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Influence of viscosity ratio and wettability on droplet displacement behavior: A mesoscale analysis

Pitambar Randive, Amaresh Dalal *

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India

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ABSTRACT

Fundamental understanding of droplet dynamics and the concomitant implications of wall wettability and viscosity are critical in the areas like enhanced oil recovery and clean energy conversion. In this work, mesoscopic illustration of droplet dynamics in a channel, based on the two-phase lattice Boltzmann model is presented in order to reveal the role of viscosity–wettability interaction. The impact of critical physicochemical determinants, including capillary number, viscosity ratio and droplet size is explored. Temporal evolution of wetted length and wetted area for a combination of viscosity ratios and wettability scenarios is furnished in detail in order to elucidate the droplet displacement dynamics. Droplet behavioral patterns stemming from uniform and mixed-wet wall characteristics in conjunction with capillary number and viscosity ratio have been investigated.

1. Introduction

The displacement of immiscible fluids is vital in the processes, such as enhanced oil recovery or the transport of non-aqueous phase liquids in the soil via water or surfactant flooding. The net efficacy of these processes depends on transportation of fluids through the network of pores and throats that make up the medium. There are many possible fluid–fluid displacement scenarios in such cases. However, viscosity ratio and wettability remain the key factors which govern the dynamics of the displacement of the fluid. Also, the interfacial instability is observed when fluid filling the voids of a porous medium is displaced by a less viscous one Baumann et al. [1], Wawersik [54]. Saffman and Taylor [40] have shown that the interface is unstable in the absence of surface tension. Homsy [19] had given a comprehensive review for instability of interface. Recent review by Govindarajan and Sahu [12] discusses the effect of variations of viscosity on the fluid flow. Several researchers Mukherjee [33], Kang et al. [23,24], Lu et al. [30], Owejan et al. [36], Bazylak [2] studied effect of wall wettability on the immiscible displacement of droplet. Karapetsas et al. [26,27] studied the droplet dynamics on an inclined, non-isothermal solid substrate. Dimi-trakopoulos and Higdon [5] studied the displacement of fluid droplets in viscous pressure-driven flows. However, the influence of viscosity–wettability interaction on displacement of the droplet remains largely overlooked. In this context, the underlying two-phase dynamics of droplet motion on the surface with uniform and mixed wettabilities is discussed.

Some of the notable works in this area are done by Taylor [50,51] who studied the viscous drop dynamics extensively. Bonnecaze [42] studied the dynamic behavior and stability of a two-dimensional immiscible droplet subject to shear or pressure-driven flow. The droplet is initially attached to the solid surface with the two contact lines that are either fixed or mobile. They applied an integral form of the Navier-slip model and allowed the droplet to slip along the wall. They assumed static contact angle model to analyze the effects of contact angle, capillary number (Ca) and droplet size and viscosity ratio on the droplet behavior. They observed the spreading of droplet along the wall until a steady shape is reached for the contact angles less than or equal to 90° followed by motion along the wall. However, they reported that the part of the droplet pinches off leaving behind a smaller attached droplet for higher capillary number. Kang et al. [23,25] has worked on uniform wettability on a surface by using lattice Boltzmann (LB) model for hydrophilic and hydrophobic range assuming static contact angle model. They studied the displacement of the two and three dimensional immiscible droplets subject to gravitational forces in a duct with lattice Boltzmann method (LBM). They investigated the effects of the contact angle and capillary number on droplet dynamics. Tomar et al. [52] analysed bubble growth in saturated film boiling using combined level-set and volume of fluid approach (CLSVOF). Ray et al. [39] performed numerical simulations to show entrapment of air bubble accompanied by high speed upward and downward water jets when a water drop impacts a pool of water surface.

* Corresponding author. Tel.: +91 361 2582677; fax: +91 361 2582699.
E-mail address: amaresh@iitg.ernet.in (A. Dalal).

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Nomenclature

A	wetted area
$\frac{A}{A_0}$	dimensionless wetted area
b	wetted length
$\frac{b}{b_0}$	dimensionless wetted length
f_i	probability density function
f_i^{eq}	equilibrium density function
$\mathbf{g}$	gravitational factor
g_{kw}	interactive strength between the component k and wall
$G_{k\bar{k}}$	interactive potential
h	width of the microchannel
V	volume of the droplet

Greek symbol

θ	contact angle
μ	dynamic viscosity
ν_k	kinematic viscosity of kth component
ρ_k	density of kth component
σ	surface tension
τ	relaxation parameter
ω	collision frequency
Ω	collision operator

Abbreviations

Ca	capillary number ($\frac{\rho_2 V g}{\sigma h}$)
HI	hydrophilic
HO	hydrophobic
LB	lattice Boltzmann
S–C	Shan and Chen

Among the aforementioned multiphase LB models, S–C interaction potential based approach is widely used due to its simplicity in implementing boundary conditions in complex porous structures. It is versatile in terms of handling fluid phases with different densities, viscosities and wettabilities, as well as having the capability of incorporating different equations of state. However, it cannot handle high viscosity ratios. On the other hand, the He's approach He et al. [17,18] is suitable for high viscosity ratio although it has issues with high density ratios. Sahu and Vanka [41] have used the algorithm proposed by He et al. [17,18], Zhang et al. [58] which is well suited for incompressible flows to study buoyancy-induced interpenetration of two immiscible fluids in a tilted channel. Zhang and Kwok [57] studied the dynamics of the wetting and movement of a three phase contact line confined between two superhydrophobic surfaces using a mean field free energy lattice Boltzmann model. Two regimes were found for the flow velocity as a function of surface roughness and can be related directly to the balance between driving force and flow resistance.

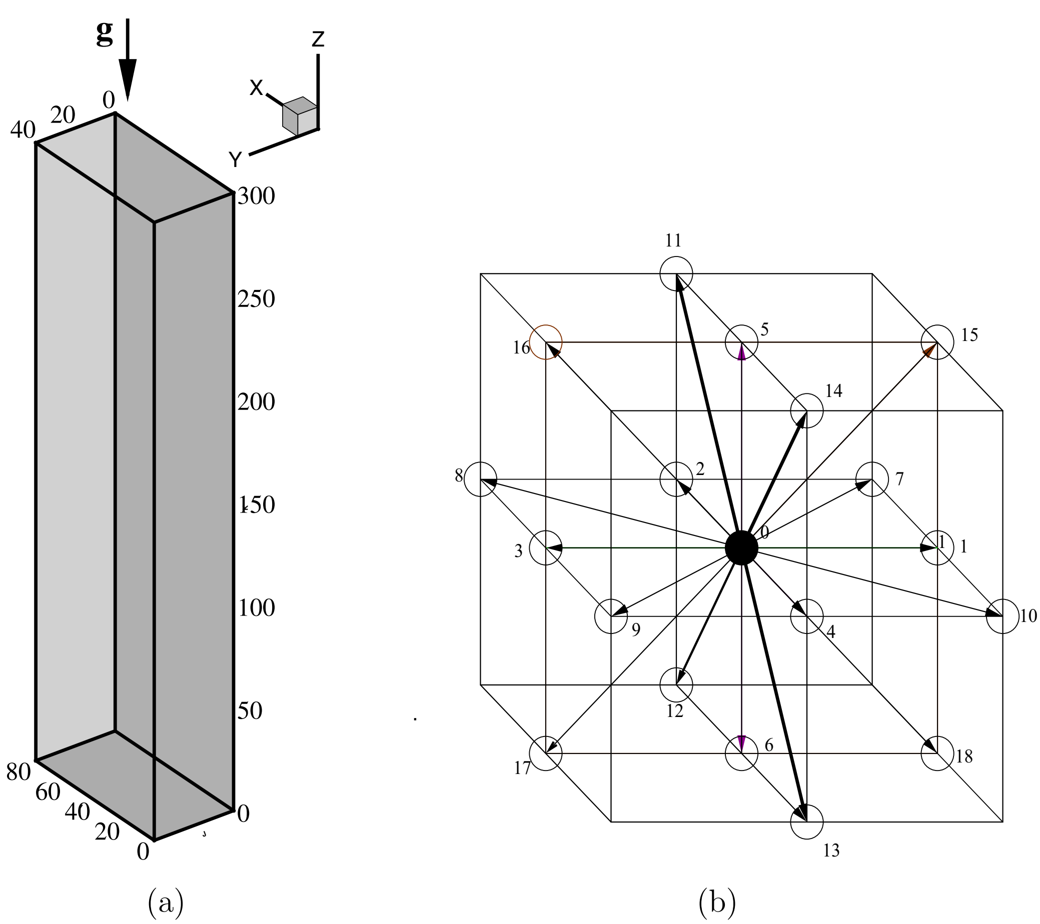

Fig. 1. (a) Computational domain, (b) $D3Q19$ lattice structure schematic.