International Journal of Multiphase Flow 000 (2017) 1–14

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Flow split characterization of two immiscible phases with different wettability scenarios: A numerical investigation using a coupled Cahn–Hilliard and Navier–Stokes system

Kai Bao[a], Amgad Salama[b,*], Shuyu Sun[c]

[a] SINTEF, Department of Applied Mathematics, Forskningsveien 1, 0373, Oslo, Norway
[b] Faculty of Engineering, University of Regina, Regina, S.K., Canada
[c] King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

ARTICLE INFO

Article history:
Received 16 June 2017
Revised 28 November 2017
Accepted 21 December 2017
Available online xxx

Keywords:
Two-phase immiscible flow
Couploupled Navier–Stokes and Cahn–Hillard
Moving contact line
Finite element method

ABSTRACT

Numerical investigation of flow branching of two-phase immiscible fluids in a Y-shaped, planner channel is conducted by solving the coupled Cahn–Hilliard and Naiver–Stokes system with finite element method. In this system a horizontal channel is branched into two identical and symmetric branches with the walls of the channels assigned several different wettability values. The studied scenarios consider a blob of one phase initially encompassed by the other phase. When an applied pressure difference induces flow, it is found that the motion of the blob in the two branches is significantly influenced by the wettability conditions at the channel walls. For the scenarios in which symmetric wettability configurations are applied, the blob divides equally among the two branches. For all the other scenarios in which the wettability configurations are asymmetric, the blob splits unequally. Comparisons between the different scenarios are performed in terms of the volume of the blob in each branch to investigate the percentage of the blob volume moving in each branch. In addition, we also considered the effect of the flow rate on the branching scenarios. In this work it is demonstrated that even though the pressure gradient is the same among the two symmetric branches, the phases partition differently when asymmetric wettability conditions are applied. The significance of this work may be that it provides evidences that relative permeability (a concept that has been introduced in the study of multiphase flow in porous media) may be more complex than just a mere scalar quantity function of saturation. It also highlights the importance of including the effects of wettability conditions in capillary pressure relationships.

1. Introduction

Porous media involve in addition to its complex internal structure, complex texture properties that could influence the motion of flowing fluids and dissolved materials. That is naturally occurring porous media involve several organic and inorganic materials which have very different affinities to the phases of flowing fluids. While the organic part of the soil has affinity to organic-based fluids like oil, inorganic and mineral rocks largely have affinities to water-based fluids. In other words, fluids moving in such formations will move under the influence of such affinity conditions in addition to the imposed pressure gradient. Furthermore, the displacement of one fluid by another immiscible with it provides a class of flow system that is complex to treat particularly if both fluids have different affinity to the confining pore surface materials. This situation can be found in many engineering applications including the displacement of oil with water or carbon dioxide, etc. The framework that is usually adapted to studying these multiphase systems in porous media is generally based on the continuum hypothesis in which overlapping continua of the phases interact with each other. In this framework, macroscopic variables represent continuous functions of space and time [e.g., (Whitaker, 1969; Hassanizadeh and Gray, 1979-a,b; Hassanizadeh and Gray, 1980; Salama and Van Geel 2008-a,b; El-Amin et al., 2011)]. Within this framework all the complexities of multiphase systems in porous media have been, in practice, lumped into only one parameter; called relative permeability, which has been assumed, primarily, function of saturation of respective phases. It has, however, been recognized the complex dependence of relative permeability on other factors (e.g., the wettability conditions of porous media surfaces). However, such dependence has always been incorporated into the saturation dependence. This implies that, for identical porous media struc-

* Corresponding author.
E-mail address: amgad.salama@uregina.ca (A. Salama).

https://doi.org/10.1016/j.ijmultiphaseflow.2017.12.016

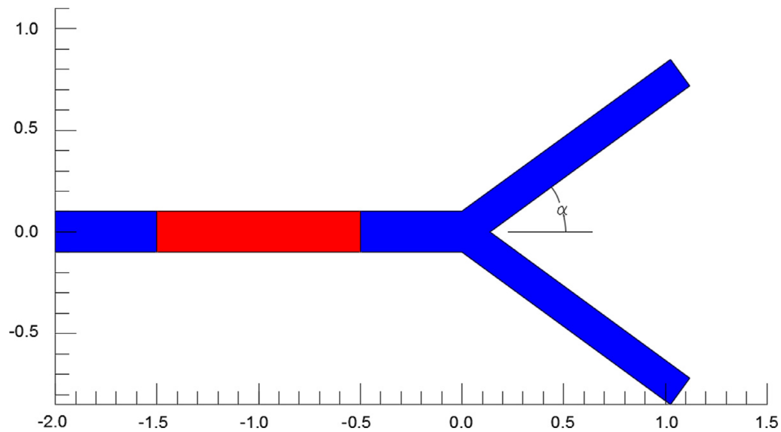

Fig. 1. Schematic diagram of branching scenarios.

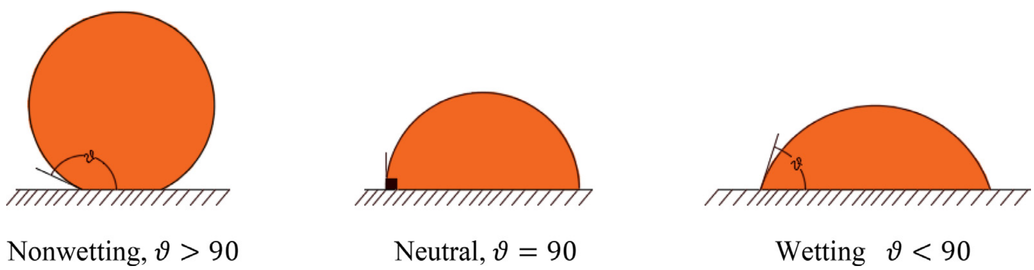

Fig. 2. Different wetting conditions.

ture we could have different relative permeability functions only because of differences of texture's wettability. In general, the role of wettability on the flow characteristics of multiphase system in porous media is not very well comprehended. It is our belief that, any success in adopting a macroscopic description to the problem of flow of multiphase system in porous media is very much provisional to our success in accurately describing fluid movement at the fluid continuum scale (i.e., at pore scale). That is, still much need to be done to accurately solve this problem, particularly on how to define the boundary conditions near the contact line of the fluid-fluid interface when they intersect the solid wall, where the traditional no-slip boundary condition may not be valid. For decades it has been a common practice in continuum fluid mechanics to consider a no-slip condition at the fluid-solid interface. However, this assumption results in an inaccurate modeling for the moving contact line problem. Several research works pointed out that, conventional theories of fluid mechanics fail to capture such slippage, which have been identified as the moving contact line problem [e.g., (Huh and Mason, 1977; Dussan and V., 1979; Joanny and de Gennes, 1984; Cox, 1986; Koplik et al., 1988; Thompson and Robbins, 1989; Thompson et al., 1993; Chen et al., 2000; Jacqmin, 2000; Qian et al., 2009)]. A few approaches have been proposed for which a good list can be found in He and Wang (2009). For example Qian et al. (2003) suggested the need to using the generalized Navier boundary condition (GNBC) to handle the moving contact line problem. With the generalized Navier boundary condition, relative slippage between the fluids and the solid surface is allowed and is assumed proportional to the sum of tangential viscous stresses and the uncompensated Young stress. In their framework, the coupled system of Cahn–Hilliard (CH) equations and the Navier–Stokes (NS) equations along with the GNBC provide a natural framework to dealing with the contact line problem. Their numerical results obtained using this framework show very good quantitative agreement with the results from the Molecular Dynamics (MD) simulations.

In this work, we investigate the influence of wettability conditions on the flow of two phase system in a branched Y-shaped channel under the effect of pressure difference. The aim is to show how wettability can entail the direction of the flow of the phases. This is extremely important in applications in which one fluid displaces another immiscible with it, e.g., in oil production. However, as explained earlier, because of the complexity of the internal structure of porous media, we consider a simple geometry at the pore scale. We consider the problem of flow divide of two immiscible fluids in a small channel. This geometry is a simplified version of flow branching in pore space within porous media and the different wettability conditions represent the heterogeneity of porous media texture. We would like to highlight the fact that splitting of phases among identical branching may be different according to their wettability characteristics. That is even if the pressure difference along the two branches is identical, yet the flow of the phases may be different along the two branches. The significance of this work is related to the idea that even if the medium may be isotropic and homogeneous with respect to the absolute permeability, a condition which entails the flux and the pressure gradient vectors to be coincident, still the direction of the flow of the two-phase system may be different than the imposed pressure gradient direction as a result of wettability conditions. In other words, the flow of the phases may preferentially select certain routes where the affinity is favorable. It is worth mentioning that Mehrabian et al. (2011) numerically investigated wicking through micropores of two-dimensional planar channels with a Y-shaped symmetric bifurcation under the influence of capillary forces. They considered steady Stokes equations coupled with Cahn–Hillard equation with a no slip boundary conditions. Since the flow under capillary forces is usually slow, the interface did not deform much from the nearly spherical shape. In this work, however, we consider the full unsteady Navier–Stokes equations as well as the generalized Navier boundary condition to account for the moving contact line dynamics. In such pressure driven flows,

Please cite this article as: K. Bao et al., Flow split characterization of two immiscible phases with different wettability scenarios: A numerical investigation using a coupled Cahn–Hilliard and Navier–Stokes system, International Journal of Multiphase Flow (2017), https://doi.org/10.1016/j.ijmultiphaseflow.2017.12.016