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Three dimensional interaction of two drops driven by buoyancy

O. Pournader, S. Mortazavi *

Department of Mechanical Engineering, Isfahan University of Technology, 84156-83111 Isfahan, Iran

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ABSTRACT

The time dependent interaction between two viscous deformable drops that move under the effect of buoyancy force are simulated numerically in three dimensions. The effects of dimensionless parameters on film drainage are studied. Drops have different sizes, so diameter of leading drop is half the diameter of trailing drop. The Navier–Stokes equations are solved with a finite difference-front tracking method. Important dimensionless numbers used, are the Bond number (Bo), the Morton number (M), the Reynolds number (Re) and viscosity ratio (λ). Bond number is considered to be large enough in order that drops deform significantly. The results obtained by Manga and Stone [M. Manga, H.A. Stone, Buoyancy-driven interactions between two deformable viscous drops, J. Fluid Mech 256 (1993) 647–683], at zero Reynolds number, show that there are three mechanisms for thin film drainage between two drops: 1-Rapid drainage 2-Uniform drainage 3-Dimple formation.

The type of fluid drainage that occurs between two drops depends on the Bond number and viscosity ratio. At a small Bond number, drainage takes place only with first method. For large Bond numbers, drainage changes to the second mode. Only for moderate Bond numbers all three methods can happen. Inertia affects collision of drops at small Bond numbers (more rigid drops). It is found that inertia effects cannot be neglected at small Bond numbers, and the separation distance obtained does not agree with simulations performed at zero Reynolds number. Also, the collision of two drops at early stages of interaction is influenced by the Reynolds number. The viscosity ratio affects the onset of dimple formation in the interaction process. At a low viscosity ratio (0.2) the separation distance increases with the Reynolds number. The dimple formation is enhanced with increasing the viscosity ratio, and it occurs at a larger distance from the axis of symmetry.

1. Introduction

The rise of bubbles and drops in viscous liquids is not only a very common process in many industrial applications, but also is an important fundamental problem in fluid dynamics. The motion and interaction of drops and bubbles due to gravity is of fundamental importance in a variety of multiphase flows, such as liquid–liquid extraction, emulsion stability and separation, and geophysical systems. Many flows contain buoyant particles that are rigid or deformable. Polymer flows, fuel sprays and the motion of the red blood cells are some such examples. Interaction of drops and bubbles in a continuous phase is frequently encountered in many industrial applications, such as food processing, production of lubricant oils, paints, pharmaceutical and cosmetic products. The presence of air bubbles in hydrodynamic systems often reveals many undesirable effects, such as early erosion, loss of efficiency or flow irregularities.

Experimental studies of the interaction and coalescence of two fluid particles in pure liquids are very limited. Only a few experimental studies have been reported in the literature dealing with buoyancy-driven interaction and coalescence of two fluid particles under low Reynolds number conditions. Olbricht and Kung [1] studied the interaction between two unequal size drops suspended in low Reynolds number flow through a capillary tube experimentally. More recently, Manga and Stone [2] studied the non-axisymmetric buoyancy driven interaction of two air bubbles rising in a large container filled with com syrup. They observed that the initial horizontal displacement of two deformable bubbles determines the type of bubble interaction that occurs. The in-line interaction of two gas bubbles rising in an unbounded domain was studied by Crabtree and Bridgewater [3], Narayanan et al. [4], and Bhaga and Weber [5] experimentally. These studies showed that the wake of the leading bubble can play a vital role both in capturing non-aligned bubbles, and in the subsequent coalescence behavior of the bubbles. Duineveld [6] investigated the behavior of two bubbles rising side by side in hyper filtrated water experimentally.

Some numerical studies have been performed on drops motion in recent years. Manga and Stone [2] studied time-dependent

* Corresponding author. Tel.: +98 3113915257; fax: +98 3113912628.
E-mail addresses: o.poornader@me.iut.ac.ir (O. Pournader), saeedm@cc.iut.ac.ir (S. Mortazavi).

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interactions between two buoyancy-driven deformable drops at zero Reynolds number. They found there are three methods for drainage of thin film between drops (rapid, uniform and dimple drainage). Rother, Zinchenko and Davis [7] studied the simultaneous effect of small deformation and short-range van der Waals attraction on the coalescence efficiency of two different-sized slowly sedimenting drops. Davis [8] developed and used an axisymmetric boundary-integral method to study the interaction of two deformable drops (or bubbles) rising (or settling) due to gravity in a viscous medium at a small Reynolds number. He concluded that when the Bond number is small, the interfacial tension keeps the drops nearly spherical, and they separate with time. At higher Bond numbers, however, deformation is significant and the trailing drop is stretched due to the flow developed by the leading drop; it may form one or more necks, and breaks when one of them pinches off. The leading drop is flatterned due to the flow created by the trailing drop; it forms a depression on its bottom which evolves into a plume that rises through its center. Moreover, at sufficiently high Bond numbers, the larger leading drop does not leave the trailing drop behind, but instead may entrain and engulf it within the depression or plume.

Bayareh and Mortazavi [9] performed a dynamic simulation of deformable drops in simple shear flow at finite Reynolds numbers. The flow was studied as a function of the Reynolds number and the Capillary number, and a shear thinning behavior was observed. Nourbakhsh and Mortazavi [10] used a finite difference-front tracking method to study the motion of three- dimensional deformable drops suspended in plane Poiseuille flow at non-zero Reynolds numbers. They studied the effect of Capillary number, the Reynolds number, and volume fraction in detail. They found that drops with small deformation behave like rigid particles and migrate to an equilibrium position about half way between the wall and the centerline (the Segre–Silberberg effect). Mortazavi and Tafreshi [11] studied the behavior of suspension of drops on an inclined channel. The density distribution of drops and the fluctuation energy of the flow across the channel was studied as a function of the dimensionless parameters.

Here, time-dependent interactions between two buoyancy-driven deformable drops are studied at finite Reynolds numbers for sufficiently large Bond numbers. We consider two drops with different sizes which translate along their line of centers due to buoyancy. For definiteness, we assume that the drops are slightly lighter than ambient fluid and that the smaller drop is above the larger one. Drops rise against gravity while their separation decreases with time. The geometry of the domain is shown in Fig. 1. The domain is periodic in the x, y and z directions.

2. Governing equations

The governing equations for the flow of multi-fluid systems are the Navier–Stokes equations. In conservative form they are:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla.\rho\mathbf{u}\mathbf{u} = -\nabla p + \rho\mathbf{f} + \nabla.\mu(\nabla\mathbf{u} + \nabla^T\mathbf{u}) + \int \sigma\kappa\mathbf{n}\delta^\beta(\mathbf{x}-\mathbf{X})ds \tag{1}$$

where, $\mathbf{u}$ is the velocity, p is the pressure, ρ and μ are the discontinuous density and viscosity fields, respectively. σ is the interfacial tension, $\mathbf{f}$ is a body force and the surface tension force is added at the interface. The term δ^β is a two or three-dimensional delta function constructed by repeated multiplication of one-dimensional delta function. κ is the curvature for two-dimensional flow and twice the mean curvature for three-dimensional flows. $\mathbf{n}$ is a unit vector normal to the front, $\mathbf{x}$ is the position in Eulerian coordinate, and $\mathbf{X}$ is a Lagrangian representation of the interface. The Navier–Stokes equations are solved by a second-order projection method using centered differences on a fixed staggered grid. Both the drop and the ambient fluid are taken to be incompressible, so the velocity field is divergence free:

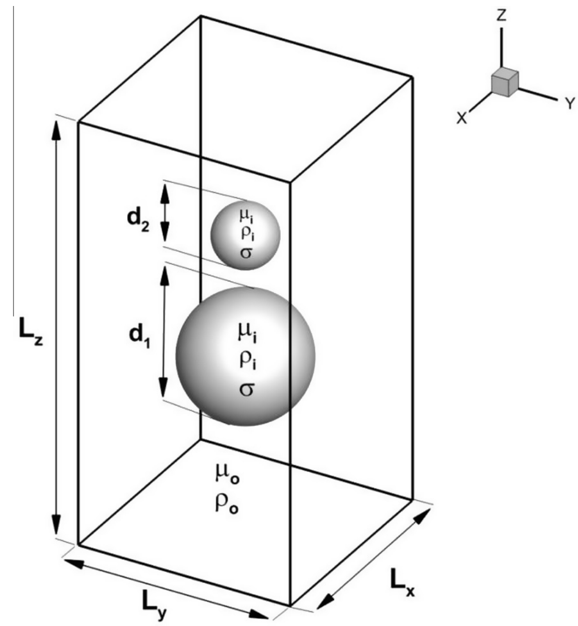

Fig. 1. Geometry of the flow.

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

Eq. (2), when combined with the momentum equation, leads to a non-separable elliptic equation for the pressure. The elliptic equation for pressure is solved by a multi-grid method [12]. Equations of state for the density and the viscosity are:

$$\frac{D\rho}{Dt} = 0 \tag{3}$$

$$\frac{D\mu}{Dt} = 0 \tag{4}$$

Eqs. (3) and (4) state that the density and the viscosity of a fluid particle remain constant.

3. Dimensionless parameters

Important dimensionless parameters are the Bond number $(Bo) = \frac{\Delta\rho g\left(\frac{d}{2}\right)^2}{\sigma}$, the Morton number $\left(M = \frac{g(\mu_o)^4}{\rho_o(\sigma)^3}\right)$, the Reynolds number $\left(Re = \frac{\rho_o U d}{\mu_o}\right)$, the viscosity ratio $\left(\lambda = \frac{\mu_i}{\mu_o}\right)$ and density ratio $\left(\alpha = \frac{\rho_i}{\rho_o}\right)$.

Here U is the steady state rise velocity of the larger drop (trailing drop) when rising alone in a full periodic domain. ρ and μ are the density and viscosity. σ is the interfacial tension, and g is the acceleration due to gravity. Also, d is the diameter of larger drop.

4. Numerical method

Different numerical methods have been developed for simulating flows with interfaces. These methods can be divided into two groups, depending on the type of grids used: moving grid and fixed grid. Two important approaches of fixed-grid methods are the volume-of-fluid (VOF), and level-set method. The volume-of-fluid method uses a marker function. The main difficulty in using VOF