FLUIDIC SWITCHING
OF HIGH-SPEED AIR-LIQUID TWO-PHASE FLOWS
USING ELECTROWETTING-ON-DIELECTRIC

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ABSTRACT
A variety of functions will be necessary for the successful implementation of a micro
total analysis system. Accurate and rapid actuation and control of continuous fluid
streams is one such function which will be invaluable for fluidic switching and mixing.
We have developed a microfluidic switch based on the actuation of a liquid stream in an
air-liquid two-phase flow system using electrowetting. This unique fluid actuation
scheme incorporates the positive aspects of two-phase flow and electrical actuation,
opening new possibilities for cell and particle sorting.

KEYWORDS: electrowetting, fluidic switching, sorting, two-phase flow

INTRODUCTION
We have previously developed an air-sheath microfluidic flow cytometer (μFC) with
aerodynamic focusing [Figure 1] and demonstrated the counting of myoblasts [1]. The
design uses polydimethylsiloxane (PDMS) slabs for vertical confinement and air for
horizontal confinement of the sample suspension, eliminating the need for large sheath
fluid reservoirs and making the design attractive for portable biological analysis devices
and for multiplexing. In this paper, we take advantage of the two-phase air-liquid flow
and sensitivity of the device to surface chemistry to create a microfluidic switch. The
unique dual-pronged fluid actuation scheme is based on the nonlinear transition of two-
phase flows between different flow patterns as well as the electrowetting-on-dielectric
(EWOD) principle which allows for control of surface wettabillity through electrical
modulation [2,3]. The design uses no moving parts and opens new possibilities for cell
and particle sorting. The switching mechanism incorporates the positive aspects of both
air-sheathed flow (resistance to clogging, high flow velocity) as well as those of electrical
actuation (no moving parts, fast response time, computerized triggering).
Sheath Flow Observation Channel

Figure 1. Sample fluid is injected through a nozzle and is enveloped by air sheath flow leading to tight aerodynamic focusing. Optically-transparent Teflon-coated ITO electrodes on a glass microscope slide comprise the observation channel floor, a modification to the previously-developed μFC. A PDMS slab with microchannel feature is placed on top. The orientation of the electrodes is perpendicular to the flow of sample solution. With voltage applied to the electrodes, a portion of the hydrophobic channel floor is temporarily rendered hydrophilic, allowing for control of fluid position.

ELECTROWETTING-ON-DIELECTRIC (EWOD) FOR SWITCHING

Electrical modulation of surface wettability is a novel approach allowing for control of liquid position. Here, we demonstrate actuation of the sample liquid stream in a high-speed air-liquid two-phase flow system utilizing electrowetting-on-dielectric techniques. EWOD is the phenomenon whereby the spreading of a liquid on a dielectric surface can be modified by applying an electrical potential to imbedded electrodes [2,3]. A hydrophobic PDMS slab with microchannel feature was attached onto a bottom EWOD substrate. The EWOD substrate formed the floor of the microfluidic channel; it consisted of a glass microscope slide with patterned indium tin oxide (ITO) electrodes underneath a SiO₂ dielectric layer and hydrophobic Teflon coating. The three device layers (ITO, SiO₂, Teflon) remain optically transparent for visual light microscopy. When an electric potential was applied to the ITO electrodes, we observed the EWOD phenomenon as the Teflon channel floor alternated between hydrophobic and hydrophilic surface conditions. By temporarily converting certain regions of the Teflon surface to the hydrophilic condition, it was possible to rapidly and reversibly change the path of the sample liquid.
stream towards one side of a channel [Figure 2]. This EWOD-based technique opens the way for a variety of fluid switching applications such as sorting cells.

**Figure 2.** EWOD-based one-sided actuation of the moving fluid stream in microfluidic channel. The bottom Teflon surface is rendered hydrophilic with applied voltage, causing centered flow stream to shift to one side. When voltage is removed, stable centered flow resumes. This provides a microfluidic switch. Channel shown is 300μm wide, 100μm deep and electrodes A and B are 5mm x 8mm with 100μm gap. This figure just shows three snapshots within the course of 0.4 seconds. The experiment itself performed many fluidic switchings over the course of several minutes.

**FLOW PATTERNS AND NONLINEAR TRANSITION**

The type of flow pattern exhibited by a dynamic two-phase continuous fluidic system depends on four main inputs: channel geometry, inertial forces, shear forces, and surface tension. As the contribution from these inputs is varied, the change in resultant flow pattern can be qualitatively observed. For example, increasing the flow rate of gas and
holding liquid flow rate constant will often convert a plug flow (a continuous liquid phase with intermittent elongated "plugs" of gas) to a slug flow (waves of liquid traveling through gas).

Flow patterns can be classified into regions on a flow regime map, which correlates flow rates of gas and liquid to a resulting flow type. Previous studies of gas-liquid two phase flows in capillary tubes have demonstrated that altering the contact angle of the surface can change the flow regime map: the pattern of a map field may be completely altered, or a shift of the map field boundaries can occur [4]. Here, we show that the change of surface wettability can alter and control the type of flow pattern that is stable in air-liquid two-phase microfluidic systems. In particular, we are switching between a focused rivulet flow characterized by a focused stream of liquid flowing along top and bottom surfaces [first micrograph of Figure 2] and a stratified air-liquid flow [second micrograph of Figure 2]. Researchers have studied flow patterns in microchannels of static surface chemistry [5], and our work is a novel approach demonstrating the use of dynamic surface wetting condition to modulate the flow pattern exhibited by an air-liquid two phase flow system.

CONCLUSION
Although there are a number of literature reports on the use of electrowetting-based techniques for actuation of discrete liquid droplets [2,3,6], this report is the first demonstration on the use of electrowetting-based actuation for continuous fluid flows. Proof of the dynamic EWOD concept and a fundamental understanding of the actuation schemes open the way for the development of a microscale cell and particle sorter with no moving parts, low cost, and low liquid volume requirements.

REFERENCES