ELECTRIC CONTROL IN DROPLET-BASED MICROFLUIDICS

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ABSTRACT

We report a new method to actively control the size of droplets in a microfluidic flow focusing device through the use of electrodes which are not in contact with the fluids. The proposed electrical control is able to change the size of the droplets in the order of millisecond and also to manipulate the size of the droplets formed at single droplet level.

KEYWORDS

Microfluidics, droplets, flow focusing, active control

INTRODUCTION

Droplet-based microfluidics is an attractive tool for many biochemical applications as it allows discrete volume of fluids to be individually handled and manipulated. Each generated droplet can act as an independent micro-reactor in which bio-chemical reactions can be processed within the droplets at high throughput. However, the full exploitation of the potential is currently limited as only a single droplet size can be produced at fixed flow rates [1]. Hence, greater control of droplet sizes is needed to realize the full potential and the usefulness of droplet-based microfluidics, for material synthesis or biotechnology applications.

Electrical control of droplets offers a good way to manipulate droplet sizes due to the fast and robust response of the droplets to the electric field. It was first reported by Link *et al* [2] using a microfluidic flow focusing device. It demonstrated that by charging the fluids, electrical forces can be used to decrease the size of the droplets. Subsequently, using a similar geometry but by inserting metals directly into the microchannels, Kim *et al* [3] also show a decrease in the size of the droplets with the increase in voltage. Following these works, Malloggi [4] and Gu *et al* [5] used an electrowetting-enhanced system to decrease the size of the droplets. This is achieved by tuning the wetting contact angle of the dispersed phase fluid through the increase in voltage. However in the above, several underlying drawbacks limit the use of them in biological applications or using droplets as microreactors. The direct contact of the metal with the fluids raised fears of possible contamination and the charging of the fluids produces unwarranted electrochemical reactions which interfere and disrupt the stability of the content of the droplets. In addition, the above reported methods also do not address the manipulation and control at single droplet level.

To address the above issues, we developed a new method of droplet size control using electrodes which are not in contact with the fluids. The system is able to tune the size of the droplets in the order of milliseconds and also control the size of the droplets at single droplet level.

EXPERIMENT

Our electric droplet microfluidic system is fabricated using standard photo- and soft-lithography techniques. Rectangular electrodes with a separation distance of about 170µm are incorporated into the system by filling the microchannels with a low melting temperature metal alloy (Indalloy 19, Indium Corporation, T_m~70°C). No alignment of the electrodes is needed as the microchannels form both the fluidic channels and the templates for the electrodes. The schematic and optical micrograph of the device is shown in figure 1. A cross-junction microfluidic channel of 100µm width and depth 35µm is used to form droplets by flowing two immiscible fluids into separate microchannels at fixed flow rates via syringe pumps (neMESYS, Cetoni). The dispersed phase (DP) fluid flows in the centre channel (Deionized water) while the continuous phase (CP) fluids (Mineral oil (M5904), 5% wt/wt SPAN 80, Sigma Aldrich) flow in the two side channels. Alternating voltages generated using a signal generator (33210A, Agilent) and amplified using a high voltage amplifier (623B, Trek) are then applied to the top pair of electrodes to exploit electrical forces to control and manipulate the size of the droplets formed.

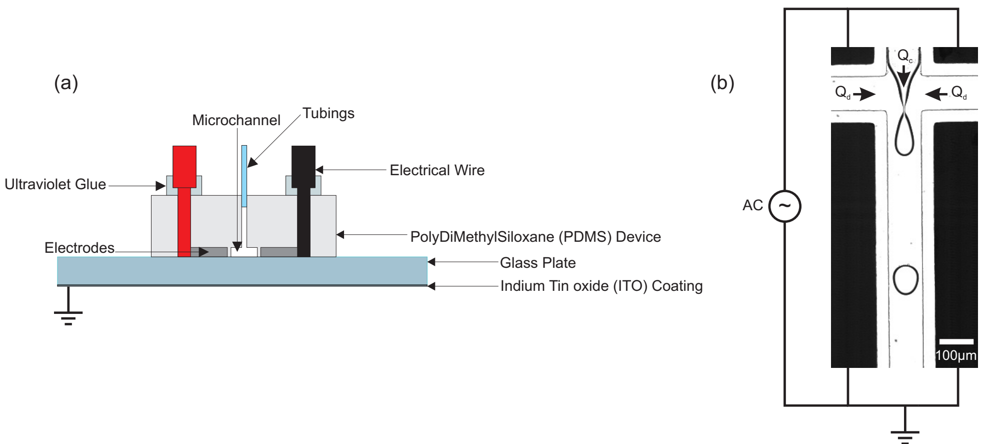
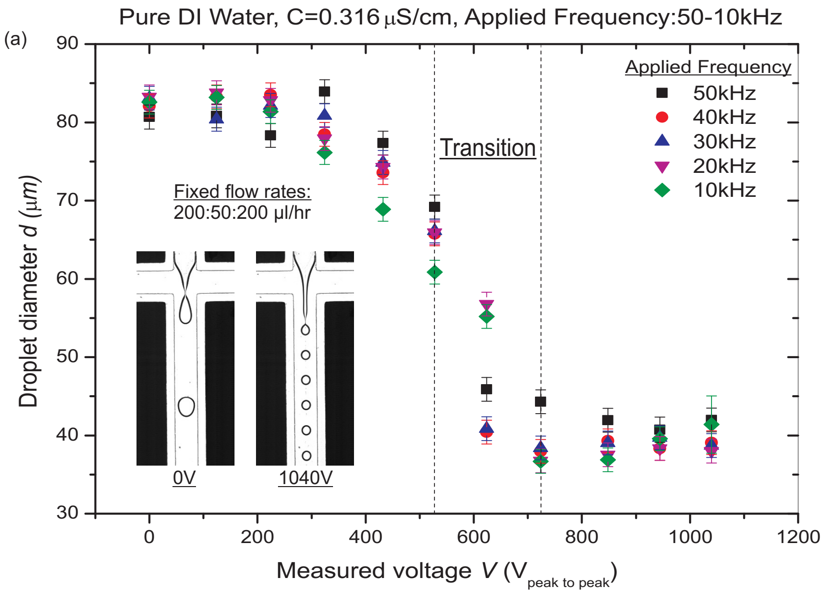


Figure 1: (a) Schematic sketch of the microfluidic device used. (b) Optical image of the geometry used.

RESULTS AND DISCUSSION

In the absence of electric field, water-in-oil (W/O) droplets are formed mainly in the squeezing, dripping or jetting regime depending on the capillary number (Ca) of the system which is determined by the flow rates used. The measured diameter of the droplets formed agrees and scales well to past literatures. In the presence of electric field at fixed flow rates of CP:DP:CP (200:50:200 µl/hr), we demonstrated that the size of the droplets produced decreases with the increase in applied voltage (Figure 2a). The droplets produced are highly monodisperse with a standard deviation of less than 5%. A change in the droplet formation regime squeezing/dripping to jetting was also observed between 500 to 700 V_{pp} without changing the applied flow rates (Figure 2a inset). This change is mainly due to the reduction of effective interfacial tension owing to the Maxwell stress during the application of electric field. For low conductivity dispersed fluids (C=0.316 µS/cm), changing the frequency from 10 to 50 kHz only leads to slight differences in the size of the droplets formed and in the observed droplet formation regime (Figure 2a). We also observed that the electric control of the droplet sizes depends significantly on the flow rates used (Figure 2b). At a fixed flow rate ratio of 8 but different total flow rates, the decrease in the size of the droplets reduces drastically as the total flow rate increases from 315 to 1125 µl/hr. At total flow rate of 2250 µl/hr, the size of the droplets produced remains fairly constant when the applied voltage increases. This dependence is due to ratio of the viscous forces to the capillary forces and also the location where the droplets are formed in the absence of the electric field.



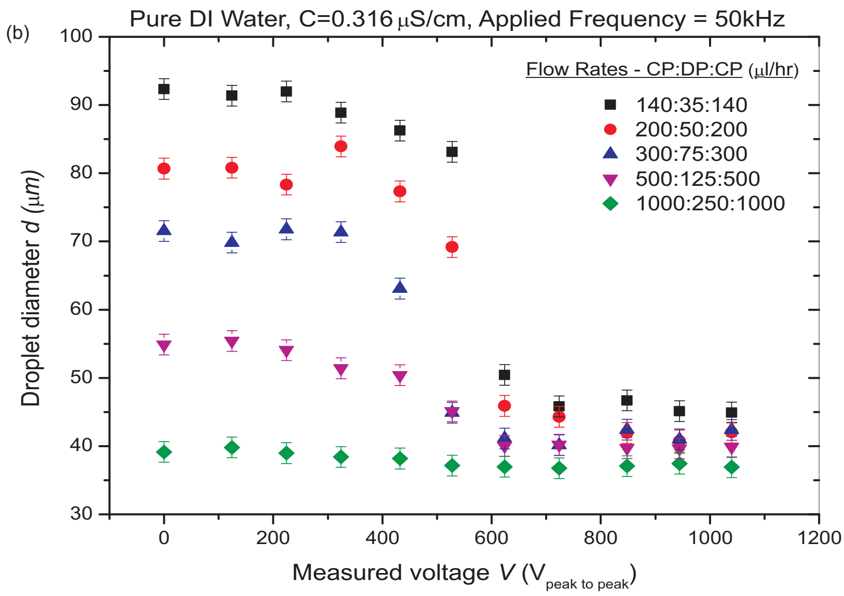


Figure 2(a) Effect of different applied frequency. (b) Effect of using different total flow rates at a fixed ratio of 8. In both experiments, alternating voltages (sinusoidal wave) are applied to the top pair of electrodes while the bottom pair of electrodes and the ITO plate is grounded.

In order to demonstrate that single droplets can be actuated at high throughput we superimposed a modulation frequency to the applied voltage. Both the flow rates and applied voltage are kept constant at 250:75:250 µl/hr and $1040V_{pp}$ respectively. A square wave of frequency between 10 Hz to 500 Hz is multiplied to a sinusoidal wave of fixed frequency of 50 KHz. Figure 3 shows the selected results at different modulation frequency.

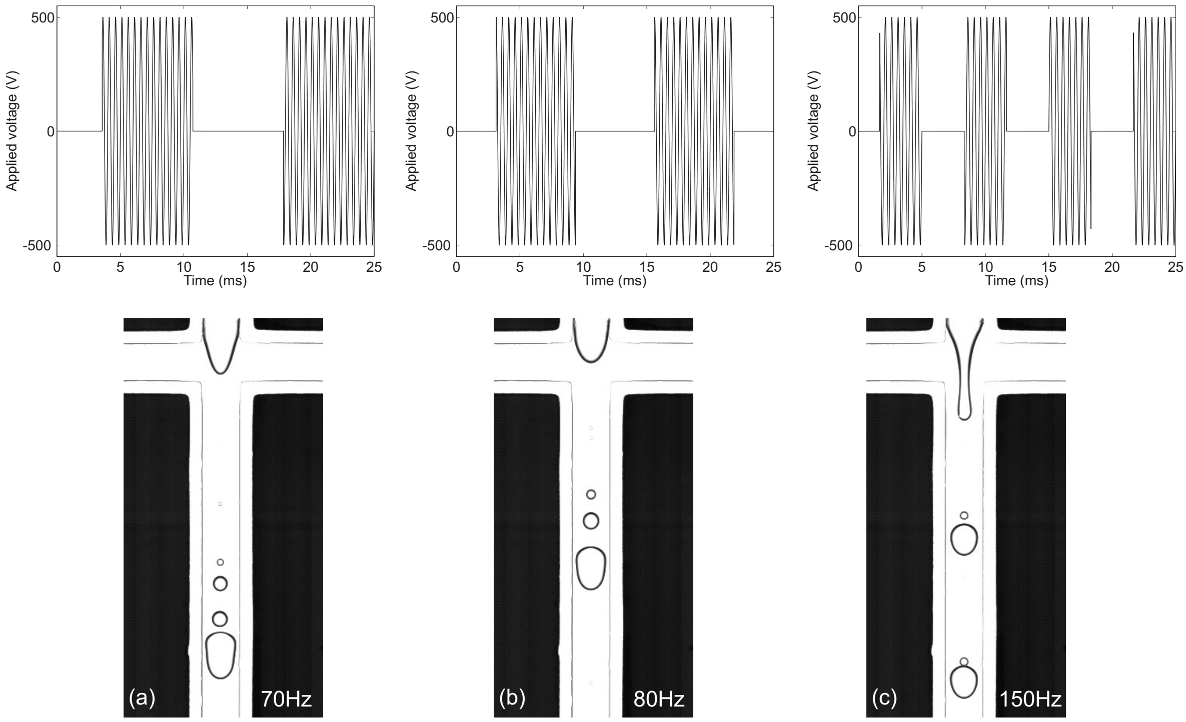


Figure 3: Controlled generation of different number of droplets. (a)4 successive droplets, (b)3 successive droplets and (c)2 successive droplets. The droplets are generated at fixed flow rates of 250:75:250 µl/hr and the droplet production frequency is about 140 Hz. For clarity, the displayed frequency (top figures) is 2 kHz (50 kHz in experiments).

When the modulation frequency is approximately equal to the droplet generation frequency, doublets of two distinct droplet sizes are produced. At lower modulation frequency of 70 and 80 Hz, triplets and quadruplets are generated as the applied frequency is lower than the droplet production frequency (140 Hz). This result demonstrated the single droplet manipulation which greatly enhances the usefulness of digital microfluidics in biochemical applications or as micro-reactors. Further experiments are planned to increase the modulation efficiency by changing the duty cycle of the modulation or pulsating the voltage between non-zeros values in order to navigate close to the transition where small changes in voltage induces larger changes of droplet sizes. Such experiments will generate a more diverse range of droplet patterns for the versatile control of emulsions structures and functions.

CONCLUSION

We have successfully demonstrated reliable control on the size of the droplets produced in a microfluidic flow focusing device using non-connected electrodes at different alternating voltages. The droplets produced are highly monodisperse and a transition in the droplet formation regime is also observed. At applied frequency of between 10 to 50 kHz, negligible differences are observed. At the higher total flow rate investigated, the change in the droplet sizes is much smaller because the jetting regime is observed even without electric field.

We have also demonstrated single droplet manipulation through the use of different modulation frequency. When the modulation frequency is approximately the same as the droplet production frequency, droplets of two distinct sizes can be produced in a controlled and reproducible manner.

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