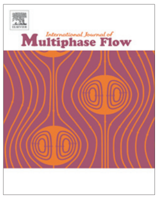
International Journal of Multiphase Flow 56 (2013) 81–92

Contents lists available at SciVerse ScienceDirect

International Journal of Multiphase Flow

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



Collision between high and low viscosity droplets: Direct Numerical Simulations and experiments

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ARTICLE INFO

Article history:
Received 8 August 2012
Received in revised form 10 May 2013
Accepted 11 May 2013
Available online 31 May 2013

Keywords:
Delayed coalescence
Non-isoviscous droplet collision
Viscous pressure jump
Volume of Fluid method

ABSTRACT

Binary droplet collisions are of importance in a variety of practical applications comprising dispersed two-phase flows. In the present work we focus on the collision of miscible droplets, where one droplet is composed of a high viscous liquid and the other one is of lower viscosity. This kind of collisions take place in, for instance, spray drying processes when droplets with different solid content collide in recirculation zones. The aim of this paper is to investigate the details of the flow inside the colliding droplets. For this purpose, two prototype cases are considered, namely the collision of equal sized droplets and the collision between a small and highly viscous droplet and a bigger low viscous droplet. A new experimental method has been developed in order to visualize the penetration and mixing process of two colliding droplets, where a fluorescence marker is added to one liquid and the droplets are excited by a laser. The results show a delay in the coalescence which takes place during the initial stage of a collision of droplets with different viscosities. Direct Numerical Simulations based on the Volume-of-Fluid method are used to study these collisions and to allow for a more detailed inspection of the mixing process. The method is extended to consider a second liquid with a different viscosity. In order to reproduce the delay of coalescence, an algorithm for the temporal suppression of the coalescence is applied. A predictive simulation of the delay is not possible, because the extremely thin air gap separating the droplets cannot be resolved by the numerics. This approach is validated by comparison with experimental data. The results provide local field data of the flow inside the collision complex, showing in particular a pressure jump at the liquid–liquid interface although no surface tension is present. The detailed analysis of the terms in the momentum balance show that the pressure jump results from the viscosity jump at the liquid–liquid interface.

1. Introduction

In numerous industrial areas, spray drying is used for producing powders of desired properties. Depending on the droplet size distribution, the residence time of droplets will vary and their viscosity will be increased as a result of the drying process. Droplets of different drying state (i.e. different solids content and viscosity) may collide with each other and influence the properties of the particulate product.

A large number of experimental studies is devoted to the collision of droplets with different liquids, i.e. different density, viscosity and surface tension. Planchette et al. (2011, 2010) investigate the outcome of collisions of immiscible droplets (including different surface tension) and the influence of the material parameters. The investigation of Gao et al. (2005) is primarily devoted to collisions of droplets with a large surface tension difference. Chen (2007) compares binary collisions of diesel drops with the collision of diesel drops and ethanol drops. Further investigations on the collision of diesel–ethanol drops are performed by Chen and Chen (2006). The largest influence on these collisions is attributed to the difference in surface tension. Roisman et al. (2012) investigate collisions of droplets of immiscible liquids experimentally and develop a theoretical model that predicts the main geometrical parameters. The internal mixing of a quiescent drop in contact with a liquid layer is discussed by Cresswell and Morton (1995) and Dooley et al. (1997) and the formation of a vortex ring could be identified. The initial contact of quiescent droplets of different liquids is analyzed in Thoroddsen et al. (2007). In both cases, a quiescent droplet in contact with a liquid layer as well as the contact with a second droplet, the mixing is attributed to the difference in surface tension.

We here investigate the collision of droplets of different Newtonian liquids with equal surface tension and density by means of

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2013.05.008

experiments and numerical simulations. In contrast to previous experimental works, the liquids are miscible and no surface tension is acting at the liquid–liquid interface. The focus of the present paper lies on the investigation of collisions between a high and a low viscous droplet. The aim is to analyze the flow inside the colliding droplets on the basis of two prototype cases. The viscosity ratio of the liquids is 23 due to the different polymer content. The experimental results show that colliding droplets in this regime do not merge at once when they come into contact, but a delay occurs until the surfaces join. In the numerical simulation the location of the liquid volume is defined by a common indicator function. An additional species is used to represent the dissolved polymer and the increased viscosity is coupled with this species.

A major difficulty arises concerning the simulation of a delayed coalescence. The thin air film separating the droplets in the experiments cannot be resolved. The result is that the approaching droplets coalesce artificially. Our approach is to suppress the numerical coalescence using the time delay obtained from experimental data as input for the coalescence suppression algorithm. A careful validation is performed to prove the reliability of the applied procedure. Although this approach is not fully predictive, it nevertheless allows for a detailed investigation of the inner flow fields, the mixing between the droplets' material and the possible phenomenon of encapsulation of the higher viscous drop by the other one. To facilitate the comparability of simulation and experiment, a ray tracing technique is applied to visualize the numerical results.

2. Numerical methods

2.1. Model description

We consider the collision of droplets as an incompressible transient two-phase flow and solve the Navier–Stokes equations in the bulk,

$$\nabla \cdot \mathbf{v} = 0, \quad \rho\partial_t \mathbf{v} + \rho(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla p + \nabla\cdot\mathbf{S} + \rho\mathbf{g}, \tag{1}$$

with the Newtonian viscous stress tensor **S**, i.e.

$$\mathbf{S} = \eta(\nabla\mathbf{v} + (\nabla\mathbf{v})^{\mathsf{T}}), \tag{2}$$

where η is a variable dynamic viscosity, being different in the different fluids. Assuming no phase change, the standard jump conditions at the interface between two viscous liquids read as

$$[\![\mathbf{v}]\!] = 0, \tag{3}$$

$$[\![p\mathbf{I} - \mathbf{S}]\!] \cdot \mathbf{n}_\Sigma = \sigma\kappa\mathbf{n}_\Sigma. \tag{4}$$

The jump bracket $[\![\cdot]\!]$ describes the jump of a quantity at the phase interface, being defined as

$$[\![\phi]\!](x) = \lim_{h\to 0+}(\phi(\mathbf{x} + h\mathbf{n}_\Sigma(x)) - \phi(\mathbf{x} - h\mathbf{n}_\Sigma(x))). \tag{5}$$

The numerical approach employed here is based on the Volume-of-Fluid (VOF) method by Hirt and Nichols (1981) and uses the VOF-code FS3D. The fundamental idea of this method is to capture the interface position implicitly by means of a phase indicator function, i.e. a scalar function $f = f(t,\mathbf{x})$ with, say, $f = 1$ in the dispersed phase and $f = 0$ in the continuous phase. Due to the absence of phase change, the transport of f is governed by the advection equation

$$\partial_t f + \mathbf{v}\cdot\nabla f = 0, \tag{6}$$

where **v** denotes the velocity field. The VOF-method inherently conserves phase volume, which is an important issue especially if the long term behavior of two-phase flow is to be studied, where other methods like Level Set or Front tracking could lose too much of the droplet volume. In the Finite Volume (FV) discretization scheme employed here, the cell centered value of f corresponds to the phase fraction inside a computational cell. Based on these values, an approximation of the interface normal can be computed as

$$\mathbf{n}_\Sigma = \frac{\nabla f}{\|\nabla f\|}. \tag{7}$$

Combination of the fractional volume of the dispersed phase with the interface normal then allows for an interface reconstruction with the so-called PLIC method (Rider and Kothe, 1998). This reconstruction of the phase geometry inside the computational cells provides important subgrid-scale information, which is employed for an accurate geometry-based convective transport of the phase indicator and, hence, allows for a sharp interface representation. Once the phase distribution is known, a one-field formulation of the Navier–Stokes system is possible in which the interfacial momentum jump condition acts as a source term in the momentum equations. This one field formulation reads as

$$\rho\partial_t\mathbf{v} + \rho(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla p + \nabla\cdot\mathbf{S} + \rho\mathbf{g} + \sigma\kappa\mathbf{n}_\Sigma\delta_\Sigma, \tag{8}$$

where the material properties ρ and η refer to the phase dependent values. The local values of the density are determined by

$$\rho = \rho_d f + \rho_c(1-f). \tag{9}$$

In FS3D, the surface tension is incorporated using the continuum surface stress (CSS)-model based on (Lafaurie et al., 1994). The algorithm of the CSS model smoothes the f-field using a 27 cell stencil (3^3 cells). Subsequently the divergence of a capillary pressure tensor is computed on the smoothed field, again using a 27 cell stencil so that the surface tension in one cell is influenced by 125 cells (5^3 cells). If this block of 125 cells contains an additional interface, the surface tension computation of the cell in the center is distorted. This leads to the (artificial) coalescence of the neighboring surfaces, if the distance between the interfaces falls below three cells. The neighboring interface could for example belong to a second droplet or it could belong to the opposite side of the same droplet. In most cases the simulated coalescence is in agreement with the physical behavior, but it is also possible that the numerical coalescence of neighboring interfaces leads to non-physical results, e.g., the rupture of a thin collision lamella arising in a head-on collision at high kinetic energy (Focke and Bothe, 2011; Focke and Bothe, 2012). The coalescence can be delayed by a modification of the CSS modell, see Section 2.3.

Since an explicit time discretization is employed, the time-step size is controlled dynamically. For the computation of the present droplet collisions, one condition is of relevance: In all simulations the time step size is limited by viscous momentum diffusion, resulting in the constraint

$$\Delta t_{max} \leqslant \frac{|\Delta x|^2_{min}}{2\eta_{max}}. \tag{10}$$

Further restrictions on the time step size are due to the CFL-condition and the speed of capillary surface waves, but these do not become active in the flows under consideration.

2.2. Modeling of non-isoviscous flows

The location of the two droplets is numerically represented by a common phase indicator function. The liquid containing the higher polymer concentration is distinguished by an additional scalar which represents the mass fraction of the solvent y. The transport equation for the solvent density ρ_i reads as

$$\partial_t\rho_i + \nabla\cdot(\rho_i(\mathbf{v} + \mathbf{u}_i)) = 0 \tag{11}$$

with **v** the barycentric velocity of the total mixture and $\mathbf{u}_i$ the diffusion velocity, i.e. the difference of velocities between the solvent