ELECTRIC-FIELD INDUCED TIP STREAMING FOR SUB-FEMTOLITER DROPLET FORMATION

Hsin-Hsien Tsai, Jhih-Jhe Wang and Yu-Chuan Su
Department of Engineering and System Science, National Tsing Hua University, Taiwan

ABSTRACT

This paper presents a novel droplet formation scheme that can electrically generate sub-femtoliter droplets in a desired manner. Typical pressure-driven flow-focusing scheme is enhanced by an AC electric field, which deforms the fluidic interface and causes droplet breakup around the tip. In the prototype demonstration, PDMS microfluidic devices with embedded alloy electrodes are fabricated and characterized. Alternating electric fields with frequencies up to 1 kHz and magnitudes less than 1 V/µm are utilized in the trials. It is demonstrated that the emulsification process is controlled by the applied electric field, and extremely-small droplets with volumes less than 1 femtoliter can be readily generated and collected.

KEYWORDS

Tip streaming, Droplet formation, Electrokinetic effect, Pressure-driven flow, Flow focsuing.

INTRODUCTION

Droplet-based microfluidic systems have recently attracted significant interest because of their potential impacts on diverse chemical and biological applications [1]. Droplet formation is the starting point and often the most critical function of a droplet-based system [2]. Most of the existing systems employ passive schemes, which are simple and self-regulated but insufficient for precise and real-time control. It is known that a suspended droplet can be deformed in an electric field [3] and charged droplets can be manipulated electrically [4]. To address the need for better and more general controllability on droplet formation, this paper presents a scheme that utilizes AC electric fields to enhance the emulsification process. As such, the demonstrated scheme could potentially realize the controlled formation of extremely-small droplets, which is desired for a variety of applications.

OPERATING PRINCIPLE

A schematic illustration of the proposed droplet formation scheme is shown in Figure 1. Typical flow-focusing scheme is enhanced by an AC electric field. The continuous- and dispersed-phase fluids are driven by pressure sources with independent control. Initially, the dispersed-phase fluid is stopped in front of the diverging channel. Once an above-threshold electric field is applied, the front end of the dispersed-phase fluid is deformed accordingly. The electric Weber number [5], which represents the ratio of deforming electric force to restoring interfacial force, is utilized to characterize the deformation. The electric force behaves like that an additional pressure is applied to the dispersed-phase fluid, which is driven into the diverging channel and broken into droplets. If an even higher electric field is applied, the dispersed-phase fluid ejects tiny droplets at its sharp pointed end. As such, droplet breakup can be controlled electrically. In the prototype demonstration, PDMS molding and bonding processes are employed to fabricate the microfluidic systems. Magnetically-responsive, carbon-coated iron nanoparticles (~30 nm in diameter) are dispersed in a low-melting-temperature In52/Sn48 alloy. As illustrated in Figure 2, Fe-In52/Sn48 alloy is melted by induction heating and vacuum molded into micro-channels to form the desired solid electrodes. It is heated up to 120°C and melted, while the surrounding PDMS substrate is warmed up to about 60°C. In 3 minutes, the desired solder electrodes are integrated into the PDMS microfluidic chip.

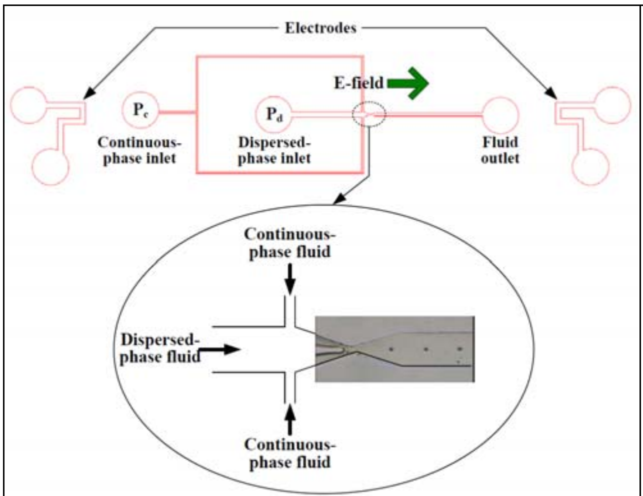

Fig. 1: Schematic illustration of the proposed droplet formation scheme

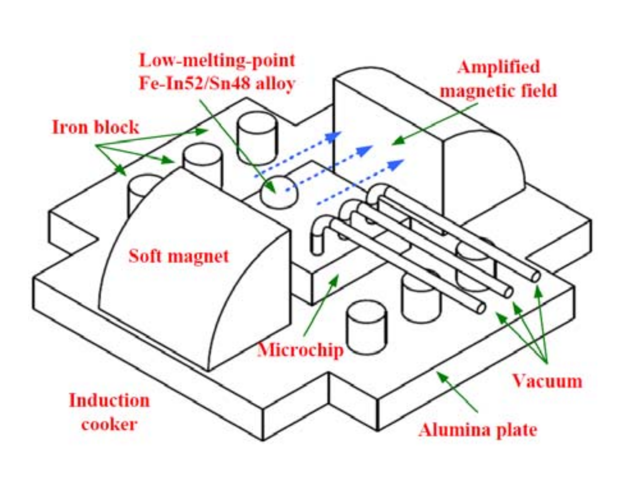

Fig. 2: Schematic illustration of the induction heating, vacuum molding process for solid electrodes

EXPERIMENT

In the prototype demonstration, the electrode molding process is operated on top of an induction cooker (Panasonic JC-615), which serves as a magnetic field generator. The photograph of a fabricated PDMS chip is shown in Figure 3. In the emulsification trials, aqueous solutions are dispersed in oleic acid with 5 wt% PGPR 90 to form water-in-oil emulsions. The function of PGPR 90 is to lower the interfacial tension and stabilize the emulsions. Meanwhile, the required electric-field strength for droplet breakup is also reduced. The two fluids, an aqueous solution and oleic acid, are driven by an air compressor with independent pressure control. Alternating electric fields with frequencies up to 1 kHz and magnitudes less than 1 V/µm are utilized in the trials. Figure 4 illustrates an observed emulsion process with a resulting droplet volume less than 1 femtoliter. By periodically applying the required electric field, droplets can be generated repeatedly and consistently. An AC electric field causes droplet breakup around the tip, while the breakup frequency is identical to the field frequency.

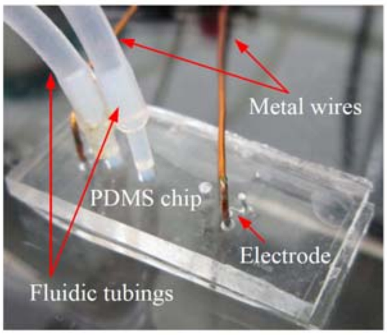

Fig. 3: Photograph of a fabricated PDMS device

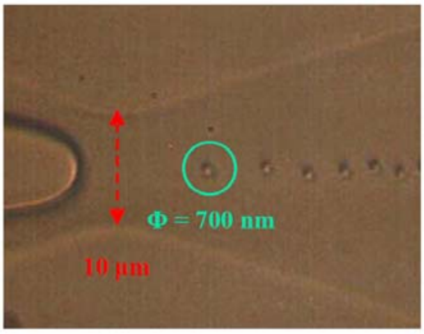

Fig. 4: An observed emulsification process

RESULTS AND DISCUSSION

As illustrated in Figure 5, dripping produces monodisperse droplets close to the entrance of diverging channel at low frequencies. The electric force drives the dispersed-phase fluid into the diverging channel, and then the continuous-phase fluid breaks it into droplets. The process is similar to flow focusing, while electric field is integrated as an extra driving approach. It is found that the emulsification process is controlled by the frequency and magnitude, as illustrated in Figure 6 and 7. By increasing the frequency and magnitude of the applied field, the resulting droplet volume is reduced.

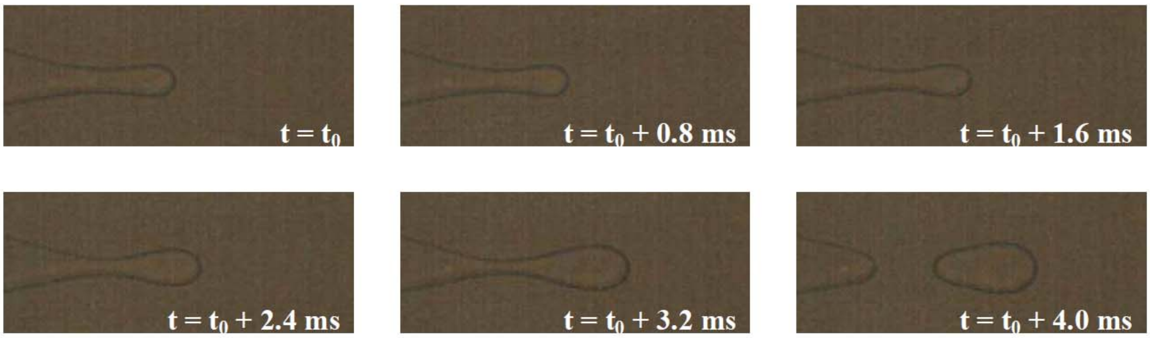

Fig. 5: A 10-Hz droplet formation sequence observed in a 0.2 V/µm electric field

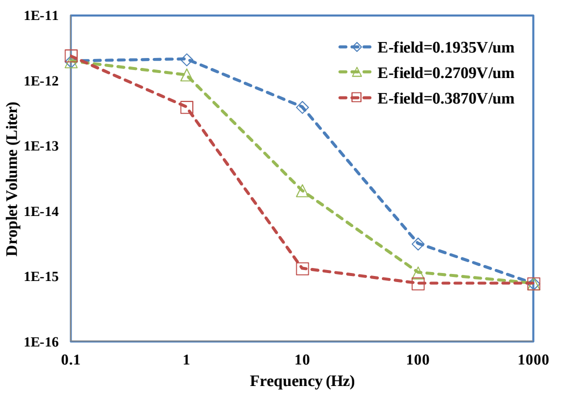

Fig. 6: Relationship between e-field frequency and droplet volume with varying e-field magnitude

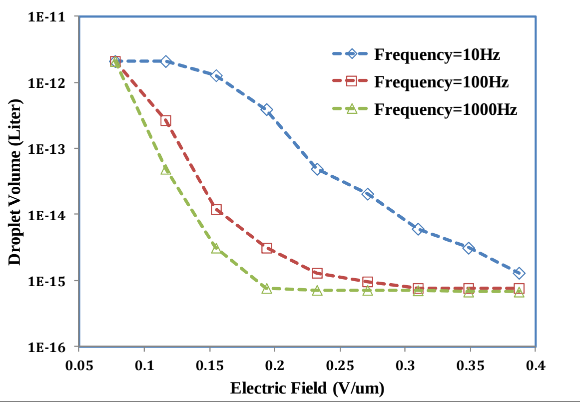

Fig. 7: Relationship between e-field magnitude and droplet volume with varying e-field frequency

In contrast, tip streaming produces much smaller droplets at high frequencies, as illustrated in Figure 8. It is found that the rapid action of the electric field deforms merely a small portion of the interface, and the dispersed-phase fluid ejects tiny droplets at its sharp pointed end. The ejection drives the resulting droplet moving in a velocity much higher than the flow velocity of the continuous-phase fluid. By increasing the frequency and magnitude of the applied field, the resulting droplet volume is reduced. At a frequency about 1 kHz and a magnitude above 0.3 V/μm, droplets with volumes less than 1 femtoliter is readily generated and collected.

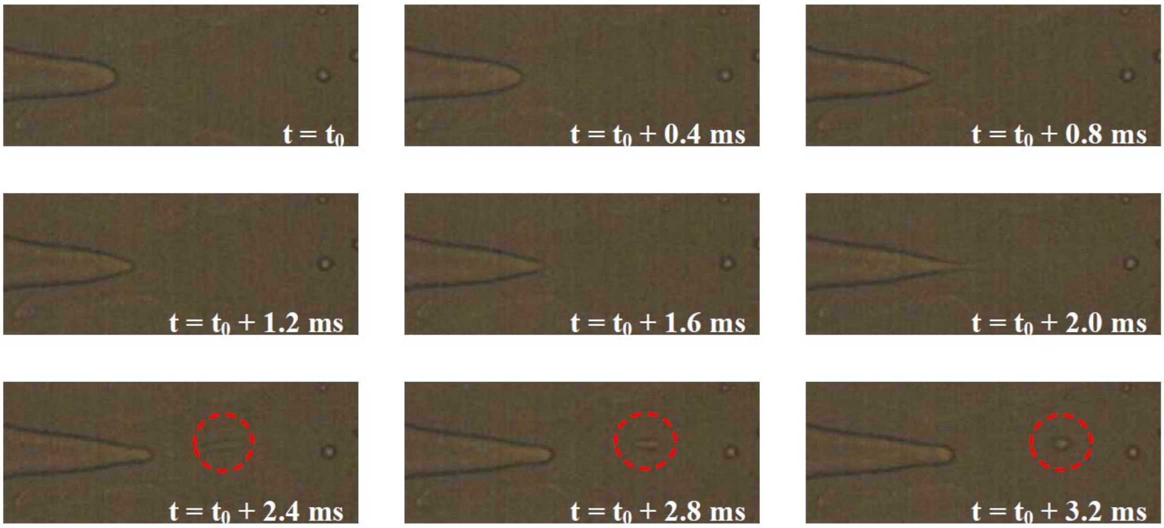

Figure 8: A 100-Hz droplet formation sequence observed in a 0.2 V/μm electric field

CONCLUSION

We have successfully demonstrated a novel droplet formation scheme that is capable of electrically generating sub-femtoliter droplets in a desired manner. Typical pressure-driven flow-focusing scheme is enhanced by an AC electric field, which deforms the fluidic interface and causes droplet breakup around the tip. In the prototype demonstration, PDMS microfluidic devices with embedded alloy electrodes are fabricated and characterized. Alternating electric fields with frequencies up to 1 kHz and magnitudes less than 1 V/μm are utilized in the trials. It is demonstrated that the emulsification process is controlled by the applied electric field, and extremely-small droplets with volumes less than 1 femtoliter can be readily generated and collected. As such, the demonstrated scheme could potentially realize the controlled formation of extremely-small droplets, which is desired for a variety of chemical and biological applications.

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CONTACT

Yu-Chuan Su, 886-3-5742374 or ycsu@ess.nthu.edu.tw