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Effects of Inertia and Viscosity on Single Droplet Deformation in Confined Shear Flow

Samaneh Farokhirad[1], Taehun Lee[1,*] and Jeffrey F. Morris[2]

[1] *Department of Mechanical Engineering, City College of City University of New York, New York, New York 10031, USA.*
[2] *Department of Chemical Engineering and Levich Institute, City College of City University of New York, New York, New York 10031, USA.*

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Abstract. Lattice Boltzmann simulations based on the Cahn-Hilliard diffuse interface approach are performed for droplet dynamics in viscous fluid under shear flow, where the degree of confinement between two parallel walls can play an important role. The effects of viscosity ratio, capillary number, Reynolds number, and confinement ratio on droplet deformation and break-up in moderately and highly confined shear flows are investigated.

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Key words: Lattice Boltzmann method, droplet deformation, confinement.

1 Introduction

The problem of deformation and break-up of an immiscible droplet in shear flows has been studied extensively since the original experiments by Taylor [1]. This problem is of great interest in many science and engineering applications such as emulsification processes, e.g., food industry, polymer blending and oil recovery, and in deformation of biological cells [2]. In these processes two immiscible fluids are mixed to obtain a distribution of droplets of one of the liquids in the other. Therefore, many investigations have been carried out from experimental, numerical, and theoretical points of view, and have shown that droplet deformation in shear flows are governed by four dimensionless parameters, namely, the capillary number (Ca) based on matrix fluid, the Reynolds number (Re) based on the matrix fluid, the viscosity ratio of the droplet viscosity to that of matrix fluid (η) [3], and the confinement ratio defined as the ratio of droplet diameter to the wall separation.

*Corresponding author. *Email addresses:* `farokhirad@gmail.com` (S. Farokhirad), `thlee@ccny.cuny.edu` (T. Lee), `jmorris@che.engr.ccny.cuny.edu` (J. F. Morris)

Megias-Alguacil *et al.* [4] performed an experimental study of droplet deformation under simple shear flow. They used the boundary integral method (BIM) as a numerical tool for validation of the experiment and for measurement of droplet deformation for a wide range of viscosity ratios. Several different values of the capillary number were considered for each η under different experimental conditions. The results showed that the major axes of a steady droplet fit the experimental ones, especially at lower capillary numbers. Chang-Zhi *et al.* [5] performed a three-dimensional (3D) numerical study. They investigated the deformation of a droplet in shear flow with unit viscosity ratio using diffuse interface method.They compared the values of deformation parameter with the results obtained by the volume of fluid (VOF) method [6], and concluded that the deformation parameter increased with the capillary number. Janssen *et al.* [7] introduced a new boundary integral method and applied it to study droplet deformation under shear flow between two parallel walls for non-unit viscosity ratio systems. For this purpose, the Green's function was modified to obey the no-slip condition at the walls. It was found that for moderate capillary numbers, the behavior of low-viscosity droplets are similar to that of droplets with unit viscosity ratio. The results also showed that for high viscosity ratio, as the confinement ratio increases the possibility of droplet rotation decreases, leading to a larger deformation and less overshoot in the droplet axes.

Inamuro *et al.* [8] presented a lattice Boltzmann method (LBM) for multi-component immiscible fluids for various values of viscosity ratios with density ratio of unity. They used the method to investigate the deformation and break-up of a droplet in shear flows with confinement ratio of 0.5. The simulation results showed that increasing the Reynolds number leads to easier deformation and break-up. Wagner *et al.* [9] used the lattice Boltzmann method to investigate the effect of inertia on the deformation and breakdown of stability of a 2D droplet surrounded by a fluid of equal viscosity in confined geometry. They showed that the increase in inertia produced larger deformation. More recently, van der Sman *et al.* [10] carried out a 2D numerical study to examine the effects of dimensionless parameters on deformation and break-up of an emulsion droplet in simple shear flow for various capillary number and viscosity ratios up to 5. It was observed that at increased viscosity ratios, the droplet deformation increases. A significant deviation from the ellipsoidal shape was seen at high capillary numbers. They also showed that the realistic physical behavior of droplet deformation could be obtained by using LBM, as long as some dimensionless numerical parameters were within certain ranges. Otherwise the droplet was either dissolved or did not deform to stable shapes at subcritical capillary numbers.

The aim of the present paper is to apply a recently proposed LBM [11, 12], which is based on the Cahn-Hilliard diffuse interface theory for binary fluids, to study droplet deformation in linear shear flow. Compared with other two-phase LBMs based on [13, 14], the present LBM is capable of eliminating the parasitic currents and dealing with higher density and viscosity ratios, but it could be more computationally expensive. The effects of viscosity ratio, capillary number, Reynolds number, and confinement ratio on droplet deformation and break-up in moderately and highly confined shear flows will