Chemical Engineering Science 126 (2015) 150–159

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# Effects of dispersed phase viscosity on drop deformation and breakup in inertial shear flow

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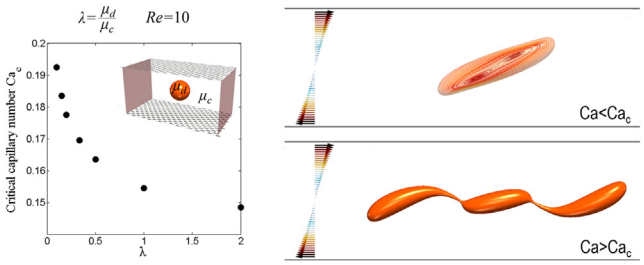
## HIGHLIGHTS

- Behavior of a single liquid drop in simple shear flow at Re = 10 is studied.
- Numerical simulations are performed using a free energy lattice Boltzmann method.
- New results for drops that are less viscous than surrounding liquid.
- For each viscosity ratio the critical capillary number $Ca_c$ is determined.
- Drop breakup processes are examined at $Ca \sim Ca_c$, $1.2Ca_c$, $1.5Ca_c$ and $2Ca_c$.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 4 August 2014
Received in revised form
31 October 2014
Accepted 2 December 2014
Available online 16 December 2014

*Keywords:*
Drop deformation and breakup
Low viscosity dispersed phase
Lattice Boltzmann method
Binary liquid model

## ABSTRACT

The deformation and breakup of a single liquid drop subjected to simple shear flow is studied numerically using a diffuse interface free energy lattice Boltzmann method. The effect of dispersed phase viscosity on the behavior of the drop at a drop Reynolds number Re = 10 is investigated over the range of viscosity ratios $\lambda = 0.1-2$ (dispersed phase viscosity over continuous phase viscosity) with a focus on $\lambda < 1$. For every $\lambda$ the critical capillary number $Ca_c$ for breakup is determined. For the range of $\lambda$ considered, $Ca_c$ decreases as $\lambda$ increases. Both the extent of deformation and the breakup mechanism depend on the viscosity ratio and the capillary number. At the highest subcritical capillary number, the drop becomes less elongated and more inclined towards the vertical axis as the viscosity ratio increases. The changes in the drop breakup process are examined as the capillary number increases from the lowest supercritical $Ca \sim Ca_c$, to 1.2, 1.5 and $2Ca_c$. Drops break by the end-pinching mechanism, except for $\lambda = 2$ at $Ca = 2Ca_c$ where the drop undergoes capillary wave breakup.

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## 1. Introduction

Studies of drop behavior in simple flow geometries have been used to interpret data on dispersion and emulsion formation due to more complex flow structures as they occur in process equipment (Rueger and Calabrese, 2013). While most experimental and simulation research has considered creeping flow (Grace, 1982; Rumscheidt and Mason, 1961; Stone, 1994; Rallison, 1984; Zhao, 2007; Marks, 1998), drops in complex flows, such as turbulence, can experience drop Reynolds numbers anywhere in the range 0.01–100 (Komrakova et al., 2014). To predict whether drops will break in turbulent flow, it is therefore necessary to understand how the conditions for breakup at moderate Reynolds numbers differ from those in creeping flow. While studies have considered the conditions for breakup in simple shear flow at Reynolds numbers up to 100 in systems with droplets that are as viscous

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http://dx.doi.org/10.1016/j.ces.2014.12.012
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or more viscous than the continuous phase (Renardy and Cristini, 2001a; Khismatullin et al., 2003), neither experiments nor simulations have been reported for the case of drops that are less viscous than their surroundings. This case is not unusual: for example, water droplets may be dispersed in a much more viscous oil (Rueger and Calabrese, 2013; Boxall et al., 2011). In the oil recovery industry, well productivity can be reduced by formation damages caused by oil-based emulsions that contain brine droplets (Fjelde, 2007). If a monodisperse emulsion is formed, then damage might occur even at low dispersed phase volume fractions. An understanding of deformation and breakup behavior of low-viscosity drops in a more viscous fluid will therefore fill an important gap in current knowledge with impact on industrial applications.

In the present work, the deformation and breakup of a single drop suspended in another liquid under simple shear flow is studied with numerical simulations using a free energy lattice Boltzmann method (Swift et al., 1996). The details of the method, its verification and validation can be found in Komrakova et al. (2014). Both liquids are Newtonian and of the same density. There are no surfactants or impurities in the system. The physical problem is determined by three dimensionless numbers: the drop Reynolds number $\mathrm{Re}=\dot{\gamma}a^2/\nu_c$, the capillary number $\mathrm{Ca}=a\dot{\gamma}\mu_c/\sigma$, and the viscosity ratio $\lambda=\mu_d/\mu_c$. Here, $a$ is the undeformed drop radius; $\dot{\gamma}$ is the shear rate; $\nu_c$ is the kinematic viscosity of the continuous phase; $\mu_c$, $\mu_d$ are the dynamic viscosities of the continuous and dispersed phases, respectively; and $\sigma$ is the interfacial tension between the liquids.

The goal of this study is to investigate the behavior of a drop at a fixed Reynolds number $\mathrm{Re}=10$ over a range of viscosity ratios $\lambda=0.1-2$, with a focus on $\lambda<1$. For each $\lambda$ it is necessary to determine the critical capillary number $\mathrm{Ca}_c$ that must be exceeded to break a drop. At subcritical capillary numbers, the drop achieves a steady final shape. The internal circulation patterns and the deformation parameters (elongation and orientation angle; see definitions below) are used to characterize the steady shape. When a supercritical capillary number is simulated, the drop breaks, and the breakup mechanism depends on the values of Ca and $\lambda$. Changes in the drop breakup process are examined as the capillary number increases from 20% above critical, to 50 and 100%.

The distinct characteristic of numerical simulations is that the entire deformation and breakup processes can be visualized revealing peculiarities of the events. However, in order to study physical processes numerically, it is necessary to select numerical parameters that produce trustworthy physical results. It was shown by Komrakova et al. (2014) that in addition to the three physical dimensionless numbers mentioned above (the Reynolds number, the capillary number and the viscosity ratio), two numerical dimensionless numbers have to be specified. In the diffuse interface method, which is used in this work, the finite thickness of the interface between the two liquids and related free energy model parameters are involved. These numerical degrees of freedom are characterized by two dimensionless numbers (van der Sman and van der Graaf, 2008): the interface Peclet number $Pe$ and the Cahn number $Ch$. The interface Peclet number $Pe=\dot{\gamma}a\xi/(MA)$ relates the convection time scale to the interface diffusion time scale. The Cahn number $Ch=\xi/a$ is the ratio of the interface thickness and drop radius. Here, $\xi$ is the interface thickness, $M$ is the mobility, and $A$ is a free energy model parameter. In the present study, the guidelines as developed by Komrakova et al. (2014) have been applied to specify $Pe$ and $Ch$.

The rest of the paper is organized as follows. In Section 2 a brief description of the numerical method and its implementation are presented. In Section 3 the ability of the method to compute flows over the required range of viscosity ratios is demonstrated. The results of drop deformation and breakup are presented in Section 4. Conclusions are drawn in Section 5.

## 2. Numerical method and its implementation

The behavior of a drop in shear flow is studied numerically with the diffuse interface free energy lattice Boltzmann method (LBM) developed by Swift et al. (1996). The details of diffuse interface (or phase field) methods can be found in Jacqmin (1999), Yue et al. (2004), and Ding et al. (2007); our implementation of the method is presented in Komrakova et al. (2014). In particular, the interface between the two components is represented by a thin transition region with a finite thickness in which the composition varies smoothly. The composition of the system is described by the order parameter $\phi$ which is the relative concentration of the two components (Cahn and Hilliard, 1958; Penrose and Fife, 1990; Badalassi et al., 2003). To simulate the fluid dynamics of the binary mixture, the continuity and momentum equations are solved in conjunction with the convection–diffusion equation for the order parameter proposed by Cahn and Hilliard (1958, 1959). Thus, the evolution of density, velocity and order parameter are governed by the continuity, momentum, and convection–diffusion equations (Swift et al., 1996):

$$\partial_t\rho+\partial_\alpha(\rho u_\alpha)=0 \tag{1a}$$

$$\partial_t(\rho u_\alpha)+\partial_\beta(\rho u_\alpha u_\beta)=-\partial_\beta P^{th}_{\alpha\beta}+\partial_\beta\nu\left(\rho\partial_\alpha u_\beta+\rho\partial_\beta u_\alpha\right) \tag{1b}$$

$$\partial_t\phi+\partial_\alpha(\phi u_\alpha)=M\partial^2_{\beta\beta}\mu \tag{1c}$$

where $u_\alpha$ is the velocity; the index $\alpha$ stands for the Cartesian directions $x$, $y$ and $z$; $\rho$ and $\nu$ are the density and the kinematic viscosity of the mixture, respectively. Here $P^{th}_{\alpha\beta}$ is the 'thermodynamic' pressure tensor. It contains two parts (Kendon et al., 2001): an isotropic contribution $P\delta_{\alpha\beta}$ that represents the ideal gas pressure and the 'chemical' pressure tensor $P^{chem}_{\alpha\beta}$. The chemical potential in Eq. (1c) is $\mu(\phi)=A\phi-A\phi^3-\kappa\partial^2_{\alpha\alpha}\phi$. Here, $A<0$ and $\kappa$ are parameters

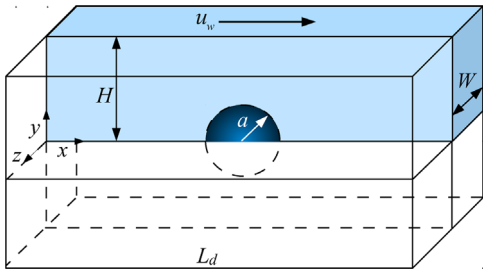


**Fig. 1.** Simulation domain with the following boundary conditions: $x=0$ and $x=L_d$ are periodic boundaries; $y=0$ has a rotational symmetry boundary condition; $y=H$ is a no-slip wall moving with constant velocity $u_w$; $z=0$ and $z=-W$ are symmetry planes. At $t=0$ the drop has a spherical shape with initial radius $a$. Due to the symmetry of the problem only one quarter of the domain needed to be simulated.

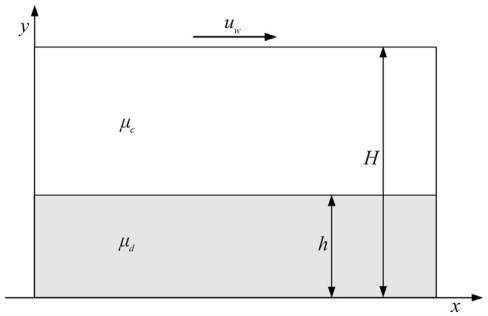


**Fig. 2.** A slice of the simulation domain at $z=0$ for validation simulations of stratified shear flow; $h=64$ [lu], $H=4\,h$, $\lambda=\mu_d/\mu_c=0.1-2$.

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