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Binary collision of drops in simple shear flow at finite Reynolds numbers: Geometry and viscosity ratio effects

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ABSTRACT

The collision of two equal-size drops in an immiscible phase undergoing a shear flow is simulated over a range of viscosity ratios (λ) and different geometries. The full Navier–Stokes equations are solved by a finite difference/front tracking method. Based on experimental data, different cases were simulated by changing the offset, size of drops, and viscosity ratio. The distance between drop centres along the velocity gradient direction (z) was measured as a function of time. It was found that Δz increases after collision and reaches a new steady-state value after separation. The values of Δz, during the interaction, increases with increasing initial offset. Our results show that the time of approaching of drops at low initial offset is greater than the other cases, but the maximum deformation is the same for equal drop sizes. The deformation decreases with decreasing the size of drops. As the initial offset increases, the drops rotate more quickly and the available contact time for film drainage decreases. We found that the trajectories of drops in the approaching stage are different owing to the different initial offsets. However, after the drops come into contact, it observed that they follow the same trajectories. As λ increases, the drops rotate more slowly, and the point at which the drops separate is delayed. The trajectories of drops become more symmetric with the increased λ.

1. Introduction

The flow of fluids composing immiscible liquid–liquid mixtures is of great interest in a wide range of research areas, such as foods, polymers, pharmaceuticals and cosmetics. The systematic study of drop deformation and break-up was initiated by Taylor [1]. Taylor's experiments revealed the existence of steady rounded and pointed drops, as well as bursting drops of the same type, depending on the viscosity ratio and the capillary number. Cox and Mason [2] have confirmed and extended Taylor's results. Most efforts have focused on drop deformation for clean fluid systems in which interfacial tension gradients are absent. For these drops, experiments, asymptotic analysis, and numerical simulations have been performed. Rallison [3] studied the time-dependent deformation and burst of a viscous drop in an arbitrary shear flow at zero Reynolds number. Magna and Stone [4] reported the time-dependent interaction between two buoyancy-driven deformable drops in a low Reynolds number flow. Calculations and experiment with initially offset drops showed that the axisymmetric drop configuration was stable for sufficiently deformable drops. They introduced three modes for film drainage between the drops: rapid drainage, uniform drainage and dimple formation. As the separation distance between the two drops decreases, the mode of film drainage may change from rapid drainage to uniform drainage and eventually a dimple may form. Zhou and Pozrikidis [5] studied the flow of periodic suspension of two-dimensional viscous drops in a channel that was bounded by two parallel plane walls. They found that there exists a critical capillary number below which the suspension exhibits stable periodic motion, and above which the drops elongate and tend to coalesce. Feng et al. [6] reported the results of a two-dimensional finite element simulation of the motion of a circular particle in a Couette and Poiseuille flow. They showed that a neutrally buoyant particle migrates to the centreline in a Couette flow and the stagnation pressure on the particle surface is particularly important in determining the direction of migration. Li et al. [7] studied the motion of two-dimensional, doubly periodic, dilute and concentrated emulsions of liquid drops with constant surface tension in a simple shear flow. Their numerical method is based on a boundary integral formulation. They showed that the shear flow is able to stabilize a concentrated emulsion against the tendency of the drops to become circular and coalesce, thereby allowing for periodic evolution. Loewenberg and Hinch [8] did a three-dimensional simulation of a concentrated emulsion in shear flow, at zero-Reynolds-number and finite capillary numbers. The collision of two

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Nomenclature

A	area (m^2)
b	minor axis of the deformed drop (m)
Ca	capillary number
D	diameter of drop (m)
De	Taylor deformation parameter
$\mathbf{F}_\sigma$	force due to surface tension on each element of front (N)
h	the grid spacing (m)
H	the height of the channel (m)
l	major axis of the deformed drop (m)
We	Weber number
x (x, y, z)	position in Eulerian coordinate (m)
X (X, Y, Z)	position in Lagrangian coordinate (m)
$\mathbf{n}$	unit vector normal to the drop surface
P	pressure (Pa)
R	radius of undeformed drop (m)
Re_b	bulk Reynolds number
Re_p	particle Reynolds number
s	a closed contour (m)
$\mathbf{t}$	tangent vector to each element (m)
t^*	dimensionless time
$\mathbf{u}$	fluid velocity vector (m/s)
u_b	bottom wall velocity (m/s)
u_t	top wall velocity (m/s)

Greek letters

β	indicate two or three-dimensional in Navier–Stokes equations
δ	delta function
δA	a surface element (m^2)
Δ	half of the initial distance between drop centres (m)
Δs	a short front element (m)
Δs_l	the area of the element (m^2)
Δt	time step (s)
ϕ_{ijk}	an approximation to the grid value ϕ_g
ϕ_f	the interface quantity
ϕ_g	the grid value
ϕ_l	a distance approximation to the front value ϕ_f
$\dot{\gamma}$	shear rate (1/s)
κ	twice the mean curvature for three-dimensional flows
λ	viscosity ratio
μ	viscosity (N s/m^2)
μ_0	viscosity of ambient fluid (N s/m^2)
μ_d	viscosity of drop (N s/m^2)
ρ	density (kg/m^3)
ρ_0	density of ambient fluid (kg/m^3)
ρ_d	density of drop (kg/m^3)
σ	surface tension (N/m)
ω^l_{ijk}	the weight of grid point ijk

equal-sized drops immersed in an immiscible liquid undergoing a shear flow in a Couette apparatus was investigated by Guido and Simeone [9] over a range of capillary numbers. Trajectories of the drops and their deformation were presented.

Mortazavi and Tryggvasson [10] studied the motion of a drop in poiseuille flow. They simulated the motion of many drops at finite Reynolds numbers. Esmaeeli and Tryggvason [11] simulated the motion of two-and three-dimensional buoyant bubbles at finite Reynolds numbers. They showed that the rise Reynolds number is nearly independent of the number of bubbles, the velocity fluctuations in the liquid (the Reynolds stresses) increase with the size of the system. Cristini et al. [12] simulated the drop break-up and coalescence by an adaptive mesh algorithm. The surface discretization was fully adaptive, thus providing accurate resolution for a highly deformed drop shapes. Their algorithm was used to study drop break-up in shear flow. Balabel et al. [13] introduced a numerical model based on the level set method for computing the unsteady motion of droplets in a channel. Yoon et al. [14] investigated experimentally the effect of the dispersed to continues-phase viscosity ratio on the flow-induced coalescence of two equal-sized drops with clean interfaces. Effects of inertia on the rheology of a dilute emulsion of drops in shear flow were investigated by Zhao [15] using direct numerical simulation. The drop shape and flow were computed by solving the Navier–Stokes equations in two phases using front tracking method. Sibillo et al. [16] investigated the deformation and break-up of a drop in an immiscible equiviscous liquid undergoing unbounded shear flow. They showed that wall effects can be exploited to obtain nearly monodisperse emulsions in microconfined shear flow.

Zhao [17] investigated the drop break-up in dilute Newtonian emulsions in simple shear flow by high-speed microscopy over a wide range of viscosity ratios, focusing on high capillary numbers. He showed that the final drop size distribution intimately links to drop break-up mechanism, which depends on viscosity ratio and capillary number.

Lac and Biesel [18] used a boundary integral formulation to investigate the collision of two identical capsules in simple shear flow. Each capsule consisted of a viscous liquid drop enclosed by an elastic membrane. The hydrodynamic interaction was characterized by an irreversible cross-flow displacement after the capsules had crossed each other. They showed for sufficiently spaced trajectories, the capsules exhibit negative deflections which displace them to closer streamlines.

Bayareh and Mortazavi [19,20] simulated the migration of a drop and the interaction of two drops in shear flow at finite Reynolds numbers using a finite difference/front tracking method. They showed that the proper dimensionless parameter for the interfacial tension is the capillary number; the interaction between deformable drops increases the cross-flow separation of their centres. At different values of capillary numbers, the deformation of drops are maximum when the drops are pressed against each other and minimum when they are drawn a part. Their results agreed qualitatively with experimental and theoretical data.

It is important to understand and control the size and size distribution of the dispersed drops because the macroscopic properties of the emulsion depend on them. The final size distribution is determined by a balance between flow-induced break-up and coalescence. The majority of numerical simulations are based on the interaction of two deformable drops in a shear flow, the drainage of the thin film between two colliding drops and the problems of coalescence of two deformable drops. Most of experimental efforts are based on blending studies that analyses the drop size distribution of a blend or a concentrated emulsion.

In this article, we present numerical simulations describing the effects of geometry and the viscosity ratio on the motion of a pair of drops under simple shear flow at finite Reynolds numbers.

2. Mathematical formulation

The governing equations for the motion of unsteady, viscous, incompressible, immiscible two- fluid systems are the Navier–Stokes equations in conservative form:

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