3-D Deformation of Newtonian droplets under simple shear investigated by experiment, numerical simulation and modelling.

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ABSTRACT

The deformation of droplets in complex flow fields is encountered in many engineering applications. In the present work, the three dimensional deformation of droplets is studied experimentally in simple shear flow and compared with numerical calculations and modeling.

INTRODUCTION

The deformation and break-up of droplets in complex flow fields is encountered in many engineering applications such as mixing and dispersing processes. To manipulate and control such operations, rheological, interfacial, and dynamical properties of the multiphase fluid as well as their interaction have to be known.

In this work, we study experimentally the 3-D deformation of Newtonian droplets submitted to a simple shear flow, and the results are compared with numerical calculations and modelling.

For this purpose, a computer-controlled parallel band apparatus equipped with two digital cameras records the time evolution of the sheared droplet and thus, analyzes digitally its shape[1].

Numerical simulations are performed to calculate the drop deformation in three-dimensional space, and compared with the experimental data. The simulations use a boundary integral method (BIM) to determine drop deformation from the mass and momentum balance equations[2]. Furthermore, a simple phenomenological model (DM) in the spirit of the Maffettone and Minale model is proposed to describe droplet deformation in homogeneous flow[3].

To describe droplet deformation, the viscosity of the dispersed fluid phase, η_d, the viscosity of the continuous fluid phase, η_c, and the interfacial tension, σ, are used. The capillary number, Ca, displays the ratio of viscous forces, which work to deform the drop, to interfacial tension, which works to restore the shape of the drop by Eq. 1.

$$Ca = \frac{\eta_c a \dot{\gamma}}{\sigma} \qquad (1)$$

where a is the radius of the undeformed drop and $\dot{\gamma}$ is the applied shear rate.

The interfacial tension is a experimental parameter which must be known in order to perform the numerical calculations. The application of the theory of Taylor[4] provides this information as a fitting parameter of the deformation parameter, $D=(L-B)/(L+B)$, as shown in Eq. 2.

$$D = \frac{19\lambda + 16}{16\lambda + 16} Ca \qquad (2)$$

Where L and B are the half-lengths of the sheared droplet in the flow direction and gradient direction, respectively, and λ is the viscosity ratio ($\lambda = \eta_d / \eta_c$).

MATERIALS AND METHODS

The measured systems are Newtonian, consisting of a solution of PEG-EtOH-H_2O as continuous phase (η_c = 290 mPa·s), and droplets of several silicon oils (Wacker, Germany) with the same density. The resulting viscosity ratios are λ = 0.165, λ = 0.331, λ = 3.35 and λ = 16.7.

The interfacial tension for these systems was previously obtained[1] using Eq. 2, and its value found to be σ=(10.1±0.2) mN/m.

The experimental setup consists of a parallel band apparatus. The ribbons are metallic and spring-loaded to avoid any bending effect; their motion is computer-controlled independently through two motors. The flow profile developed in this device is linear and the shear-rate is simply obtained as the ratio between the relative speed at which the bands move and the distance between them.

The time sequence of the droplets behaviour is recorded with two CCD digital cameras (Sony DFW-V500, Japan), one placed along the z-axis (vorticity direction) and the second along the x-axis (flow direction). This configuration let us to obtain directly a complete observation of the three dimensions of the droplet.

RESULTS AND DISCUSSION

Experiments on deformation of sheared droplets were carried out at different shear-rates for each viscosity ratio. Under the action of a constant shear flow, the droplet –initially at rest immersed in the continuous fluid phase- progressively deforms into an ellipsoid, and after a transient time it reaches a steady-state shape as long as flow conditions remain the same.

Fig. 1 shows this behaviour for the case λ=16.7 at a shear-rate=5.8 s^{-1}. The drop size evolution is quantified by L, B and W (half-length of the droplet in the vorticiy axis). For these conditions, the droplet adopts an prolate ellipsoid (W<a) under the action of the flow.

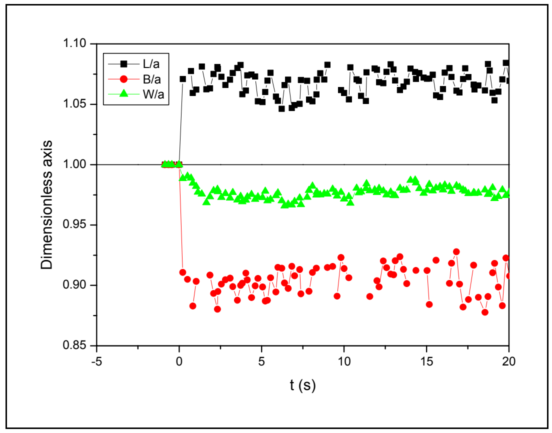

Figure 1. Dimensionless axis of a droplet with λ=16.7 as a function of the experimental time, t, at a shear-rate of 5.8 s^{-1}.for the different systems

Analogous experiments were carried out with the rest of the systems, and the steady normalized axes are plotted in Figs. 2-4, as a function of the corresponding capillary numbers.

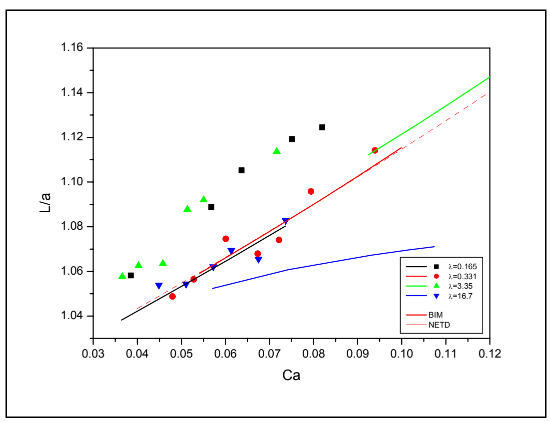

Figure 2. Normalized major axis, *L/a*, as a function of the capillary number, *Ca*, for the different systems. Lines correspond to BIM (solid) and DM (dotted) calculations.

Simulations of drop deformation were performed using the three-dimensional boundary integral method, as well as the dynamical model (shown in Figs. 2-4 as solid and dotted lines, respectively). Since the simulated drop is three-dimensional, we can completely determine the shape of the drop in all three directions. The cases considered were those performed in the experiments. Both numerical methods agree between them.

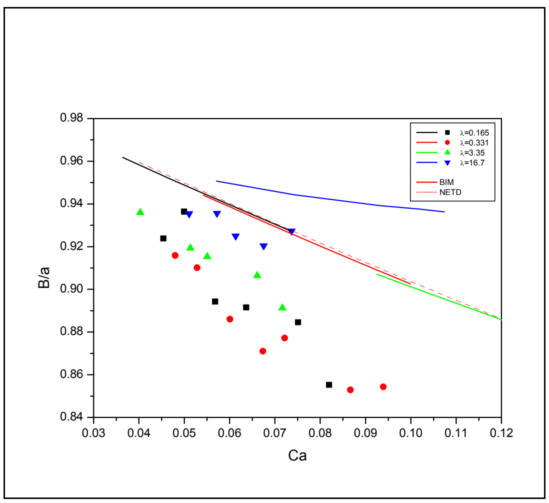

Figure 3. Normalized minor axis, *B/a*, as a function of the capillary number, *Ca*, for the different systems. Lines correspond to BIM (solid) and DM (dotted) calculations.

The numerical predictions agree qualitatively with the experimental data, for the dimensionless *L* and *B* axis.

Notice the behaviour of the droplet vorticity axis. It is found experimentally that for droplets less viscous than the continuous matrix, $\lambda<1$, it expands in the z-axis conforming an "prolate" ellipsoid.

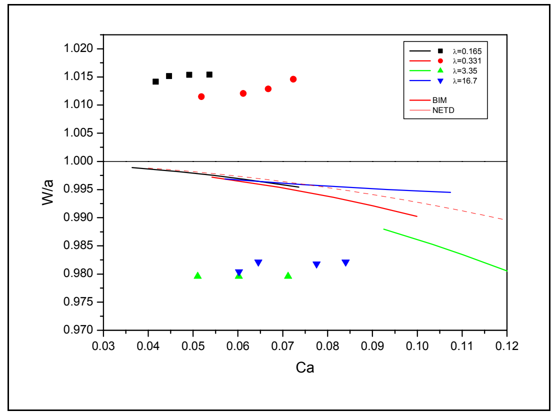

Figure 4. Normalized vorticity axis, *W/a*, as a function of the capillary number, *Ca*, for the different systems. Lines correspond to BIM (solid) and DM (dotted) calculations.

In the other hand, when the droplet is more viscous than the fluid phase, $\lambda<1$, the expected "oblate" configuration is observed, and thus, $W/a<1$, according to the simulations.

SUMMARY

In the present investigation, we compare experimentally obtained droplet deformation with a Boundary Integral Method simulation and modeling efforts.

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