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Modeling and analysis of multiphase flow in flow-focusing microchannel

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Highlights

- Numerical investigation of microfluidic droplet formation is presented using CLSVOF method.
- Scaling laws are proposed to address the effect of shear thinning behavior on droplet length.
- Flow regimes are identified based on droplet shape and breakup mechanism.

1 Introduction

Over the last decade, research on microfluidic devices having dimensions in the sub-millimeter scale has significantly increased owing to process intensification demands. In a microfluidic device, each droplet provides a compartment microreactor in which species transport or reactions can occur. Recently, there has been a rapid development on emulsion generation in microfluidic devices. Flow-focusing device is one of the most effective microfluidic methods for production of uniform droplets. Interestingly, most of the reported research are concerned with the droplet formation mechanism and flow regimes in Newtonian fluids, while in several applications, liquid phases are likely to exhibit complex behaviors, such as non–Newtonian properties. For the design of microfluidic devices operating in liquid-liquid droplet/plug flow, knowledge of hydrodynamic parameters such as, near-wall film thickness, droplet/plug length, velocity and pressure drop is of paramount importance. Here, Newtonian and non-Newtonian droplet/plug flow formation is investigated numerically to understand the effect of rheological properties, interfacial tension, and flow rate ratio on droplet characteristics. In addition, velocity and pressure fields in both phases are also analyzed for the insight on droplet formation mechanism.

2 Computational model

A three–dimensional square flow–focusing device having 600 μm width and 600 μm depth is considered for the analysis. The dispersed phase (oil) and the continuous phase (glycerol and xanthan gum) are introduced from the main channel and two side channels, respectively. In this study, coupled level–set and volume–of–fluid (CLSVOF) method [1] is used to overcome the deficiencies of the level set as well as the volume–of–fluid method. A finite volume solver is utilized to solve the governing partial differential time dependent equations.

3 Results and discussion

Firstly, the developed CFD model is validated with the experimental data of Fu et al. [2] for droplet formation phenomena, which showed good agreement. It is then extended for understanding the influence of various rheological and physical parameters on droplet formation phenomenon. Different concentrations of xanthan gum solutions are considered as the continuous liquid phase. The fluid properties of the continuous and dispersed phases are taken from the literature [3]. It is

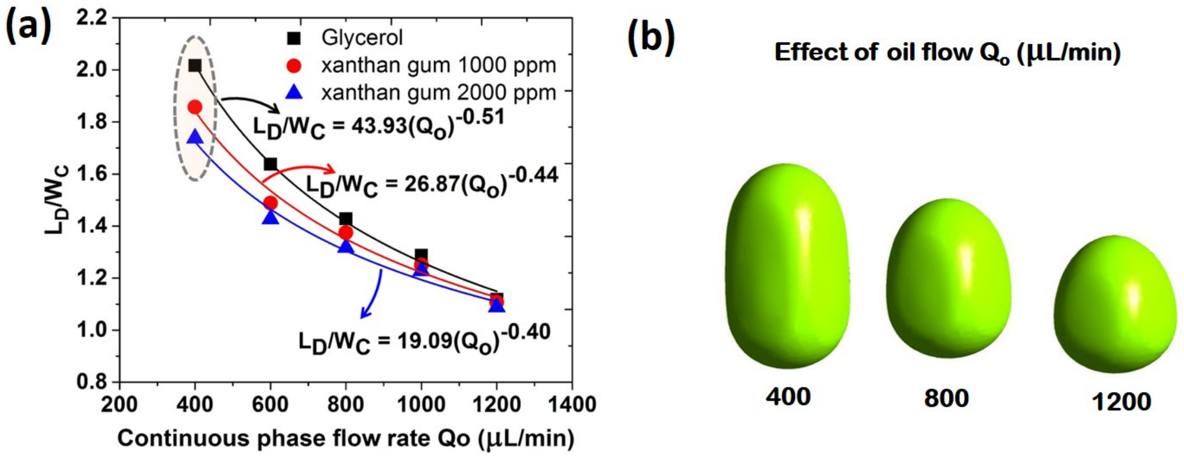

Figure 1: (a) Scaling of non-dimensional droplet length and (b) effect of continuous phase flow rate on droplet shape at fixed $Q_o = 400\ \mu L/min$.

found that the evolution of dispersed phase is considerably influenced by the continuous phase viscosity. In the droplet growth stage, nose of the droplet partially blocks the outlet channel, which impedes the flow of continuous phase. At the cross junction, continuous phase squeezes the dispersed phase symmetrically and pushes the droplet for detachment. Droplet length decreases with increasing xanthan gum concentration as shown in Fig.1a with dotted enclosure. This is due to increase in effective viscosity of the continuous phase. Droplet length also decreases with increasing continuous phase flow rate for all the solutions. However, at higher flow rate, droplet length is almost identical in all cases. Simple power-law relations are proposed for the solutions with a maximum deviation of 3%. Interestingly, a noticeable change in droplet shape from plug to near spherical shape is observed with increasing continuous phase flow rate, as illustrated in Fig.1b. Velocity field inside the droplet is also examined, which is found to increase with increasing the xanthan gum concentration due to higher viscous stress.

4 Conclusions

A comprehensive computational study of Newtonian droplet formation in non–Newtonian power-law liquids is carried out in a flow-focusing microchannel using CLSVOF method. With increasing xanthan gum concentration and continuous phase flow rate, droplet length is found to decrease as effective viscosity and shear force increases. Scaling laws are proposed to predict the droplet length in flow-focusing device for various operating conditions. This work effectively emphasizes the importance of controlling viscosity, continuous phase flow rate, and interfacial tension in formation of desired shaped droplets.

References

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Keywords

Multiphase flow, CLSVOF, Non-Newtonian liquid, Microreactor, Droplet