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Reversible Switching of High-Speed Air−Liquid Two-Phase Flows Using Electrowetting-Assisted Flow-Pattern Change

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Gas−liquid two-phase flow configurations are advantageous for the development of various microfluidic systems such as bioreactors,[1] electronic chip cooling systems,[2] fuel cells,[3] digitally controlled microflows,[4] surface micropatterning,[5] biochemical assays,[6] and cell analysis.[7] A key to the success of two-phase processes is the ability to manipulate fluid flows in a rapid, reversible, and accurate manner to enhance mixing, to promote phase change, and to localize reagents and analytes stably. This paper describes a novel fluidic actuation scheme that uses a combination of electrical modulation of surface wettability (i.e., electrowetting) and spatially directed flow transitions to switch lateral positions of high-speed gas−liquid two-phase flows reversibly.

The opportunity and challenge of handling microscale two-phase flows lie in the control of interfacial effects. Dynamic two-phase systems with continuous flows are especially interesting because the combination of surface tension, inertial, and viscous forces gives rise to the formation of different flow regimes with distinct stable flow patterns.[8] The distribution of moving fluids within any given channel is complex, but can be qualitatively categorized into flow regime maps where different flow patterns are correlated to different flow rates of the gas and liquid phases.[8] Thus, a variation of gas and liquid flow rates has been the conventional way to control two-phase flow patterns and transitions. Here, we show that even with fixed driving forces for air and liquid flows, the position and the type of flow pattern can be manipulated in high-speed air−liquid two-phase microfluidic systems by reversibly changing the surface energy of the microchannel floor through electrowetting.[4] In particular, we switch flow regimes between a focused "rivulet" flow that touches the top and bottom surfaces of the channel (Figure 1a) and a "semi-annular" liquid flow that streams along the sidewalls (Figure 1b). Although the effect of flow rates and surface contact angles necessary for obtaining various stable two-phase flow patterns in microchannels has been investigated,[8] our work presents a unique application of electrowetting combined with fluid dynamics to modulate the patterns of high-speed two-phase fluid streams reversibly. We demonstrate the use of this phenomenon to precisely position and mix two-phase fluid streams.

Figure 1 shows an example of electrically switchable positioning of high-speed (bulk liquid velocity of 0.3−1 m/s) two-phase flows. The system consists of a hydrophobic poly(dimethylsiloxane) (PDMS) slab having channel features sealed against a Teflon substrate with embedded indium-tin-oxide (ITO) electrodes (Figure 2a). Parallel fluid streams are driven in the resulting closed channel by vacuum suction at the outlet and syringe injection of liquid at the middle inlet. Interaction of water with the hydrophobic microchannel surfaces leads to the formation of a stably focused aqueous stream in the middle (Figure 1a). When an electrical potential is applied to the ITO electrodes embedded under one-half of the channel floor, the inherently hydrophobic Teflon surface becomes hydrophilic. This surface energy change causes the middle aqueous stream to shift to its right and flow along the sidewall (Figure 1b).

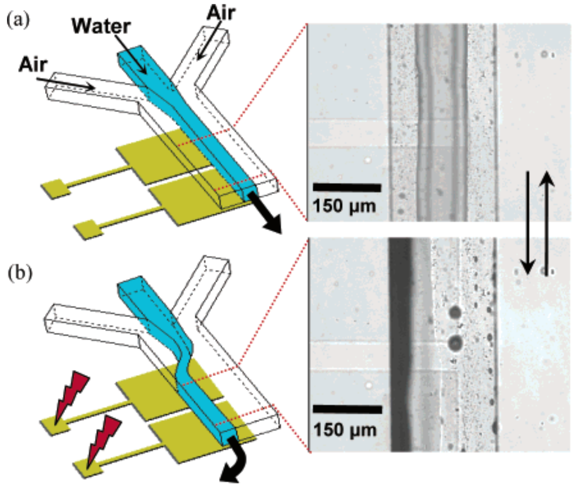

Figure 1. Electrically induced switching of surface energy caused (a) a focused high-speed water stream in the middle to (b) swerve to its right (relative to the direction of fluid flow), guiding the flow along the sidewall. Water was injected at 20 mL/h, and air flows were driven by 400 mmHg vacuum at the outlet. Channel height is 100 μm.

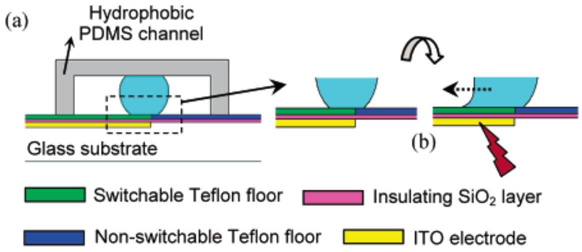

Figure 2. Channel floor consisting of dielectric Teflon coating (250 nm), insulating oxide layer (350 nm), ITO electrodes (150 nm), and glass substrate mediates localized wetting of the water column.

The underlying mechanism of the flow pattern changes described above is outlined in Figure 2b. When the embedded ITO electrodes are energized, the contact angle decreases, giving rise to the selective deformation of the air−water interface above the embedded electrodes. The other air−water interface on the nonswitchable

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10.1021/ja037350g CCC: $25.00 © 2003 American Chemical Society

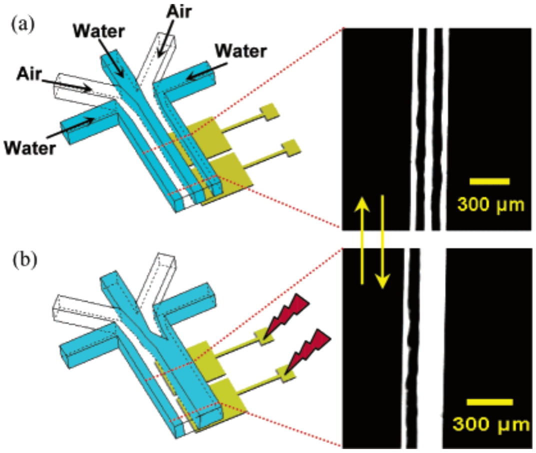

Figure 3. (a) Three stable water columns (flow rate of each water stream: 100 mL/h) focused by two streams of air. (b) When voltage is applied, a water column in the center moves to its left (relative to the direction of fluid flow) and merges with a side-stream. Water mixed with fluorescein was used for fluorescent imaging.

Teflon surface, however, retains its convex shape (Figure 2b). This asymmetric configuration of the air−water interfaces generates a lateral pressure gradient inside the flowing water column, resulting in rapid movement of the aqueous stream to its right. The spatially directed change in the flow pattern initiated by the asymmetric wetting of the water column is further driven by air flow until the aqueous stream redistributes itself and is localized along the sidewall (a thick dark line along the sidewall in the micrograph of Figure 1b). We presume that this flow configuration is energetically most stable because it minimizes the surface area of the aqueous stream contacting the flowing air. When the applied voltage is released, the lining of water along the sidewall is quickly swept away downstream by incoming air flows and the switchable Teflon floor which is now hydrophobic permits reversible formation of a stable aqueous stream in the center of the channel. The observed changes in flow pattern suggest that the mechanism of liquid actuation in the high-speed two-phase flow system differs from previously reported surface tension-mediated manipulation of discrete liquid droplets[4] or steady guidance of slow liquid streams along prepatterned surface energies.[5] The interaction of liquid sample with dynamic gas flows and microchannel walls, in addition to the initial driving force generated by a surface energy change, plays a crucial role in determining and controlling flow patterns.

Figure 3 demonstrates fluidic switching where modulation of surface energy causes merging and separation between three aqueous laminar streams flowing in parallel and separated by two air streams in between. To cause the middle stream to swerve to its left, the edges of ITO electrodes were aligned along the center line of the aqueous stream flowing in the middle and one-half of the Teflon channel floor was made hydrophilic by an electric potential. Upon voltage application, the Teflon surface over the energized electrodes became hydrophilic and prompted the middle aqueous stream to advance to its left, causing the merging of two aqueous columns (Figure 3b). The thick water stream generated by the merging of the two water columns was stably maintained until applied voltage was released and the merged streams were separated into two discrete water columns by incoming air flows.

Observation of flow pattern changes in a microchannel having a hydrophobic upstream region and a hydrophilic downstream region provides insights into the time frame of the electrowetting-assisted fluidic switching phenomena (Figure 4). The distance that a focused water column travels downstream before redistributing along the side walls was measured to be smaller than 1 mm (in Figure 4, $d < 1$ mm). Considering that the bulk velocity of water stream was approximately 0.5 m/s, the water flow responded to the change of surface chemistry within 2 ms. Although not optimized, this result suggests that the flow manipulation mediated by changing surface wettability may potentially be used for laterally positioning or mixing gas−liquid two-phase flows more than hundreds of times per second.

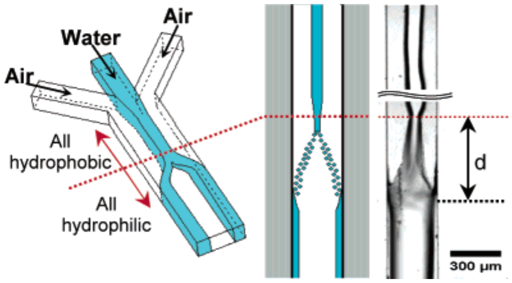

Figure 4. Focused water flow (flow rate: 20 mL/h) in a hydrophobic region (upper half) spreads in lateral directions and rapidly redistributes water along the sidewalls in the hydrophilic region (lower half).

In conclusion, we have demonstrated the reversible switching of high-speed air−liquid two-phase flow systems by electrically modifying surface energy of microchannels. The actuation method introduces a novel mechanism that takes advantage of two-phase flow dynamics in combination with the engineering of surface chemistry and provides a robust means to achieve reversible, precise, and potentially rapid flow control without any need for mechanical complexity of moving components. We believe that the capability of creating and maneuvering different two-phase flow patterns using surface energy changes will serve as a novel and enabling tool for the development of dynamic biochemical microsystems and for various cell/particle sorting applications.[9]

Acknowledgment. This research was supported by a Ralph E. Powe Junior Faculty Award, NSF, NIH, and DARPA (BioFlips).

Supporting Information Available: Fabrication of multilayered channel floor; details of switching experiments; movie of fluidic switching; specifications of applied electric potential (PDF and AVI). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) de Mas, N.; Gunther, A.; Schmidt, M. A.; Jensen, K. F. *Ind. Eng. Chem. Res.* **2003**, *42*, 698. (b) Losey, M. W.; Jackman, R. J.; Firebaugh, S. L.; Jensen, K. F. *J. Microelectromech. Syst.* **2002**, *11*, 709.
(2) Zhang, L.; Koo, J. M.; Jiang, L.; Asheghi, M.; Goodson, K. E.; Santiago, J. G.; Kenny, T. W. *J. Microelectromech. Syst.* **2002**, *11*, 2002.
(3) Djilali, N.; Lu, D. M. *Int. J. Therm. Sci.* **2002**, *41*, 29.
(4) (a) Cho, S. K.; Moon, H.; Kim, C.-J. *J. Microelectromech. Syst.* **2003**, *12*, 70. (b) Lee, J.; Moon, H.; Fowler, J.; Schoellhammer, T.; Kim, C.-J. *Sens. Actuators, A-Phys.* **2002**, *95*, 259.
(5) (a) Zhao, B.; Moore, J. S.; Beebe, D. J. *Science* **2001**, *291*, 1023. (b) Lam, P.; Wynne, K. J.; Wnek, G. E. *Langmuir* **2002**, *18*, 948.
(6) Ding, H.; Chakrabarty, K.; Fair, R. B. *IEEE Trans. Comput-Aided Des. Integr. Circuits Syst.* **2001**, *20*, 1463.
(7) Huh, D.; Tung, Y. C.; Wei, H. H.; Grotberg, J. B.; Skerlos, S. J.; Kurabayashi, K.; Takayama, S. *Biomed. Microdevices* **2002**, *4*, 141.
(8) (a) Barajas, A. M.; Panton, R. L. *Int. J. Multiphase Flow* **1993**, *19*, 337. (b) Hetsroni, G.; Mosyak, A.; Segal, Z.; Pogrebnyak, E. *Int. J. Multiphase Flow* **2003**, *29*, 341.
(9) We have confirmed that a majority of cells (C2C12 myoblasts) transported in liquid streams of air−liquid two-phase flows survive.

JA037350G