Pressure perturbation influence on the length and formation of immiscible liquid plugs in a T-shaped microchannel

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Abstract. The influence of input pressure perturbations on the plug length and plug formation stages during liquid-liquid plug flow was studied experimentally. Sine-shaped perturbations with amplitudes equal to 1 and 2 magnitudes of average pressure in the unperturbed flow were shown to have a strong influence on the plug length distribution. Stabilization of plug flow and reduction of plug length standard deviation was found for the perturbation period equal to the natural period of a system. The effect of backflow in the dispersed liquid entrainment was observed in the local minima of the perturbation signal.

1. Introduction
Miniaturization of technological devices is a trend of the last decades in a range of areas such as electronics, biology, chemistry, and medicine. Microfluidic devices working with small volumes of liquids have proved their ability to enhance heat and mass transfer coefficients dramatically and to increase the safety of the processes. Plug and droplet flow of immiscible liquids is widely used in microfluidic devices due to the benefits from the circulations inside plugs and slugs, leading to heat and mass transfer enhancement [1]. Moreover, plugs and droplets can be utilized as carriers for cells and bacteria or reservoirs for chemical reactions with the capacity of several picolitres [2,3]. The design of microfluidic devices demands the precise control of plug/droplet length, velocity, circulation values inside plugs and slugs at certain operational conditions.

There are passive and active methods for plug generation and its length control. The passive approach includes the adjustment of inlet flow rates of dispersed and continuous phases in combination with geometrical flow confinement owing to specific microchannel geometry: flow-focusing or T-junction. Several dependences were suggested to describe plug and droplet sizes depending on flow parameters in a passive way of plug generation. Garstecki et al. [4] elicited that the plug length is defined by the flow rate ratio of the phases at a squeezing regime when the capillary number is less than 0.01. Xu et al. [5] took into account the influence of shear stress on plug formation introducing a capillary number of carrying liquid into the equation of plug length for the case with moderate capillary numbers. The main drawback of the passive techniques of droplet generation is a limited degree of variance of plug and droplet size and break-up frequency at a defined flow parameters range [6]. Besides, the plug length is limited by the channel diameter from below and reaches its maximum when the transition to the continuous flow regimes, such as parallel, occurs.

Active droplet production methods are based on external actuation of the flow. This technique, called a droplet-on-demand approach, utilizes external forces, such as electrical, magnetic, mechanical, centrifugal, or modifies the intrinsic forces [7]. In [8], surface acoustic waves were introduced to the T-junction microchannel to control plugs length. The approach using dynamic changes in the dimensions of the flow-focusing device presented in [9] allowed controlling drop size and frequency. In the work of Li et al. [10], mechanical perturbation of the flow was applied to
precisely control the droplet size by tuning perturbation frequency. Another method to control the volume of drops was presented in [11]. The authors of this work varied the local temperature of the flow-focusing nozzle, which resulted in the change of the continuous phase viscosity. Most of the existing works on active methods of droplet production focused on external actuation of the flow with flow rates of the dispersed and continuous phases when the plugs or droplets are not formed without perturbations. Meanwhile, there is no information on how the fluctuation of the flow rate or pressure in the inlets of the microchannel will affect stable plug flow, plug length, velocity, and flow structure in continuous and dispersed phases.

The present study aims at elucidating the effect of pressure perturbation amplitude and frequency on stable plug flow of immiscible liquids in a T-shaped microchannel. Using high-speed flow visualization and micro-PTV technique, the plug length and the flow structure inside plugs are obtained. The effect of the ratio of flow perturbation frequency to the frequency of the plug break-off without perturbation is shown.

2. Experimental setup

The experiments were performed in a T-shaped microchannel made of PMMA material by machine milling. The dimensions of the microchannel are shown in Figure 1 where a, b and c are equal to 200, 400, and 200 µm, respectively. The length of the outlet channel is equal to 22.5 mm, which corresponds to 84 hydraulic diameters. The roughness of the walls is less than 1 µm. Castor oil (with density of 962 kg/m³, and viscosity of 760 mPa·s) is used as a continuous phase; and distilled water (with density of 997 kg/m³, and viscosity of 0.89 mPa·s) is used as a dispersed phase. The interfacial tension between phases is equal to 15.6 mN/m.

![Figure 1. The schematic diagram of the experimental setup for pressure perturbations in a T-shaped microchannel.](image)

The flow was operated using the Elveflow OB1 pressure controller with two independent pressure sources, which allowed changing the pressure from -900 to 6000 mbar with 40 ms settling time. The schematic diagram of equipment arrangement is presented in Figure 1. The nitrogen gas cylinder was
used as a pressure supply for the pressure controller. The outlets of the pressure controller were connected to the pressurized reservoirs containing castor oil and distilled water. The flow from the pressurized reservoirs was fed to flow restrictors, i.e., long capillaries with hydraulic diameters of 100 and 160 μm. The length of capillaries was adjusted so that pressure drop along them was not less than 90% of the whole system pressure drop, which allowed performing system flow rate calibration. Flow visualization was done at the T-junction and the end of the microchannel using high-speed CMOS with a 500 Hz frame rate and an inverted microscope with a 5x magnification lens. Fluorescent particles with 2 μm diameter were added in the water and illuminated by Nd:YAG laser to measure velocity fields in the center plane of the channel. Resulting velocity fields were calculated using PTV (Particle Tracking Velocimetry) algorithm applied to the images of tracer particles.

3. Results and discussion

3.1. Plug length

The flow pattern under study was the plug flow at different inlet conditions. Inlet pressures varied within the following ranges: $1000 < P_{co} < 2500$ mbar, $150 < P_{w} < 300$ mbar for the castor oil and the distilled water, respectively, which corresponds to flow rate ranges $3.34 < Q_{co} < 8.34$ µl/min and $11.21 < Q_{w} < 22.41$ µl/min. Typical pictures of plugs and their lengths in unperturbed stable flow are presented in Figure 2. Natural periods of plug breakage $T_0$ for concerned case are of the order of magnitude of several seconds. We applied external perturbations in the form of sine signal with periods proportional to $T_0$ with factors of 0.25, 0.5 ... 2, and magnitudes equal to $P_{avg}$ and $2P_{avg}$, where $P_{avg}$ is the inlet pressure in unperturbed flow.

![Figure 2. Typical images of plugs in the flow without external perturbations and corresponding plug length distribution over time.](image-url)
3.2. Plug formation mechanism

To elucidate flow structure in a dispersed phase, micro-PTV measurements of velocity fields in the middle of the channel cross-section were performed. Measurements were synchronized with a phase of external perturbation signal. Four different phases of the signal were studied: local minimum, local maximum, and $P_{avg}$ point with positive and negative first derivative. Example of velocity distributions in the dispersed phase for two different signal phases and various stages of plug formation at $T=0.25T_0$ are presented in Fig. 5. The case of $P_{avg}$ point with positive derivative (phase 2 at the right side of Fig. 5) is similar to the unperturbed flow case, which is not presented here. Three different stages of plug
formation can be highlighted: I - squeezing of the water entrainment by the continuous phase, when a plug is growing due to increased water velocity; II - plug breakage and fast retraction of liquid entrainment to initial position; III - the slow growth of water entrainment influenced by shear from the continuous liquid. All these stages are strongly affected by external pulses at local minima and maxima of the perturbation signal. One of the main effects is a backflow inside liquid entrainment, which can be observed on the left side of Fig. 5. This backflow arises at the local minima of perturbation signal and can lead to the plug length change when occurring at stage I. However since plug length is weakly affected by perturbation at $T<T_0$ this effect can be used to enhance mass transfer in the extraction process due to additional recirculation of liquid in the plug formation region.

Figure 5. Velocity distribution in plug formation zone at external perturbation with $T=0.25T_0$ and a magnitude $A = P_{\text{avg}}$. 
Conclusion

The influence of external perturbations on the plug flow of immiscible liquids inside the T-shaped microchannel has been studied experimentally. External perturbations with a magnitude equal to one and two times average pressure in the unperturbed flow are shown to have a strong impact on the resulting plug length. The ratio of the perturbation period to the natural period of the liquid-liquid microfluidic system is found to be a crucial parameter, which determines plug length distribution. Stabilization of plug flow and reduction of plug length standard deviation is observed for $T=T_0$ and $T=T_0/2$. At $T<T_0$, influence of perturbations is less pronounced than at $T>T_0$. Average plug length and its standard deviation are found to increase with the period of perturbation signal for $T>T_0$.

Velocity fields have been measured inside the dispersed phase at the plug formation area. The effect of backflow in the dispersed liquid entrainment is observed in the local minima of the perturbation signal. This effect can be useful for mixing and mass transfer enhancement in the plug formation area.

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