Electrowetting Driven Mobile Oscillating Bubble for Microfluidic Mixing Enhancement

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This paper describes a novel microfluidic mixing method using an alternating current electrowetting-on-dielectric (AC-EWOD)-driven mobile oscillating bubble. An AC-EWOD-driven bubble can generate a microstreaming flow and be simultaneously transported on the two-dimensional surface of patterned electrodes covered with a hydrophobic dielectric layer in a microfluidic chip filled with an aqueous medium. When a bubble is actuated by AC-EWOD at a certain frequency (100 Hz), it oscillates and simultaneously generates a microstreaming flow around itself owing to its compressibility. The flow induced by the bubble oscillation is strong enough to be applied for enhancement of fluid mixing. The oscillating bubble also can be transported on the array of EWOD electrodes using the same AC-EWOD actuation. For a relative comparison of mixing enhancement, four cases with different combinations of the two actuations (bubble oscillation and transportation) have been tested; the results show that a bubble simultaneously actuated by both ~~actuation~~actuations~~s~~ shows overwhelming mixing performance with reduced mixing time. This method can be applied to efficient mixing tools in microfluidic systems, with merits of the size and high compatibility.

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1. Introduction

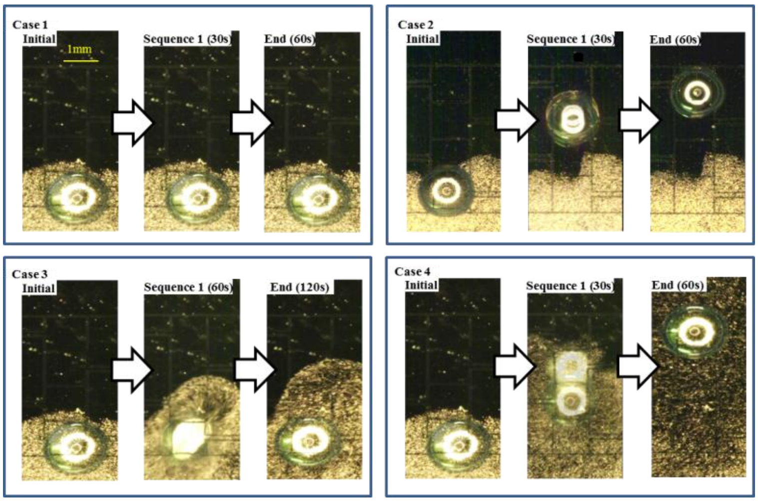
Fluid mixing is an essential operation in microfluidic systems and, in particular, takes the greatest portion of the total processing time for the incubation of biochips and micro total analysis systems (μTAS) [1]. The mixing process in microfluidic systems is typically slow because of the low Reynolds number ($Re = \rho VL/\mu$, where ρ, V, L, and μ are the density, mean velocity, characteristic length, and dynamic viscosity of a fluid, respectively), which is the ratio of inertia forces to viscous forces under given flow conditions. In low Reynolds number regimes, fluid mixing highly depends on molecular diffusion [1]. To increase the efficiency and speed of fluid mixing in microfluidic systems, various techniques have been developed. These techniques can be characterized as passive and active depending on whether external disturbances exist or not. Passive mixing methods have focused to increase the interfacial area between different fluids, along with the creation of multiple laminations, chaotic advection, and injection of substreams. On the other hand, in the active mixing methods, various external disturbances such as acoustics, pressure, thermal actuation, electrohydrodynamics, dielectrophoretics, electrokinetics, and magnetohydrodynamics have been applied [2].

In this paper, an alternating current electrowetting-on-dielectric (AC-EWOD)-driven bubble is applied to enhance fluid mixing in a microfluidic chip. When a bubble in an aqueous medium is actuated by AC-EWOD at a certain frequency (100 Hz), it also oscillates and generates a streaming flow around itself like an acoustically oscillating bubble. Moreover, the bubble can be simultaneously transported in a microfluidic chip by using the same EWOD actuation. This microfluidic mixing method can not only provide highly efficient fluid mixing but also provide high compatibility with the currently developed μTAS.

2. Results and Discussions

To test fluid mixing using an AC-EWOD-driven mobile oscillating bubble, testing devices were fabricated using the standard microfabrication technology. For EWOD actuation, a sine wave voltage was generated by a function generator (33210A, Agilent Co.), and amplified up to a few hundred volts by a voltage amplifier (PZD700, Trek Co.). The amplified voltage signal was transmitted to the EWOD electrodes through photo-coupled relays (PhotoMos® , AQW614EH, Aromat Co.) controlled by a digital I/O board (DAQpad-6229 BNC~~6507~~, NI Co.) along with a programmed Labview code. Experimental results were observed through a charge coupled device (CCD, EO-1312C, Edmund Optics) integrated with a zoom lens (VZMTM 450i eo, Edmund Optics) and saved on a personal computer.

To compare the enhancement of fluid mixing in a microfluidic chip, four different cases with different combinations of actuation (bubble oscillation and transportation) are tested as follows: (case 1) no actuation (mixing by diffusion only); (case 2) a mobile bubble actuated by AC-EWOD at 1 Hz (mixing using a mobile bubble without microstreaming flow); (case 3) a stationary oscillating bubble actuated by AC-EWOD at 100 Hz (mixing using a microstreaming flow without bubble transportation); (case 4) a mobile oscillating bubble actuated by AC-EWOD at 100 Hz (mixing using a mobile oscillating bubble with microstreaming flow). Figure 1 shows the sequentially captured images for the four cases. In the tests, a bubble (1 mm in diameter) is initially placed on the lowest side of the array of EWOD electrodes, and polymer particles (10 μm in diameter) are seeded around the bubble. It should be noted that the particles initially cover roughly 30% of the total lower area of a testing chip; however, virtually no particles exist in the middle and upper areas of the chip. A series of experiments shows that ~~These results indicate that an~~an AC-EWOD-driven mobile oscillating bubble with microstreaming flow(case 4) produces the highest mixing among all the cases. Furthermore, the highest mixing is also prominent in section A in case 4, indicating that combined actuation is highly effective in carrying fluids the farthest,



i.e., from one end to another.

Fig. 1 Sequential images of mixing comparison for the four cases with different combinations of two actuation (bubble oscillation and transportation): (case 1) no actuation; (case 2) bubble transportation without oscillation; (case 3) bubble oscillation without transportation; (case 4) bubble transportation with oscillation. In the order from case 1 to case 4, the mixing performance becomes better.

3. Conclusions

This paper presents a novel micro-mixer where an alternating current electrowetting-on-dielectric (AC-EWOD)-driven mobile oscillating bubble stirs and mixes the surrounding fluids in microfluidic systems. In the array of EWOD electrodes covered with a hydrophobic dielectric layer, a bubble can be transported and simultaneously oscillated to generate a microstreaming flow around the oscillating bubble by controlling the input signals of AC-EWOD. The input frequency has been used as a parameter to control the microstreaming flow. At a certain frequency (around 100 Hz) the oscillating bubble generates a strong microstreaming flow; however, at other frequencies, the strength of the flow becomes weak. The efficiency of the flow for fluid mixing can be maximized by transportation of the bubble. One of the greatest merits of this mixing method is that a sole AC-EWOD can simultaneously carry out both actuations—bubble oscillation and transportation—without using other actuators. To compare the enhancement of fluid mixing, four different cases were tested as follows: (case 1) no actuation, (case 2) bubble transportation without oscillation, (case 3) bubble oscillation without transportation, (case 4) bubble transportation with oscillation. A series of experiments shows that the combined actuation of bubble oscillation and transportation (case 4) produces the highest mixing among all the cases and significantly reduces the chamber mixing time.

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