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Lattice Boltzmann Simulation of Droplet Formation in Non-Newtonian Fluids

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Abstract. Newtonian and non-Newtonian dispersed phase droplet formation in non-Newtonian continuous phase in T-junction and cross junction microchannels are investigated by the immiscible lattice BGK model. The effects of the non-Newtonian fluid power-law exponent, viscosity and interfacial tension on the generation of the droplet are studied. The final droplet size, droplet generation frequency, and detachment point of the droplet change with the power-law exponent. The results reveal that it is necessary to take into account the non-Newtonian rheology instead of simple Newtonian fluid assumption in numerical simulations. The present analysis also demonstrates that the lattice Boltzmann method is of potential to investigate the non-Newtonian droplet generation in multiphase flow.

AMS subject classifications: 76T10, 68U20

Key words: Droplet, non-Newtonian fluid, lattice Boltzmann method, multiphase flow, microchannel.

1 Introduction

Monodispersed droplets have been generated via a number of methods in microfluidic devices, among which T-junction and cross junction microchannels are the most popular devices. The wide usage of T-junction and cross junction is due to the ease of droplet generation and uniformity of the formed droplets. Thorsen et al. [1] were the first to observe water droplet formation in oil in microchannel, and they found that the droplet generation was dominated by the relationship between the shear stress forces and the interfacial tension in the microfluidic device. Ever since, droplet formation by T-junction has been extensively studied by many scholars. De Menech et al. [2] identified the three distinct regimes during the formation of droplets: squeezing, dripping, and jetting by

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the diffuse interface method. Garstecki et al. [3] established a simple scaling law for the length of the droplet that was independent of the capillary number and merely related with the flow rate ratio of the two immiscible fluids. Liu and Zhang [4] systematically investigated the influences of capillary number, viscosity ratio of two phases, and flow rate ratio on water droplet generation in oil fluid in cross junction by using the lattice Boltzmann method. Tan et al. [5] prepared water droplet generation in oil phase (W/O) and oil droplet generation in water phase (O/W) in cross junction experimentally, and they found that the dispersed plug decreased with the increase of continuous phase viscosity, while increased slightly with the increase of dispersed phase flow rate.

From the available literature, it is clear that the W/O or the O/W in T-junction and cross junction microchannels has been broadly numerically studied [6–9]. For simplicity, the oil phase is usually considered as the Newtonian fluid. However, oil is non-Newtonian fluid indeed, therefore the shear stress property of the non-Newtonian fluid could not be ignored. Besides, emulsions are mixtures that have rheology properties far from those of a simple molecular fluid having a Newtonian viscosity, so considering the oil phase and emulsion as non-Newtonian fluid is more practical and reasonable.

Up to now, very limited works have been reported on the droplet generation in non-Newtonian fluid in microchannel. Qiu et al. [10] numerically investigated oil droplet formation into continuous phase fluid through a microchannel made of apertured substrate, and they found that the rheology of the continuous phase affected the formation and size of the droplet greatly. Sang et al. [11] investigated the viscosity effect for power-law fluid and Bingham fluid on droplet formation in T-shaped microchannel. The commercial software FLUENT package was employed in the both works.

Simulation of two immiscible Newtonian and non-Newtonian fluid flow in complicated geometry is a complex work, and a systematic understanding of the relevant physics of droplet generation in non-Newtonian fluids is still lacking. It is necessary to distinguish the different characteristics of Newtonian and non-Newtonian droplet generation in the Newtonian and non-Newtonian fluid, so as to provide desirable emulsions of a highly controlled uniform size. In recent years, the lattice Boltzmann method has been proved to be a powerful method to simulate complex flow problems, including single phase non-Newtonian fluid flow in microchannels [12], multiphase fluid flow [13], and single phase Newtonian or non-Newtonian fluid flow in porous media [14, 15], etc. Therefore, the lattice Boltzmann method is of potential to simulate non-Newtonian fluid for multiphase flow in complex geometry.

The goal of this paper is to provide deep insight into the process of Newtonian and non-Newtonian droplet generation in the non-Newtonian fluid in both T-junction and cross-junction microchannels using the lattice Boltzmann method. To the authors' best knowledge, the lattice Boltzmann method has not yet been extended to study non-Newtonian multiphase flow. Here, we attempt to show that the lattice Boltzmann method is effective to simulate the droplet generation in non-Newtonian fluid in T-junction and cross junction microchannels.

In the next section, the phase-field theory and the immiscible lattice BGK model for