Towards Droplet on Demand for Microfluidic Networks

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I. Introduction

Two-phase flow microfluidics, where the droplets flow in closed microchannels, is a promising platform for the realization of *Labs-on-Chips* (LoCs). In order to achieve specific functionality of LoC, it is crucial to be able to control the droplets' path throughout the microfluidic chip. Two approaches have been developed to guide the droplets towards selective locations on the chip: *Active Droplet Control* (ADC) and *Passive Droplet Control* (PDC). ADC uses integrated microvalves or externally applies electric forces, magnetic fields or surface acoustic waves. These means of manipulation can provide precise droplet control, but suffer from complex and costly fabrication as well as biocompatibility for some biological settings [1]. In contrast, PDC exploits only hydrodynamic principles to control the path of the droplet, and, thus, can be fabricated at low cost and offer a higher degree of chemical compatibility. For these systems, channel geometries and applied hydrodynamic forces are critical design parameters.

Recently, microfluidic networks for two-phase flow microfluidics (cf. [2], [3] and references therein), as well as corresponding design methods [4]–[6] have been introduced, which aims at realizing programmable and flexible LoC devices using PDC. In particular, microfluidic networking targets to dynamically assign the droplets' path through a microfluidic network in order to perform specific analyses. The key element in microfluidic networks are microfluidic switches, which are able to control the path of a single or multiple droplets, based on the distance between the individual droplets [2], [3]. However, the current microfluidic network research only includes little experimental work [7], [8], considering only single switches and trains of droplets with a given volume and distance.

In order to fully exploit the potential of microfluidic networks it is crucial to create individual droplets of desired volumes (microliter to nanoliter in volume) at a prescribed time and with precisely controlled droplet distances – motivating *Droplet on Demand* (DoD) solutions for microfluidic networks. Most of the reported DoD systems use integrated microvalves to control the flow of the fluids required for the droplet generation (e.g., [9]). However, these systems require complex fabrication and may introduce limitations in chemical compatibility. Only a few DoD systems externally controlling the fluids flow are proposed [10], [11]. In [10] a microfluidic flow-focusing geometry with a negative pressure induced at its outlet is used. However, this approach is not applicable for microfluidic networks, since the negative pressure would affect the functionality of the network. In [11], the flow of the continuous and dispersed phase in a T-junction is controlled through two external valves that are mutually switched on and off.

In this work we propose an alternative DoD system, which only needs to control the flow of the dispersed phase while keeping the flow of the continuous phase undisturbed[1]. We derive a mathematical model for the equilibrium state, which is an important step towards the practical realization of the proposed DoD system – a crucial accomplishment in order to exploit the potential of microfluidic networks for practical purposes.

II. Towards Droplet on Demand

A. Stable Droplet Formation

For the droplet formation we consider a T-junction. A stable droplet formation is obtained within the squeezing regime [13], which is conditioned with a low capillary number ($C_{\mathrm{a}} << 1$) and a recommended channel geometry ratio $0.33 < w_{\mathrm{D}}/w_{\mathrm{C}} < 3$ [13], where w_{D} and w_{C} denote the channel width of the dispersed and continuous phase, respectively. For the proposed DoD system we consider a T-junction with $w_{\mathrm{D}} = 150\ \mu$m and $w_{\mathrm{D}}/w_{\mathrm{C}} = 0.5$ and ensure $C_a << 0.01$. Moreover, we consider rectangular cross-sections of the channels with a uniform height of $h = 40\ \mu$m, satisfying $h < w_{\mathrm{C}}$ [1].

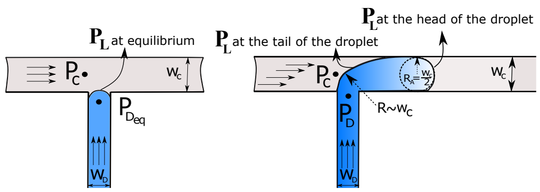
B. Equilibrium State

During the process of droplet formation, the system initially enters the equilibrium state as shown in Fig.1(a). In this state, the dispersed phase forms a stable interface with the continuous phase, but no droplets are formed due to the accurate balance of the input pressures

$$P_{\mathrm{D,eq}} = P_{\mathrm{C,eq}} + P_{\mathrm{L,eq}}, \tag{1}$$

where $P_{\mathrm{D,eq}}$ and $P_{\mathrm{C,eq}}$ are the equilibrium values of the applied pressures on the dispersed and continuous phase, respectively. The Laplace pressure $P_{\mathrm{L,eq}}$ corresponds to the pressure difference at curved interfaces between two immiscible phases. Once the system is in equilibrium state the droplet generation can be initiated on demand by overcoming the equilibrium forces, i.e. momentarily increasing the dispersed phase pressure $P_{\mathrm{D}} > P_{\mathrm{D,eq}}$. Similarly, the droplet is released by taking the system back to the equilibrium state, i.e. instantly reducing the

[1] A similar approach with a slightly different technical solution was proposed in [12], but without providing a thoroughly mathematical model.



(a) Equilibrium state (b) Non-equilibrium state

Fig. 1. A schematic illustration (top view) of the shape of the tip of the dispersed phase at two different states of droplet formation; P_C and P_D indicate pressure measuring positions for the continuous and dispersed phase

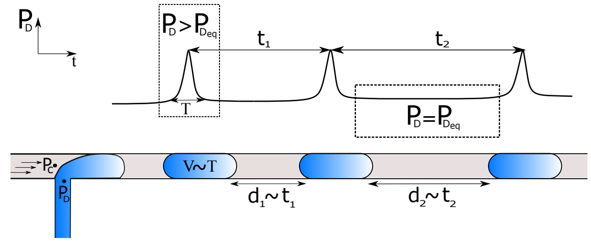


Fig. 2. Illustration of DoD generation using a series of positive pulses.

dispersed phase pressure to $P_D = P_{D,eq}$. In order to achieve the equilibrium state it is crucial to derive the Laplace pressure. Based on Fig. 1 the Laplace pressure for the proposed DoD system can be calculated as follows

$$P_{L,eq} = \gamma\left(\frac{1}{r_h}+\frac{1}{r_w}\right) = \gamma\left(\frac{2}{h}+\frac{2}{w_D}\right) = 15.83\,\text{mBar}, \qquad (2)$$

where γ is the interfacial tension between the continuous (oil) and dispersed (water) phase given by $\gamma = 25 \cdot 10^{-3}$ N/m. The r_w and r_h are the radii of curvatures due to the channel width and height. The droplet generation process starts with increasing the dispersed phase pressure above equilibrium ($P_D > P_{D,eq}$), and is carried as long as $P_D > P_C + P_L$ [1]. At this stage, the dispersed phase obstructs the continuous flow, thus creating the droplet, as shown in Fig.1(b). The droplet grows in size until the the moment when $P_C < P_D + P_L$, at which point the droplet breaks off from the dispersed phase. At the final stage, the dispersed phase recoils to the inlet channel and the equilibrium state ($P_D = P_{D,eq}$) is reinitiated [1]. Thus, the precise control of the dispersed phase pressure P_D enables the precise generation of droplets.

C. Droplet on Demand System

For the droplet on demand generation, we propose to apply a series of positive pulses to the dispersed phase, while maintaining the continuous flow undisturbed as shown in Fig. 2. The volume of generated droplets is proportional to the duration of the applied pulse, while the distance between consecutive droplets is proportional to the distance between consecutive pulses.

III. Next Steps

We will fabricate the proposed DoD system in *poly-dimethylsiloxane* (PDMS) polymer using standard soft lithography methods. We will use a pressure controller (Elveflow®, OB1MK3) to induce pressure to the continuous and dispersed phase. Moreover, the pressure controller is able to apply a sequence of pulses either through the Elveflow® Smart Interface or by using the provided Matlab libraries. For the evaluation of the the DoD system (droplet size and distance) we will use a high speed camera or a microscope together with a Matlab-based image processing software. After verifying the proposed DoD system we will, for the first time, experimentally validate the microfluidic networking concept [2], [3]. Moreover, we will compare our DoD system with other approaches (e.g., [11]).

IV. Conclusions

We have proposed a DoD system, which only requires an external control of the dispersed phase. We have derived the equilibrium state and suggested the use of pulses to overcome the equilibrium state and start the droplet generation. Finally, have discussed future work, including fabrication and evaluation of the proposed DoD system. The practical realization of the proposed DoD system is very important in order to fully exploit its potential for practical purposes (e.g., fast and flexible drug screening [14]) and to experimentally validate existing microfluidic networking concepts.

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