

Experimental investigation of pressure disturbances influence on a parallel flow of viscous immiscible liquids in a T-shaped microchannel

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Abstract. In the present paper pressure disturbances influence on parallel flow of immiscible liquids, *viz.* castor oil and paraffin oil, in a T-shaped microchannel with 320 μm hydraulic diameter is studied experimentally. Pressure disturbances with sinusoidal and meander wave shape were applied at different frequencies and pulse ratio to the flow of carrying phase, dispersed phase or both of them simultaneously. It was shown that pressure disturbances can lead to the transition to the slug flow. A parameter taking into account signal amplitude and frequency was introduced for flow map construction. Slug length and velocity was measured for all regimes studied.

1 Introduction

In recent years flows of immiscible liquids in microchannels have become of a great interest to study. Using liquid-liquid flows in microchannel can enhance such technological processes as chemical reactions [1], biological analysis [2], microparticle production [3], *etc.* However, in most of applications it is essential to operate devices in a slug or droplet flow regime, where elongated bubbles or drops of a dispersed phase are carried by continuous one. Usually, passive methods of a droplet generation are used for this purpose, but they have a lot of drawbacks such as a narrow range of slug flow existence, high dispersion of slug lengths, geometric limitation of a slug length for low flow rates.

A number of research works on active droplet generation were performed to overcome the problems listed above. Bransky et al. applied a piezoelectric actuator for droplet generation in a liquid-liquid flow [4]. In their setup an actuator perturbed constant flow rate of dispersed phase in T-shaped and cross-flow microchannel geometry. High droplet uniformity was shown in such droplet generator. Cheung et al. conducted a comprehensive study of acoustic disturbances created by a piezoelectric actuator on the flow of immiscible liquids in a flow-focusing microchannel geometry [5]. They studied viscosity influence of a continuous phase and a frequency of disturbances on the process of droplet generation in the squeezing regime. In the case of a more viscous carrier fluid, the effect of disturbances

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was less pronounced due to the partial energy dissipation by viscous forces. In works [6] and [7] a piezo actuator was used to generate droplets in systems of immiscible liquids with low interfacial tension. The perturbation signal in the form of a meander was applied, the droplet size dependence on frequency was obtained, and a simple equation was proposed for droplet size estimation.

Although there are different ways of active droplet generation, the effect of disturbances in two-phase flows in microchannels remains poorly understood. Most of works in the field are aimed at creating or designing a specific device for generation of droplets with a certain size, while there is a lack of studies of the disturbance influence on flow pattern maps and physics of flows. In the present study we consider disturbances influence on a parallel liquid-liquid flow with high viscosity in a T-shaped microchannel. Different signal shapes, frequencies and amplitudes were applied to the flow of carrying phase, dispersed phase or both of them simultaneously. Flow disturbances were shown to cause a transition from parallel to slug flow regime. Length and velocities of resulting slugs were investigated.

2 Experimental setup and procedures

In the present work paraffin oil and castor oil were used for flow regimes visualization in a T-shaped microchannel. Measured liquid properties are noted in Table 1. The T-shaped microchannel used is made of SU-8. Castor oil wetting angle of channel walls is much smaller than of paraffin oil, which leads the paraffin oil to be a dispersed phase. The inlet channels cross-section has dimension of 200x400 μm , the outlet channel cross-section has dimension 200x800 μm , which corresponds to 360 μm hydraulic diameter. The length of inlet and outlet channels is 11.5 and 22.5 mm, respectively which is sufficient to get steady flow. For flow visualization pco.1200 hs high speed camera and inverted Zeiss Axio Observer.Z1 microscope with 5x magnification lens were used. Halogen lamp was used for flow illumination. Flow visualization was done at the T-zone and at the end of the channel, which is 84 channel hydraulic diameters far from T-zone.

Table 1. Physical properties of liquids.

	Paraffin oil	Castor oil
Density, kg/m^3	845	935
Viscosity, $\text{mPa}\cdot\text{s}$	110	650
Interfacial tension, mN/m	17	
θ (liquid-liquid-substrate), deg	152	25

Liquids were injected in the channel by Elveflow OB1 pressure controller with two independent outlet channels. The controller is able to set the pressure in the range from -900 to 6000 mbar with 40 ms settling time. The inlet channel of the pressure controller was connected to the vessel with nitrogen, while outlet channels were connected to reservoirs filled with liquids.

In order to maximize the pressure range and to perform calibration of the system flow restrictors, *viz.* long capillaries with diameters of 100 and 170 μm , were imbedded between flow reservoirs and microchannel inlets. The length and diameter of the capillaries were chosen so that pressure drop along them was not less than 90% of the whole system pressure drop. That allowed performing system calibration. The flow rate dependence on the controller outlet pressure was established by weighing of the liquid flowing out from the system for a specific time.

The flow under the study was parallel flow regime. The pressure applied on the both outlet channels of the pressure controller was equal to 100 mbar, which, according to the system calibration, leads to flow rate of castor oil and paraffin oil equal to 0.17 $\mu\text{l}/\text{min}$ and 0.24 $\mu\text{l}/\text{min}$, correspondingly. Pressure disturbances with sinusoidal and meander signal shape were applied to the reservoir with paraffin oil, castor oil or to the both of them simultaneously. The average pressure for the cases studied was kept constant and equal to 100 mbar. The signal amplitude ($P_{\text{max}}-P_{\text{min}}$) was varied from 1 to 2 of average pressure for sinusoidal signal and from 0.5 to 2 of average pressure for meander signal. For meander signal different pulse ratio from 0.5 to 2 was also studied. Pressure disturbances of both liquid flows simultaneously were applied with 0 and 180⁰ phase lag. The periods of pressure disturbances signals varied from 20 to 80 s.

3 Results and discussion

Flow visualization showed that at certain pressure disturbances parameters the transition to the slug flow occurs. The examples of flow images at the end of the channel are presented in Figure 1.

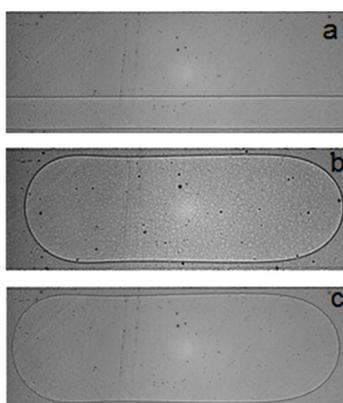


Fig. 1. a) Parallel flow regime without pressure disturbances b) Slug flow, sinusoidal disturbances of continuous phase, $T = 60$ s c) Slug flow, meander disturbances of continuous phase, $T = 60$ s.

In order to sum up visualization results into flow pattern map the dimensional analysis of physical variables affecting the flow was performed. As soon as mean velocity and channel hydraulic diameter was kept constant they were excluded from the analysis. The physical variables are disturbance frequency f and amplitude A , liquid viscosity μ , interfacial tension σ and liquid density ρ . Combining these variables in power series terms, neglecting higher order terms and substituting the dimensions of the corresponding physical variables, the following dimensionless group was obtained:

$$K = A \cdot \frac{\rho \sigma^2}{f \mu^3} \quad (1)$$

Here A is non-dimensional disturbance amplitude which can be expressed as the maximum deviation of pressures applied to both liquids divided by the sum of average pressures which is equal to 200 mbar:

$$A = \frac{|P_{po} - P_{co}|_{\text{max}}}{[P_{po} + P_{co}]_{\text{avg}}} \quad (2)$$

The application of parameter K calculated for both liquids allowed construction of flow pattern map. Flow pattern maps for sinusoidal and meander signal shapes are presented in Figure 2 (left and right, correspondingly). One can see that the transition from parallel flow to slug flow occurs at $K_{po} \approx 4000$ for paraffin oil and $K_{co} \approx 20$ for castor oil for both shapes of signals. It is worth to note that the value of the parameter at which the regime change occurs does not depend on whether one or both liquids are subjected to disturbances.

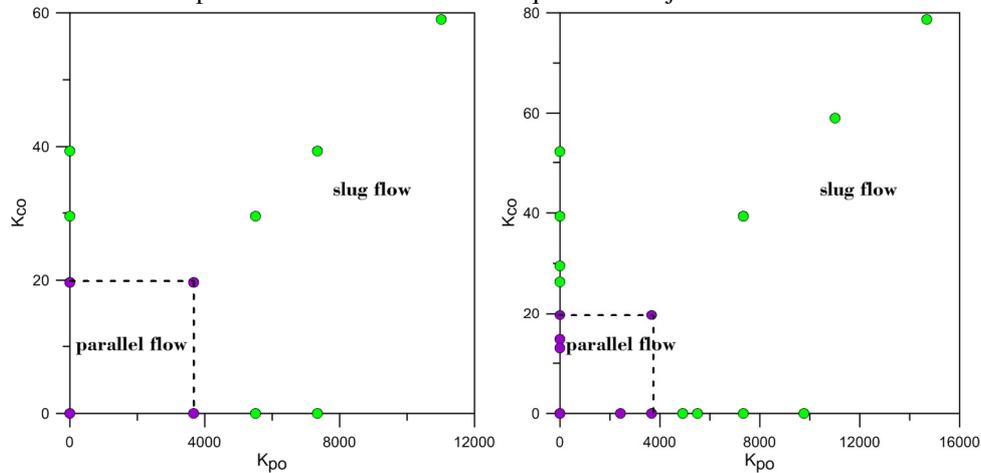


Fig. 2. Flow maps for paraffin oil - castor oil flow with pressure disturbances. Left: sinusoidal pressure signal shape. Right: meander pressure signal shape.

Slug lengths and velocities were measured using ImageJ software for all applied cases of pressure signals and were summed up into the plots presented in Figure 3. It was found that slug length L is mainly determined by the period of pressure signal T and almost independent on other parameters, such as signal amplitude and pulse ratio. Slug velocity V_{slug} is found to be independent on the period of signal. One of the main observations consists in that slug length and velocity has much narrower distribution ($\approx 2\%$) in the case of pressure disturbance application with sinusoidal signal to both phases with 180° phase lag. The frequency of slug break-off was equal to the pressure signal frequency for all the cases studied.

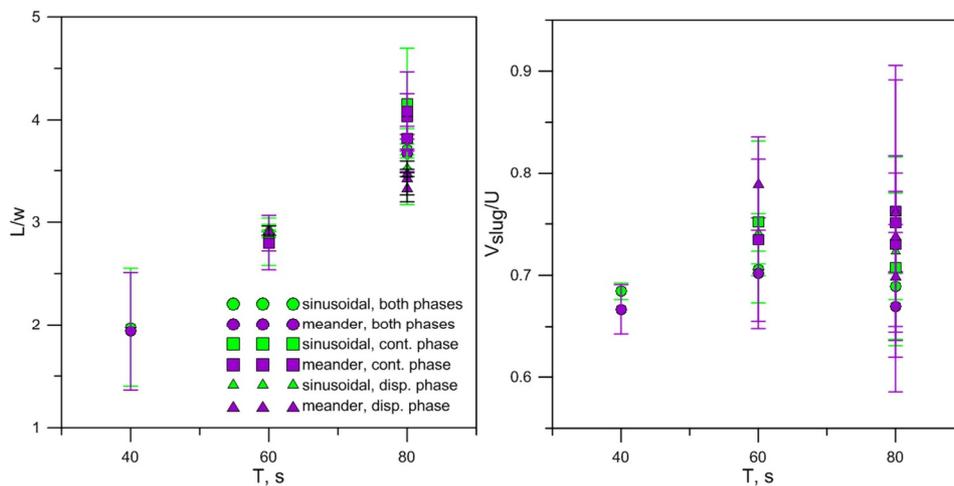


Fig. 3. Slug length L normalized by channel width w (left) and slug velocity V_{slug} normalized by bulk velocity U (right) in dependence of pressure disturbance period T .

4 Conclusion

Pressure disturbances with high amplitude and low frequency influence on the parallel flow of viscous immiscible liquids in a T-shaped microchannel was studied experimentally. The transition to the slug flow regime was observed. A non-dimensional parameter was introduced to determine the boundary between slug and parallel flow and to construct flow pattern map. Slug lengths and velocity were measured for all the cases studied. It was found that pressure disturbances with sinusoidal signal shape applied to both liquids lead to very narrow slug length and velocity distribution. The last can be useful in design and optimization of microdevices operating with immiscible liquids.

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