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Droplet formation via squeezing mechanism in a microfluidic flow-focusing device

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ABSTRACT

In this work, the formation of droplets in a microfluidic flow-focusing device is studied and presented. Spurious velocities at the fluid–fluid interface were found to be very small in the lattice Boltzmann simulations. Using this technique, simulations have been performed to study the effect of geometry on formation of droplets for a microfluidic flow-focusing device. The effect of orifice width, orifice length and distance of the orifice on the mechanism of droplet formation and size of droplets is presented for different Capillary numbers. It is shown that, for $Ca \ll 1$, creation of droplets proceeds through the squeezing process that has earlier been observed in the T-junction configuration. The size of droplets increases with an increase in the (a) width, and (b) distance of orifice from the inlet. On increasing orifice length, droplet size first decreases to a minimum and increases thereafter. This study also reveals that the size of droplets becomes independent and approaches a constant beyond a critical value of the orifice length.

1. Introduction

Different methods of forming microsized droplets using passive breakup has been a focus of active research for the past two decades. Microscale droplets formed in a controlled size and frequency are particularly useful in a wide range of applications, such as food processing, drug delivery, tumor destruction, performing chemical reactions, in creation of emulsions, personal health care products and bubble generators [1,2]. There are a variety of devices that can be used to generate droplets at the microscopic scale. Primarily, three device geometries have received significant attention: using coflowing fluids [3,4], droplet formation at T-junction [5–9,10], and passing immiscible fluids through an orifice [11,12,13,14,15,16].

A microfluidic flow-focusing device combines the flow-focusing geometry into a microchannel, a schematic of which is shown in Fig. 1. As is shown, there exist three flow inlets to the device: the outer ones carry the continuous fluid and the inner one carries the to-be-dispersed fluid. As the two immiscible liquids interact, the three streams are made to pass through a narrow orifice placed at a distance from the inlet. Depending upon the flow and geometrical parameters, the interaction of the fluids results in the breakup of the inner liquid stream into droplets, which then flow downstream into the collection tube.

In one of the earliest studies conducted on the flow-focusing device, droplet formation scenarios for different flow regimes was documented by Anna et al. [11]. These experiments were conducted on a fixed geometry for different flow rate ratios using a combination of silicone oil (with surfactants to discourage coalescence of droplets formed past a narrow orifice) and water. Different regimes were observed, with droplet sizes ranging from the width of orifice to much smaller droplets of monodisperse to polydisperse distributions. Garstecki et al. [13], through experiments on the microfluidic flow-focusing device, provided evidence that the dynamics of the interface are dictated by inertia of the flow. More recently, Romero and Abate [15] have shown that droplet formation for low to moderate Capillary numbers in the flow-focusing device occurs as a result of plugging-squeezing process, similar to that observed in a T-junction device.

Numerical study of the flow-focusing device has also received some attention. Jensen et al. [14], using a Stokes' flow representation of the liquid phase, presented the dynamics of formation of gas bubbles in an axisymmetric flow-focusing device. Their results were used to derive a scaling law for the volume of bubbles created. Zhou et al. [16] studied the flow-focusing device through an adaptive meshing phase-field model. The mechanism of droplet formation for some of the observed flow regimes was explained. Scaling laws for dependence of droplet radius on the Bond number

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Nomenclature

c_s	speed of sound
C	color distribution variable
Ca	$\mu_c U_0/\sigma$, Capillary number
d^*	d/h_i, non-dimensionalised orifice width
d	width of orifice
$\vec{e_i}$	phase space velocity vector
f^a	particle distribution of fluid a
f^t	particle distribution after collision
$\vec{F}$	interfacial force
h_f^*	h_f/h_i, non-dimensionalised orifice distance from inlet
h_c	channel width of collecting tube
h_i	channel width of to-be-dispersed phase
h_0	channel width of continuous phase
l_{or}^*	l_{or}/h_i, non-dimensionalised orifice length
l_{or}	length of orifice
$\vec{n}$	normal to surface
n_x	number of lattice units along x-axis
n_y	number of lattice units along y-axis
Q_d	flow rate of dispersed phase
Q_c	flow rate of continuous phase
Q	Q_d/Q_c, flow rate ratio
U_0	average velocity of continuous phase

Greek symbols

β	anti-diffusion parameter
ρ	density of the fluid
ρ_r	density of the red fluid
ρ_b	density of the blue fluid
κ	local curvature
τ	relaxation time
∇_s	surface gradient operator
Φ_i	source term
σ	surface tension
μ_d	viscosity of dispersed phase
μ_c	viscosity of continuous phase
Λ	μ_d/μ_c, viscosity ratio

and flow rate ratio were given, which were shown to agree with their simulation results. It was also shown that inclusion of two extra channels to the geometry could be used to form compound droplets. Dupin et al. [12] have developed a lattice Boltzmann based framework that controls the coalescence of droplets formed downstream of the orifice in a flow-focusing device.

However, despite these studies, the effect of geometry of a flow-focusing device on droplet formation behavior has not received any attention. The dimensions and orifice position in the device can play an important role in destabilizing the interface and enforcing breakup. An understanding of the geometry and its influence on size of droplets formed can assist in meeting required targets for microfluidics devices. Thus, the objectives of this study are:

(1) Identify the mechanism through which formation of droplets occurs in a flow-focusing device at low Capillary numbers, and
(2) Quantify the dependence of droplet size on the size and location of the orifice in a flow-focusing device.

As shown in Fig. 1, three different geometrical parameters are associated with a flow-focusing device. These are the width of the orifice (d), the length of the orifice (l_{or}) and the distance of the orifice from inlet channels (h_f). Simulations for different Capillary numbers for a wide range of each of the three geometric parameters are conducted and presented.

2. Methodology

The simulation of multiphase flows can be performed using the front-capturing/diffuse-interface (for e.g., marker-and-cell, volume-of-fluid, level-set, lattice Boltzmann) or the front-tracking (for e.g., boundary integral) methods. The diffuse-interface methods are easy to model and can accommodate large surface topology changes, whereas the front-tracking methods tend to suffer from singularities that occur due to a rapidly evolving interface. In the present study, our focus has been on implementing a lattice Boltzmann based multicomponent model to simulate the droplet formation process in a two-dimensional microfluidic flow-focusing device.

2.1. Lattice Boltzmann method (LBM)

In recent years, the lattice Boltzmann method has emerged as a promising numerical technique to model fluid flows. LBM has been proven to be particularly successful in modeling fluid flows involving complex boundaries and interfacial dynamics. This method is based on microscopic kinetic equations that solve for the distribution function(f) of the fluid. The governing equations are such that the essential physics of mesoscopic processes is incorporated, and at the same time the averaged properties obey the macroscopic governing equations. The simplified kinetic model can accurately predict the flow behavior since the macroscopic fluid dynamics is the result of microscopic behavior of the particles of system collectively [17].

LBM modeling of fluid flows has several benefits over the conventional Navier–Stokes based simulation methods. For example, in LBM a linear partial differential equation is solved which is relatively easier than the Navier–Stokes equation in which convective terms lead to a non-linear partial differential equation. Also, static pressure in LBM is solved by using the equation of state, while in Navier–Stokes modeling it is calculated by solving the Poisson's

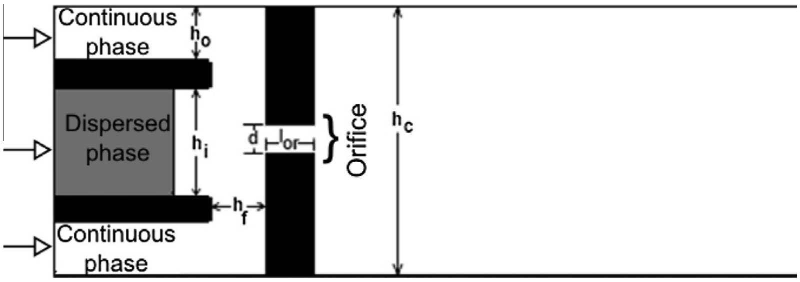

Fig. 1. Schematic diagram of flow focusing device.