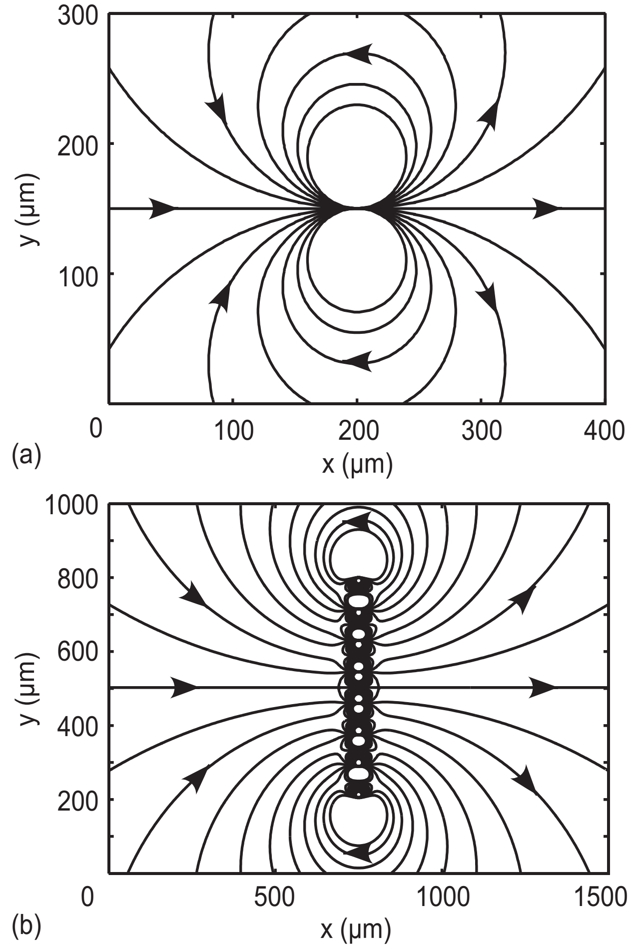

Fig. 2: Theoretical flow patterns generated by single and multiple doublets. (a) Streamlines for a single doublet located at (200 μm, 150 μm) on a Cartesian plane. The contours of the stream function (Eq. 1) were plotted using a value of 1 for the constant μ. (b) Streamlines generated by an array of 8 doublets with 85 μm spacing obtained by summing the respective stream functions.

In this effort, high-speed doublet flow at the surface of water is driven by a micromachined heat source suspended at varying heights and angles above the surface of a reservoir (Fig. 1). When the source is brought close to the surface of the water (<50 μm), the thin air gap allows transfer of heat to the liquid surface. The mechanism of how the heated region drives the doublet flow is not yet clear; however, initial data suggests that localized evaporation plays a role.

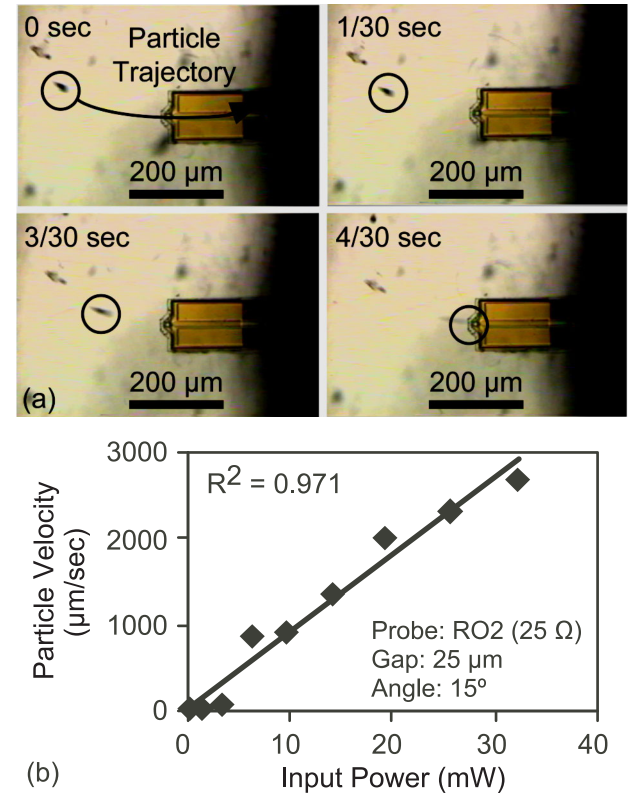

Fig. 3: (a) High-speed flow is illustrated in 4 sequential micrographs taken at 1/30 second intervals. 3 μm beads are used to visualize the flow. (e) Particle velocities scale linearly with the input power to the heat source. Angle and air gap are fixed at 25 μm and 15°.

The heat source is a micromachined thermal probe reported in [6], consisting of a joule heater integrated near the tip of a cantilever. Thin film metal forming the heater and leads are embedded within a 3 μm-thick polyimide cantilever. The excellent thermal isolation provided by a polymer-based cantilever allows the probe tips to be heated to temperatures up to 250 ºC with <20 mW input power. The length and width of the cantilever as well as probe resistance vary depending on the type of probe. In this work, two probe geometries are used: R01 (length 360 μm, width 42 μm, resistance 25-40 Ω), and R02 (length 360 μm, width 120 μm, resistance 20-35 Ω). In addition to the single probes, an 8-probe array reported in [7] is also used to drive multi-doublet flow patterns as shown in Fig. 2. In this device, the cantilevers have 85 μm pitch and can be heated individually.

III. EXPERIMENTAL RESULTS

Experiments were carried out on a 50-150 μm thick layer of water placed on a glass slide. Polystyrene beads with 3 μm diameter were immersed in the liquid for flow visualization. The micromachined cantilever was held at a fixed angle and lowered towards the surface of the liquid using a motorized micromanipulator. Micrographs and video were recorded using a CCD camera, and speed was determined by measuring distance covered by sequential frames spaced 1/30 second apart. In accordance with doublet flow model, the velocity of a traveling particle increases as it approaches the center of the doublet, which in this case appears to be directly beneath the heated cantilever tip. In all experiments, the velocities indicated are the maximum values measured.

In order to show that the doublet flow is in fact thermally driven, the flow and rotational velocities were characterized as a function of input power (Fig. 3). The cantilever was held at a fixed angle and air gap above the liquid surface, and the input power was ramped from 0-32 mW. Particle velocities scale approximately linearly,

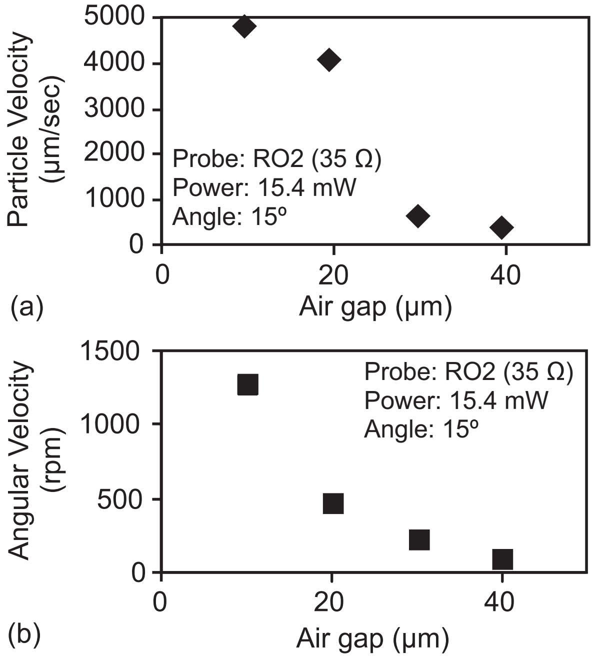

Fig. 4: The doublet speed can be controlled by modulating the air gap. For a fixed 15 mW input power to a 35 ohm probe, particle velocities increase nearly 5000 μm/sec as the air gap is reduced to <10 μm. Rotational rates in the adjacent vortices approach 1300 rpm.

increasing 90 μm/sec for every 1 mW applied. These results imply that the flow is proportional to tip temperature, since it is well known that tip temperature increases linearly with input power [6].

Reduction of the air gap permits more efficient heat transfer, also resulting in increased velocities. A probe was biased at a fixed input power and lowered at 10 μm intervals until it came into contact with the liquid. Figure 4 shows that with a 15 mW input power, particle velocities of nearly 5000 μm/sec are achieved at air gaps of <10 μm, along with rotational velocities of 1200 rpm in the adjacent eddies. Particle velocities decrease as 1/x with increasing air gap, indicating that heat transmission through the gap is inversely proportional to the gap thickness.

The dependence of particle velocities on liquid temperature (Fig. 5) provides further evidence supporting thermally driven flow. In this experiment, the glass slide below the water sample was biased at 13, 27, and 41 °C using a circulating heating/cooling plate. At each temperature, particle velocities were measured as a function of air gap while holding the probe at constant power and angle. Trends of faster velocities with smaller air gaps hold true as before, but it can also be seen that higher liquid temperatures shift the entire trend upwards. For example, at a ~10 μm air gap, the particle velocity at 13 ºC is only 165 μm/sec, compared to nearly 900 μm/sec at 41 ºC. Increased liquid temperatures, therefore, enhance the speed of doublet flow. Overall, particle velocities in this experiment were slower than the results shown in Fig. 4 due to lower input powers, and possibly due to the fact that a thinner probe (R01) was used.

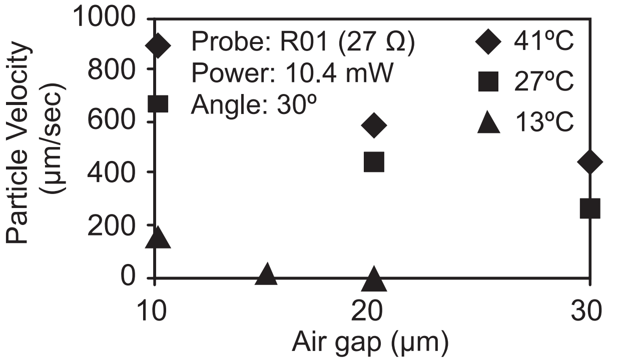

Fig. 5: Effect of liquid temperature on doublet flow. Particle velocities are plotted as a function of air gap while biasing the glass slide at 3 different temperatures. Increased liquid temperatures and reduced air gaps enhance the speed of the doublet flow. A 27 ohm probe fixed at 30° angle and 10.4 mW input power was used in this experiment.

The geometry of the heat source plays a significant role in the doublet pattern. For example, a probe (R02) suspended at a 15° angle with respect to the liquid plane results in doublet flow from left to right; however, when the probe angle is doubled to 30° (keeping all other parameters constant), the direction of flow is reversed, and the location of the adjacent vortices shifts to the left as shown in Fig. 6.

The flow can also be manipulated into a linear channel-like pattern by generating multiple doublets with arrayed heat sources. The 8-probe array was biased at 2.3V, dissipating 92 mW total power in six probes (probes 1 and 4 were nonfunctional). The resulting flow pattern (Fig. 7) has a linear flow region with adjacent rotational regions as predicted by simulations (Fig. 2b). Distortions in flow are observed in several regions, such as the trajectory marked with a triangle, and can be attributed to the difference in air gap between the various probes in the array in addition to the fact that two probes were not operational. The noticeably smaller velocities (190 μm/sec) compared to single probes may be attributed to the reduced temperatues of the heaters in the multiprobe array. These results illustrate that flow is

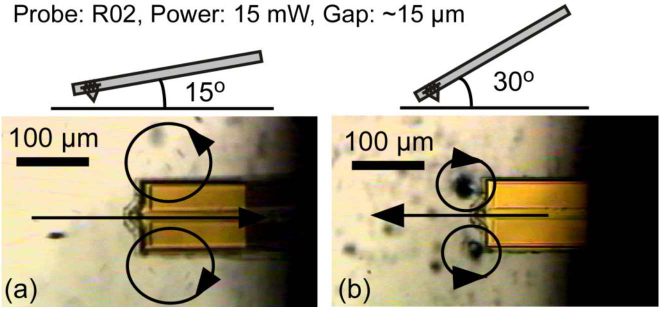

Fig. 6: The direction of the flow can be reversed by changing the angle of the heater. For example, using probe R02 at a 15° tilt, 15 mW input power, and a ~15 μm air gap, the doublet flows left to right, and the rotation in the vortices is counter-clockwise (a). Increasing the angle to 30° while keeping all other parameters constant reverses the direction of the flow and rotation and shifts the location of the vortices to the left of the cantilever (b).

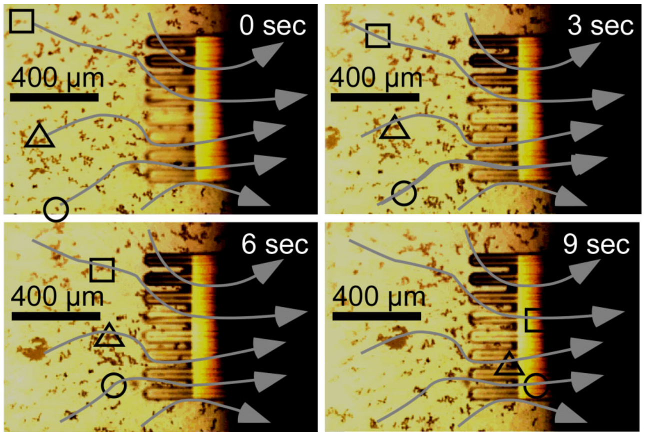

Fig 7: Linear flow generation using an 8-probe array, numbered 1-8 from the top down. The array was placed ~15-20 μm above the liquid surface, held at a 15° tilt, and biased with a total power of 92 mW. Probes 1 and 4 were nonfunctional. Trajectories for 3 particles are marked with a square, triangle, and circle on micrographs taken at 3 second intervals.

highly dependent on the geometry of the heat transmitted to the liquid surface. Therefore, it is possible to obtain custom flow patterns by arranging the heat sources in various configurations.

Subsurface particle flow, visualized by focusing the microscope at the bottom of an 80 μm thick layer of water, differs significantly from the doublet flow patterns observed at the surface. Particles flow radially inward over time, converging on a point directly below the tip of the cantilever. Once at this point, the particles are accelerated upwards towards the surface of the liquid film (Fig. 8). The column of vertically-directed current may be due to convection and/or localized evaporation driven by the high liquid temperatures beneath the probe tip. Further modeling and experimentation is needed to clarify the mechanism driving both the surface and subsurface flow patterns observed.

IV. CONCLUSIONS

In summary, we have shown that high speed doublet flow can be thermally generated by a micromachined heat source operating without contact to the liquid, and a linear flow profile can be achieved using by arraying the heat sources. Characterization of the flow patterns indicate that it is thermally driven by heat transmitted through the thin air gap. The high-speed particle velocities and rotational velocities have potential applications in pumping and mixing.

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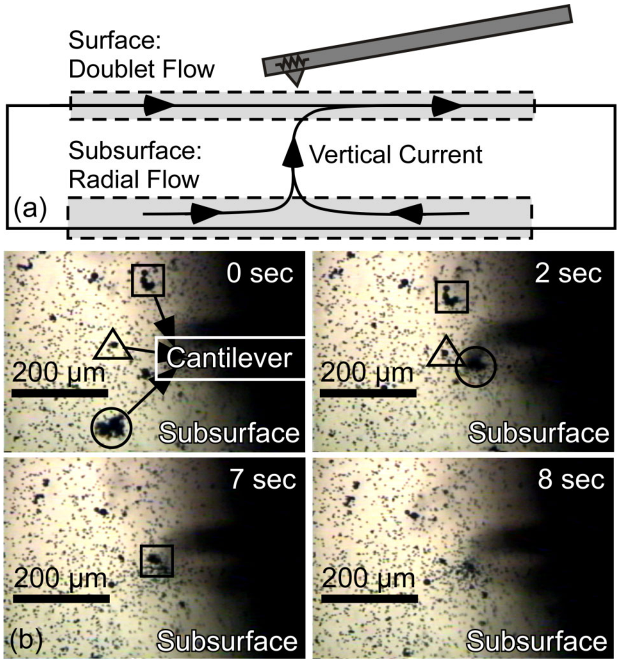

Fig 8: (a) Schematic of subsurface particle flow (80 μm below the surface). Particles flow radially inward towards the area underneath the microheater tip. Upon reaching this point, they are immediately propelled upwards to the surface. (b) Sequential micrographs show the particles (marked with a square, triangle, and circle) converge towards the center and then disappear from the field of view as they are propelled upwards.

REFERENCES

[1] A. Mizuno, M. Nishioka, Y. Ohno, and L. Dascalescu, "Liquid Micro-Vortex Generated around a Laser Focal Point in an Intense High-frequency Electric Field," *Proc. Industry Applications Society Annual Meeting*, 1993, pp. 1774-1778.

[2] W.L.W. Hau, L.M. Lee, Y.K. Lee, M. Wong, and Y. Zohar, "Experimental Investigation of Electrokinetically Generated In-Plane Vorticity in a Microchannel," *Proc. Intl. Conf. on Solid State Sensors, Actuators, and Microsystems*, June 2003, pp. 651-654.

[3] G.R. Wang, J.G. Santiago, M.G. Mungal, B. Young, and S. Papademetriou, "A Laser Induced Cavitation Pump," *J. Micromech. Microeng.*, 14(7), July 2004, pp. 1037-1046.

[4] L. Lu, K. Ryu, and C. Liu, "A Magnetic Micro-Stirrer and Array for Microfluidic Mixing," *J. Microelectromech. Syst.*, 11(5), Oct. 2002, pp. 462-469.

[5] D. Young, B. Munson, and T. Okiishi, *A Brief Introduction to Fluid Mechanics,* Wiley, NY, 1997.

[6] M.H. Li and Y.B. Gianchandani, "Applications of a Low Contact Force Polyimide Shank Bolometer Probe for Chemical and Biological Diagnostics," *Sensors and Actuators A: (Physical)*, 104(3), May 2003, pp. 236-245.

[7] S. McNamara, A. Basu, and Y. B. Gianchandani, "Ultracompliant Thermal Probe Arrays: Large Area Mapping of Non-Planar Surfaces without Force Feedback," *Proc. Intl. Conf. on Micro Electro Mechanical Sys*, Maastrich, The Netherlands, January 2004, pp. 825-828.