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A numerical procedure for scaling droplet deformation in a microfluidic expansion channel

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HIGHLIGHTS

- Numerical study on the droplet deformation in a planar sudden expansion microfluidic.
- Boundary element method is applied to solve the Darcy equation.
- Maximum deformation depends on droplet size, Capillary number, and lateral position.
- Numerical results show a good agreement with experimental results.

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ABSTRACT

Motivated by recent experiments, deformation and relaxation of a droplet flowing through a narrow channel opening to a planar sudden expansion are studied. Using the boundary element method (BEM), we numerically solve the Darcy equation in the two-dimensional microfluidic channel and investigate droplet motion as the droplet enters the sudden expansion channel. We find two regimes of deformation with a dependency on relative droplet size compared to narrow channel width. A first regime, for droplet smaller than the narrow channel width, is characterized by a deformation affected by the droplet size and capillary number. The second regime, in which droplet larger than the narrow channel width, deformation is characterized by dependence on the capillary number and the width ratio of two channels. Our numerical scalings are in good agreement with reported experimental scalings. Finally, by employing the Fourier analysis method, the relation between the Fourier coefficients and droplet shape is investigated.

1. Introduction

Soft liquid interfaces are easily generated by using separated techniques and two-phase flow in a microfluidic chip. Microfluidic techniques have a wide potential for study of interfaces at small scales together with enhanced control possibilities. In microfluidic application, where droplet diameter is typically smaller than channel height, the flow behavior and droplet shape are significantly affected by the channel walls. Droplet deformation in microfluidic system is an important field in soft matter research. The deformation of a droplet in microchannel is also used to probe various processes occurring at the liquid interface [1–5]. Several empirical studies have been recently addressed to elucidate the behavior of droplet deformation, which is successfully described by the classical methods, through different channel geometries.

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The first empirical research on the droplet deformation was carried out by Taylor who studied experimentally the droplet deformation in various flow profile, range of viscosity ratio and capillary number [6,7].

Exploring effects of shear stress give us fundamental information on the rheological [8] and mechanical properties of the interface [9], particularly in the presence of adsorbed layers (surfactants). An essential part of the droplet-based microfluidic technology is surfactants by which droplet interfaces will be stabilized. One of the important challenges (for use of surfactant) is to understand various influence of surfactant adsorption on droplet deformation. The measurement of interfacial tension of immiscible fluids based on the deformation and retraction dynamics of droplets under extensional flow was invented for the first time by Hudson [10]. Flow constriction causes droplets to be deformed progressively in extensional flow gradient. It was shown that droplets elongate along the direction of the flow in the hyperbolic contraction. In this way, Franses et al. [11] have used different experimental techniques to measure surface tension. They have measured surface tension by using hydrodynamic deformation of droplet interface. Cabral et al. have obtained the surface tension through the analysis of the rate of droplet deformation in an extensional flow [12]. Mulligan [13] reported the addition of surfactant to the droplets flowing in the extensional microchannel results in production of tail at the rear of droplets, and hence, leads to droplet breakup. Brosseau et al. [14,15] designed a series of expansions distributed along a delay line for the measurement of surfactant adsorption dynamics on a microfluidic chip by measuring droplet deformation. Their experimental results illustrate that maximum droplet deformation in a planar sudden expansion channel scales with capillary number with an exponent 0.9 for high confinement system [15]. They have also studied influence of channel height on the droplet deformation [15]. They have reported that dependency of maximum droplet deformation on capillary number scales with a power law which depends on the ratio of channel height to channel width. Recently, Ulloa et al. [16] have experimentally investigated droplet deformation in the presence of hyperbolic flow rate in a high confinement system. Their results indicate that droplet deformation scales with capillary number and droplet radius with an exponent 0.92 and 2.59, respectively.

Several simulation methods like Lattice Boltzmann [17,18], finite difference [19], two-phase Lattice Boltzmann [20] and etc. have been applied to investigate the effects of droplet deformation through two/three-dimensional microfluidic channel. Eggleton and Stebe [21] have numerically studied effect of surfactant-laden interface on the droplet deformation in an external flow. They have found that droplet behavior is strongly influenced both by surfactant mass transfer rate and concentration of surfactant present. Their results indicate that, at low concentrations, droplet deformation decreases monotonically with increasing mass transfer rate when accumulation of surfactant near droplet tips is eliminated. At high concentrations, however, deformation varies nonmonotonically as mass transfer rate increases. Xi and Duncan [17] have simulated droplet deformation and also shear rates on droplet breakup in a straight channel. Boruah et al. [22] computationally showed that the intersecting flows at the cross-junction act like a constriction. So, droplet possesses rich deformation behavior as the droplet passes through the micro-junction. An ellipsoidal model for deformation of a Newtonian droplet in a dilute or semi-dilute emulsion was presented on the basis of the boundary integral method by Yu [23].

Studies for two-dimensional microfluidic channel have been first conducted by Romm [24] to perform kerosene and water flow through Hele–Shaw cell. It has been reported that these flows are not linear through porous media [25]. An approximate numerical scheme based on the boundary integral method has been developed to study the droplet deformation in extensional flow [26] and showed two distinct effects of surfactant on the droplet deformation in the case of low and large capillary numbers. Droplet formation in a Hele–Shaw cell has been studied by Shad et al. [27]. They also considered effects of various flow structures such as small bubbles, elongated bubbles, churn flow in a Hele–Shaw cell [28]. Deng et al. [29] employed arbitrary-Lagrangian–Eulerian numerical algorithm to study two-dimensional cylindrical/spherical deformation, oscillation and compared their findings with the analytical perturbation analysis. Nagel and Gallaire [30] have numerically calculated droplet deformation by using 2-D Darcy-Brinkmann equation in a Hele–Shaw cell. Relaxation of symmetrical droplet deformation has been numerically investigated by Brun [31]. Effects of interfacial slip on the dynamics of deformation, relaxation and breakup of single droplet in an uniaxial extensional flow under creeping-flow conditions have been investigated by using the boundary-integral technique [32]. It was reported that drop shape for a particular elongation ratio is relatively insensitive to slip [32].

Motivated by the recent experimental works of Brosseau et al. [12,14], in this work, the deformation and relaxation of droplet flowing through a microfluidic channel having a planar sudden expansion in a Hele–Shaw cell are investigated. We focus our attention on the Hele–Shaw cell in which ratio of channel height to channel width is small compared to one. Therefore, it is suitable to assume a two-dimensional flow of droplet and continuous phase which can be governed by Darcy equation. The droplet deformation is numerically calculated as function of droplet size, surface tension, and flow rate. Finally, we will investigate relation between droplet shape and Fourier coefficients.

This paper is organized as follows: In Section 2 we will formulate Darcy equation and boundary conditions for pressure and velocity fields belong to two-dimensional droplet in a Hele–Shaw cell. The numerical procedure used to solve the integral equation for the pressure field and, thus, the droplet motion will be explained in 2.1. Numerical solutions including droplet deformation, relaxation time and Fourier coefficients will be reported in Section 3. Finally, in Section 4 we will summarize our findings, draw conclusions and give an outlook on possible future work in this field.

2. Physical model and numerical methods

The idea of this work is to provide better understanding of the effect of capillary number and droplet size on droplet deformation. In this way, we numerically investigate the droplet deformation and relaxation in a planar sudden expansion.