Dynamics of Shear-Induced Drop Formation in T-Shaped Microchannels

Joeska Husny¹, Hengyi Jin², Erol Harvey¹, Justin Cooper-White¹*

¹Department of Chemical and Biomolecular Engineering, Particular Fluid Processing Centre, The University of Melbourne. Parkville, Victoria 3010, Australia.
²Industrial Research Institute Swinburne, Swinburne University of Technology 533-545 Burwood Road, P.O.Box 218. Hawthorn, Melbourne. Victoria 3122, Australia.
*corresponding author: jcw@unimelb.edu.au

Abstract

A study of drop formation under cross-flow conditions within a T-shaped polycarbonate microchannel was performed. Monodisperse water drops were formed in cross-flowing silicone oil. The drop size was found to decrease with increasing cross-flow velocity under the low cross-flow velocity conditions studied (i.e. below 0.01 m/s). The dependency of drop size on the cross-flow velocity decreased with higher dispersed phase flowrates.

Keywords: Drop formation, shear, microchannel, Laser-LIGA

1. Introduction

It is widely acknowledged that monodisperse micro drops have numerous applications in analytical chemistry, medical and bio-medical science. Such applications often require precious chemical substances or biological fluids to be delivered in minute amounts but still enclosed in the form of droplets or bubbles for further processing. This minimizes premature chemical reactions or unnecessary degradation of the products. Current technological advances in microfluidics have led to the development of many new ideas for microdevice applications. T-shaped microchannels have been used previously to produce monodisperse drops by simple shear-induced detachment [1,2]. Despite the fact that several methods have been attempted to produce microdrops with microfluidic devices, the fundamental physical understanding of drop formation using these various techniques is not well understood. Drop formation behaviour from a nozzle in quiescent, co-current and counter-current flow has been studied extensively in the past [3,4]. However, fluid behaviour in a macroscale device is very different to that in a microscale device where surface forces are dominant. In this paper, a T-shaped microchannel was used to provide detailed insight into the physics of drop formation by shear-induced detachment in a cross-flow environment.
2. Theory

The dominant forces in drop formation by shear-induced detachment within a T-shaped microchannel are shown in Figure 1 and defined in equations 1-6. In this configuration, two immiscible liquids are introduced from different inlets to create dispersed and continuous phase flows. The growth and detachment stages of the drop are governed by forces associated with shear or drag, which depends on the continuous phase average velocity, surface tension, buoyancy, momentum and inertia of both phases. The final drop volume at the end of the growth and detachment stages is determined by the balance of forces at the point of detachment. The drop is formed once the force balance is achieved (Equation 6).

\[ F_D = \frac{1}{2} \rho u_{eff}^2 A_{eff}^2 \]  
\[ F_S = \sigma \pi D_N \eta n(\phi) \]  
\[ F_I = \frac{d}{dt} \left( M \frac{dS}{dt} \right) \]  
\[ F_M = \rho_d \frac{Q_d^2}{\eta D_N^2} \]  
\[ F_B = \frac{\pi}{6} D_d^3 (\rho_c - \rho_d) g \]  
\[ F_D + F_S + F_I + F_B + F_M = 0 \]

where \( F_D \), \( F_S \), \( F_I \), \( F_M \) and \( F_B \) are the drag force, surface tension force, inertia force, momentum force and buoyancy force respectively. \( A_{eff} \) is the projected area of the drop, \( D_d \) is the drop diameter, \( D_N \) is the dispersed phase channel diameter, \( M \) is the drop mass, \( \rho \) is the fluid density, \( S \) is the moving distance of the drop, \( u_{eff} \) is the effective average velocity in the channel and \( C_D \) is the drag coefficient.

3. Experiments

Two high accuracy syringe pumps PHD 2000 from Harvard Apparatus were used to inject both the continuous and dispersed phase fluids into the microchannel. A Nikon Inverted Microscope TE-2000 and a Phantom V5 CMOS High Speed Video Camera
were used for high speed imaging purposes. The drop diameters were determined by pixel measurement from the images obtained. Bisphenol-A polycarbonate (PC) sheets with different thicknesses were purchased from GoodFellow Corporation. Silicone oil (50 cst), supplied by Dow Corning, was used as the continuous phase. Distilled and deionised Milli-Q water was used as the dispersed phase. T-shaped microchannels were fabricated based on excimer laser ablation and LIGA concepts. The T-shaped microchannel widths are 60 μm and 300 μm for the dispersed phase channel and continuous phase channel respectively with the depth of 100 μm (Figure 2).

Figure 2. (a) SEM images of T-shaped microchannel made by modified laser-LIGA method. (b) drop generation visualised by an optical microscope.

4. Results and Discussion

Figure 3 shows the measured drop size as a function of the continuous flowrate \( Q_c \) and dispersed flowrate \( Q_d \). The velocities studied were all below 0.01 m/s for the continuous phase with Weber numbers of the order of 10^6. At such low velocities, surface tension is the dominant force and controls the drop formation behaviour. The measured drop size was found to decrease with increasing cross-flow velocity (continuous flowrate). This behavior can be explained by the fact that at a higher cross-flow velocity, a higher shear force near the wall is present. This leads to a decrease in the drop growth and detachment time, resulting in a reduction in final drop volume. The effect of dispersed flowrate on drop size in these low cross-flow velocity conditions have not been studied previously. It can be seen from Figure 3 that the slope of \( Q_c \) versus \( D_d \) generally decreases with decreasing \( Q_d \) value. This means that drop size dependency on dispersed phase flowrate \( Q_d \) is smaller at higher \( Q_d \). The change in the drop size is larger for lower \( Q_d \) than at the higher flowrates with the same change of the continuous phase flowrate. At higher dispersed phase flowrate, the momentum force and inertia force of the dispersed phase generated during the formation of the drop are high enough to match the opposing drag force. This leads to a smaller effect of the drag force on changes in drop size for higher \( Q_d \). For lower \( Q_d \), the drag force is the major force compared to the momentum and inertia forces associated with the flowrate.
5. Conclusions

In this study, we have demonstrated the effect of both continuous and dispersed flowrates on the drop size in a T-shaped microchannel. Drop size was found to decrease with increasing cross-flow velocity. This result confirms the works done by many researchers in this area both in macro-scale and micro-scale devices. The effect of cross-flow velocity on the drop size was found to be dependent on the dispersed phase flowrates. Drop size became more independent on cross-flow velocity with increasing dispersed phase flowrate. Future work will concentrate on investigations into the effect of different viscosity ratios and surfactant concentration on the dynamics of drop formation.

References