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Effect of flow type, channel height, and viscosity on drop production from micro-pores

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HIGHLIGHTS

- Numerical simulations are used to investigate drop detachment from micro-pores.
- The effect of shear flow type, channel height and viscosity on drop sizes is studied.
- Under certain conditions, drop sizes depended only on the applied wall shear rate.
- Under some conditions, the applied average shear rate was a good drop size indicator.
- Increasing the viscosity of the disperse phase produced smaller drops.

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ABSTRACT

The formation and detachment of drops from micron-sized pores into shear flow fields is investigated using numerical simulations. The open source software OpenFOAM is used for the simulations. The numerical algorithm employs the finite volume method for solving the mass and momentum conservation equations with a volume-of-fluid approach for capturing the fluid–fluid interface. In addition, a contact model accounts for the interaction between the fluids and the walls of the channel and pore. After validating the numerical models and methods by comparison to experimental data, a parameter study is performed to investigate the effect of various geometrical, flow and fluid parameters on the characteristics of drop production, in particular, drop size. The effect of the type of imposed channel shear flow (pressure-driven or plane Couette), channel height and fluid viscosity is considered. It is found that, in one range of Reynolds and capillary numbers, the channel wall shear rate is a good indicator of drop sizes, regardless of imposed shear flow type, channel height or viscosity ratio. In this flow regime, a master drop size curve is produced for each viscosity ratio considered, with the curve being shifted lower for the higher viscous disperse phase. In another flow regime, when Reynolds numbers are very large relative to capillary numbers, the average shear rate in the channel was a better drop size indicator, although a different master curve was produced for each channel height.

1. Introduction

Immiscible multiphase fluid systems are relevant in many applications in industries such as the food, pharmaceutical, and polymer industry. Despite being the focus of an extensive number of investigations, the efficient and reliable production of these fluid systems with desired properties remains a challenge. Of particular importance in many applications is the production of uniformly, or near uniformly, sized drops on the micro- or nano-scale. One approach used to create small drops of one liquid in another liquid relies on membrane devices in which drops are formed and detached from pores. Specifically, a disperse phase fluid is transported through pores and into a channel (or gap) containing a continuous phase fluid. Drops of the disperse phase are detached and transported through the channel by the imposed stresses and flow of the continuous phase. In traditional membrane devices, the membrane is stationary and a pressure-driven flow is imposed on the continuous phase fluid in order to detach drops. Other membrane devices have been used in which one or both of these conditions are modified. In the rotating membrane device (ROME), the membrane is cylindrical and rotates within an outer cylinder while the continuous phase fluid is pumped through the gap between the cylinders (e.g., Holdrich et al., 2010; Jaffrin, 2008; Mueller-Fischer et al., 2007; Schadler and Windhab,

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2006; Vladisavljevic and Williams, 2006; Yuan et al., 2008). The imposed continuous phase flow field is primarily Couette flow. Holzapfel et al. (2013) considered a membrane in a cone-and-plate-type device in which a rotor moves above the membrane, producing a homogeneous shear flow.

There have been many experimental, theoretical and computational studies on the production of drops from micro-pores, particularly in the single-pore T-shaped micro-channel, or T-cell. These studies have helped determine the influence of various fluid, flow, and geometrical parameters on drop formation and drop characteristics. Relevant parameters include the channel Reynolds number, capillary number, flow rate ratio, viscosity ratio, contact angle, and T-cell dimensions. From these studies, three regimes, or mechanisms, have been identified for the formation of drops in the T-shaped micro-channel (de Menech, 2006; Garstecki et al., 2006). When the channel height is large, so that the channel flow can be considered unbounded, the regimes are dripping and jetting; whereas when the channel height is small, so that the channel flow is influenced by its confinement, a squeezing regime is also present for small continuous phase flow rates. In this squeezing regime, the disperse phase extends to the outer wall and acts like an obstacle in the flow, causing a large pressure increase upstream of the pore. This large pressure buildup has a larger influence on the detachment of a drop than the relatively weak viscous forces which occur in this case.

Other behavior observed from experiments and simulations is related to the size and frequency of the detached drops. For a given fluid system in a given T-cell geometry, drop sizes are seen to decrease with increased continuous phase flow rate (or, equivalently, with increased Reynolds number or capillary number) when the disperse phase flow rate is held constant (e.g., Feigl et al., 2010; Husny and Cooper-White, 2006; Liu and Zhang, 2009; Nisisako et al., 2004; Sang et al., 2009). On the other hand, there is only a weak dependence of disperse phase flow rate on drop sizes.

It has also been seen that better drop detachment behavior occurs when the contact angle, measured from the disperse phase, is large, that is when the disperse phase does not significantly wet the walls. Simulations have shown that the (static) contact angle can have a significant effect on drop detachment characteristics, such as the frequency and point of detachment, as well as the drop sizes. For example, Liu and Zhang (2009) showed that drop sizes decreased as the static contact angle increased from 110° to 180°, that is, as the degree of non-wetting increased.

The effect of the viscosity ratio has been seen to depend on the detachment regime (e.g., squeezing or dripping) and on the individual viscosities of the two phases. In the dripping regime, if the viscosity ratio $\lambda = \mu_d/\mu_c$ is increased by decreasing the viscosity μ_c of the continuous phase fluid, there is an increase in drop sizes as a function of continuous phase flow rate (e.g., Husny and Cooper-White, 2006). The opposite relation has been seen in the dripping regime when the viscosity ratio was increased by increasing the dispersed phase viscosity μ_d (Liu and Zhang, 2009; Timgren et al., 2009). That is, smaller drops were produced when the viscosity of the disperse phase was increased. Experiments and simulations have also been used to determine the effect of non-Newtonian viscosity and yield stress on drop detachment in the T-cell (e.g., Husny and Cooper-White, 2006; Sang et al., 2009), as well as the effect of surfactants (e.g., van der Graaf et al., 2005).

In many of the above cited studies, empirical models and correlations were derived to related drop sizes to the relevant parameters, such as viscosity ratio, capillary number, and flow rate ratio. For example, Garstecki et al. (2006) proposed a linear relationship between the flow rate ratio and the plug length in the case when the drops were very large relative to the T-cell height. Husny and Cooper-White (2006) derived an expression to related drop sizes to a modified capillary number, defined as the product of the usual capillary number and a quotient involving the viscosity ratio.

While there have been many studies of the T-shaped micro-channel, there have been fewer studies in the other membrane devices, where the imposed channel flow field is not pressure-driven. Recently, Holzapfel et al. (2013) studied a flow cell in which a conical rotor is positioned above a flat membrane and imposes a homogeneous (linear) shear flow on the continuous phase. Among other relations, these authors found that the wall shear stress in the shear gap played a dominant role in the drop sizes.

The primary goal of the present study is to determine the relative capabilities of linear shear flow (or plane Couette) versus pressure-driven shear flow for drop production. The former is present in the cone-and-plate-type membrane device, and may also be considered as an idealization of the flow in a rotating membrane device, while the latter is imposed in the T-cell. The focus of the study is on the sizes of the detached drops. Numerical simulations are used to solve the two-phase flow problem in a single-pore geometry in two dimensions. In addition to the type of the imposed channel shear flow, the effect of the channel height and fluid viscosity on drop sizes is also determined.

2. Mathematical model and computational methods

The flow problem to be solved is that of a two-phase immiscible fluid system whose fluid–fluid interface interacts with solid walls. Both fluid phases are considered to be Newtonian and the interfacial tension is constant. The governing system of equations for this flow problem consists of (1) the mass and momentum balance equations for incompressible flow; (2) interface conditions to enforce continuity of velocity and jump in surface traction across the fluid–fluid interface; (3) boundary conditions on both fluid phases; (4) an equation to describe the evolution of the fluid–fluid interface in the flow field; and (5) a contact model for describing the interaction between the solid walls and the fluid–fluid interface.

The interface conditions are accounted for in the momentum equation by the addition of a surface force term which results from a force balance derivation in which the surface tension is treated as a body force concentrated along the interface (Brackbill et al., 1992). This leads to the following mass and momentum balance equations for the two-phase flow, which hold over the whole domain:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}\right) = -\nabla p + \nabla \cdot (\mu \dot{\boldsymbol{\gamma}}) + \sigma \kappa \delta_s \boldsymbol{n} \tag{2}$$

where $\boldsymbol{u}$ is the velocity field, p is the pressure, $\dot{\boldsymbol{\gamma}} = \nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\mathrm{T}}$ is the rate-of-strain tensor, and μ and ρ are the dynamic viscosity and density, respectively, whose values depend on the fluid phase. The last term on the right-hand side of Eq. (2) represents the continuum surface force (CSF) of Brackbill et al. (1992) and is nonzero only on the interface, as indicated by the Dirac delta function $\delta_s \equiv \delta(\boldsymbol{x} - \boldsymbol{x}_s)$ where $\boldsymbol{x}_s$ is a point on the interface. This force term is given as the product of the constant interfacial tension σ, the local mean curvature κ, and the unit normal vector $\boldsymbol{n}$ to the interface.

The fluid phases and location of the interface is described by a scalar function ϕ. In this paper, the volume-of-fluid (VOF) approach (e.g., Buwa et al., 2007; Francois et al., 2006; Renardy et al., 2001) is used in which ϕ is a volume fraction function. Specifically, $\phi(\boldsymbol{x}, t)$ is a spatially discontinuous function, having a value 0 or 1 for $\boldsymbol{x}$ in the continuous or the disperse phase, respectively. On a computational grid, ϕ is the volume fraction