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Droplet Deformation Between Two Moving Parallel Plates

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ABSTRACT: One of the most important and challenging subjects for scientists is the numerical simulation of the transport phenomena in heterogeneous media. The discontinuity in the properties causes computational errors leading to incorrect estimation of the exact values. The extended finite element method is one of the powerful tools to predict the behavior of heterogenic materials and phenomena. In the present study, we attempted to adapt the extended finite element method to study the flow of a two phase system and investigate the effect of different material and operational parameters such as Capillary number on the drop deformation process in Newtonian/Newtonian and non-Newtonian/ Newtonian systems. The results showed a good agreement with the experimental ones and complete compliance with other methods in benchmark studies. The results indicated that increasing the initial radius of the droplet would increase the steady-state deformation parameter. Moreover, it was shown that increasing viscosity ratio suppressed the droplet deformation. The effect of non-Newtonian fluid behavior was also investigated for a Carreau fluid. Furthermore, the distribution of shear rate around the droplet was discussed.

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1. Introduction

The deformation of an isolated droplet under shear flow is a topic of growing interest starting from the pioneering work of Taylor [1] and has been the subject of several reviews [2]. In the classical analysis by Taylor the following physical quantities were considered as controlling parameters: shear rate $\gamma^{\cdot}$, droplet radius R, continuous and droplet phase viscosities μ_c and μ_d , respectively, and interfacial tension σ. The assumptions are a steady laminar simple shear flow of Newtonian immiscible fluids with no interfacial agents. The five physical quantities are grouped in two dimensionless numbers, i.e., the capillary number:

$$Ca = \frac{\mu_c R \dot{\gamma}}{\alpha} \tag{1}$$

Which can be seen as droplet deforming shear stress divided by the restoring action of interfacial tension, and the viscosity ratio

$$\lambda = \frac{\mu_d}{\mu_c} \tag{2}$$

going from zero to infinity. Droplet shape is described in terms of a deformation Parameter

$$D = \frac{(a-b)}{(a+b)} \tag{3}$$

where a and b are the droplet semi-axes in the shear plane and the case of D=0 shows the undeformed state (see Fig. 1). Due to the restraint of experimental studies in investigating the micro-mechanics of the droplet deformation other researched used theoretical and numerical methods. As mentioned above, researchers used various methods such as Lattice-Boltzmann, finite difference and finite element method to solve the governing equations. Since the calculation domain in studying drop deformation is discontinuous, proper techniques should capture the discontinuities in pressure and velocity fields. There are two different discontinuity types: weak and strong. A strong discontinuity is characterized by a jump in the function (e.g. the pressure field of a two-phase flow with surface tension), while a weak discontinuity features a kink in the function. The method used in this paper is called the extended finite element method (XFEM). The XFEM accounts for these jumps and kinks by enriching the approximation function space. Through adding an enriched function to the standard shape function. In the present study, we focused on the droplet deformation and investigated the effect of different parameters such as surface tension, the viscosity of matrix and droplet using extended finite element method. The droplet deformation behavior of different systems Newtonian and non-Newtonian systems was discussed and some new aspects of the deformation process dependencies were introduced.

2. Methodology

An isothermal, incompressible, two-dimensional, and two-phase flow was considered. It was assumed that both

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immiscible phases were viscous fluids (Newtonian or non-Newtonian). The surface tension was assumed to be constant along the interface. The incompressible Navier-Stokes equation with surface tension effect was considered as follow:

$$\rho_i \frac{\partial \mathrm{u}}{\partial t} + \rho_i \mathrm{u} \cdot \nabla \mathrm{u} - \nabla \cdot (2\mu_i \mathrm{Z}) + \nabla p = \rho_i \mathrm{g} + \mathrm{f}_\Gamma \quad (4)$$

Where, P, u, g and Z are pressure, velocity, acceleration of gravity and deformation tensor, respectively. Computational domain was a 2D square with dimension depicted in Fig. 1 the upper wall was considered moving with the velocity of +U and the lower one with the velocity –U.

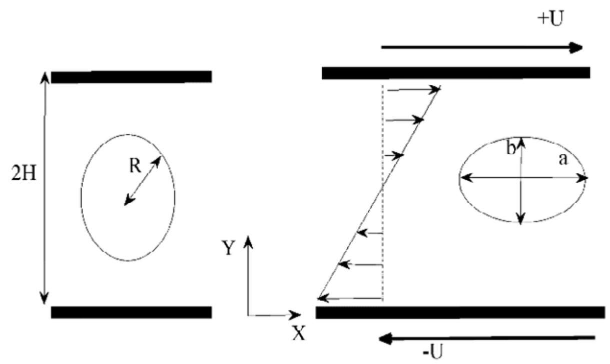

Fig. 1. Schematic of the problem geometry and boundary conditions.

3. Results and Discussion

Fig. 2 shows the deformation of the droplet in Stokes' flow at different capillary numbers. Decreasing capillary number decreased the drop deformation as the interfacial tension confronted viscose stress suppressing droplet deformation. As it can be seen from Fig. 2, increasing the interfacial tension would change the final droplet shape. It was because of the effect of the two factors acting in opposite direction. These two factors were stress transferring between matrix and droplet and the compatibility/interaction of two-phase. So, the confrontation of these two factors would be the cause of the changing the shape of the droplet to an ellipsoid like shape. Two different fluids including a Newtonian and a non-Newtonian fluid were considered to investigate the effect of rheological behavior of the fluids on the droplet deformation process.

The non-Newtonian fluid was considered to obey Carreau's model as:

$$\mu = \mu_0 + (\mu_0 - \mu_\infty)\left(1 + (G\dot{\gamma})^2\right)^{(n-1)/2} \quad (5)$$

where μ_0 and μ_∞ are viscosity at zero and infinity shear rate, respectively, n and G are the intrinsic characteristics of the fluid. Fig. 3 depicts the final steady-state shape of the Newtonian droplet in a non-Newtonian matrix (NN-N) with different power-law index, n. Decreasing n from 0.7 down to 0.3, apparently, decrease the extent of droplet deformation. The pseudo-plastic behavior of the matrix would cause its viscosity to decrease reducing the exerted stress on the droplet and lowering the extent of droplet deformation

Fig. 4 shows the final droplet size versus R/H in different viscosity ratio at Ca=0.6. It was found that as λ increase up to 1 the maximum D_{ss} was observed as it was reported in the literature. Based on the results, it could be suggested that around $\lambda \cong 1$ the viscous force could act more effectively than interfacial one and drop deformation increased. Moreover, it was shown that increasing viscosity ratio beyond λ=1 would

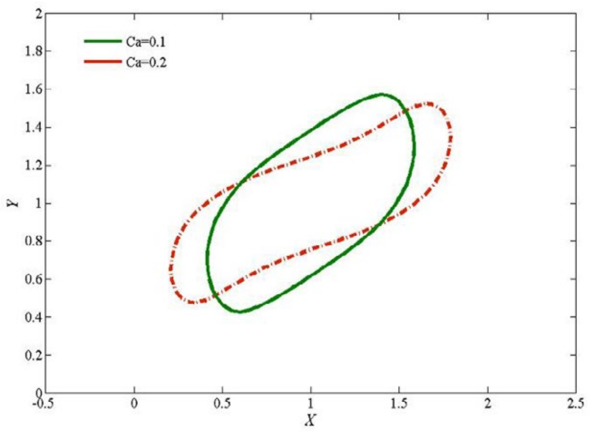

Fig. 2. Final droplet shape in the N-N system for different Capillary numbers.

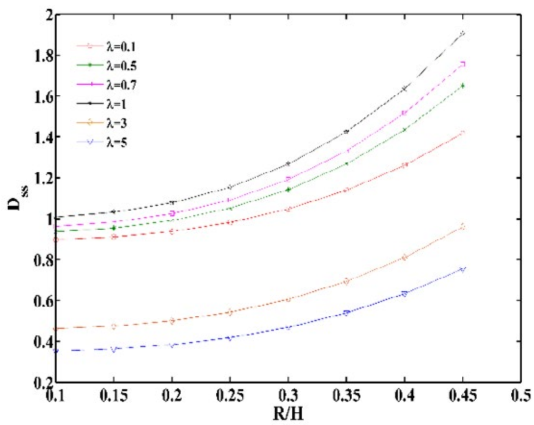

Fig. 3. The effect of the power-law index (n) on the steady-state droplet shape for NN-N system with k=0.1, Re=1, and Ca=0.5.

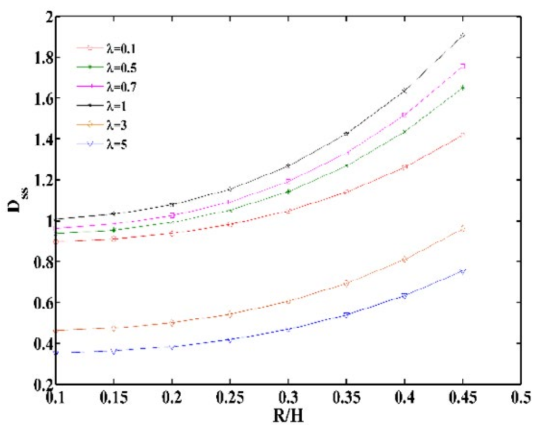

Fig. 4. Variation of D_{ss} vs. R/H for different λ at Ca=0.6.

decrease the final droplet size. It was shown that increasing *R/H* increased the final droplet size for all λ at *Ca*=0.6.

4. Conclusion

In the present work, an XFEM scheme has been adopted to solve the two-phase flow in conjunction with the level set method to track the interface. The numerical results showed a good agreement with earlier investigations. The employed method showed an accurate resolution of the phase discontinuity and velocity gradient at the interface without remeshing, even for materials with significantly differing viscosities. It showed that, as reported in the literature, increasing capillary number (*Ca*) would cause to increase the droplet deformation in almost all viscosity ratio (λ) values. It was found out that the ratio of the droplet initial size to shearing gap (*R/H*) had a great impact on the droplet deformation. Increasing *R/H* increased the droplet deformation for all values of λ and *Ca*. Results demonstrate that by increasing the interfacial tension, the spherical shape of the droplet would tend to become an ellipsoidal one.

Reference

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