Journal of Colloid and Interface Science 522 (2018) 299–310

Contents lists available at ScienceDirect

Journal of Colloid and Interface Science

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

Regular Article

A study to investigate viscous coupling effects on the hydraulic conductance of fluid layers in two-phase flow at the pore level

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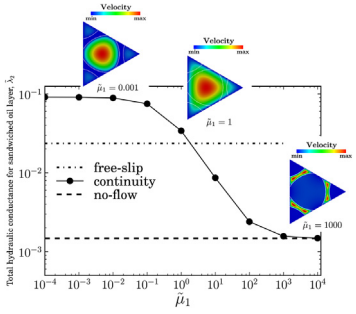
GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 January 2018
Accepted 11 March 2018
Available online 22 March 2018

Keywords:
Direct numerical simulation
Two-phase flow
Viscous coupling
Pore-network model

ABSTRACT

This paper examines the role of momentum transfer across fluid-fluid interfaces in two-phase flow. A volume-of-fluid finite-volume numerical method is used to solve the Navier-Stokes equations for two-phase flow at the micro-scale. The model is applied to investigate viscous coupling effects as a function of the viscosity ratio, the wetting phase saturation and the wettability, for different fluid configurations in simple pore geometries. It is shown that viscous coupling effects can be significant for certain pore geometries such as oil layers sandwiched between water in the corner of mixed wettability capillaries. A simple parametric model is then presented to estimate general mobility terms as a function of geometric properties and viscosity ratio. Finally, the model is validated by comparison with the mobilities computed using direct numerical simulation.

1. Introduction

Immiscible two-phase flow through porous media occurs routinely in a wide range of environmental and industrial processes, including enhanced oil recovery [1], carbon dioxide storage in subsurface aquifers [2,3], remediation of contaminated soils [4] and fuel cell technology [5,6].

The macro-scale modelling of these processes requires the specification of macroscopic momentum equations for each of the two fluids. These equations can be conventionally approximated as the extension of Darcy's law to two-phase flow with relative permeabilities for each phase [7]. However, this traditional approach often does not take into account the viscous coupling of the fluids due to the momentum transfer across the fluid-fluid interface [8]. The assumption of uncoupled flows of the fluids can lead to inaccurate results for those two-phase flow regimes in which coupling drag between fluid phases can be significant [9,10].

Several experimental and theoretical studies have reported the significance and effects of viscous coupling in two-phase flows. Whitaker [11] employed a method of volume averaging to analyze immiscible two-phase flow in a general porous medium. He

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https://doi.org/10.1016/j.jcis.2018.03.028
0021-9797/

developed a form of coupled Darcy-like equations containing additional terms that represent the influence of viscous drag exerted between fluid phases. Kalaydjian [12] studied the spontaneous counter-current flow of a non-wetting fluid ganglion by a wetting fluid in a square capillary tube. He proposed a new form of the two-phase Darcy equation in which a matrix of relative permeabilities, with equal off-diagonal terms representing the contribution of the viscous coupling, relates flow rates to pressure gradients. Avraam and Payatakes [13] employed a parameter estimation approach to obtain all four terms of the relative permeability matrix based upon a statistical analysis of experimental data, obtained from a set of steady-state co-current two-phase flows in a micro-model. They disputed the validity of Onsager-Casimir reciprocal relation and found that the off-diagonal coupling coefficients are not necessarily equal. Ehrlich [14] used semi-analytical equations to study the effect of viscous coupling on relative permeabilities in two-phase flow through an idealized model of a porous medium consisting of a bundle of regular polygonal capillary tubes, suggesting that the rheology of the interface can affect the magnitude of viscous coupling.

In addition to empirical and theoretical studies, numerical simulations have been recently used to uncover mechanisms that control and describe viscous coupling effects in two-phase flow at the pore level. Various pore-scale modelling approaches, such as pore-network models [15,16], lattice Boltzman methods [17,18], mesh-free Lagrangian particle methods [19] and Eulerian grid-based methods [20,21], have been employed. Li et al. [22] used a two-phase lattice Boltzmann model for two-phase flow through a homogeneous sphere-pack and systematically studied viscous coupling effects over a broad range of conditions, suggesting fluid-fluid interfacial area as a key parameter which can affect relative permeabilities. Dehghanpour et al. [23] employed a high-resolution finite-element numerical method to investigate viscous coupling for sandwiched layers in angular capillaries in three-phase flow. Xie et al. [24] proposed an improved pore-network model to accommodate viscous coupling effects and examined its efficiency through computing relative permeabilities for some mixed- and water-wet rock samples and provided comparisons with experimental results.

Among pore-scale modelling methods, pore-network models have grown in popularity due to their computational efficiency, which enables them to study large realistic rock samples [25–29]. These models rely upon a simplified representation of the pore space geometry and empirical models for hydraulic conductance and capillary entry pressure in pore/throat elements. The hydraulic conductance for each phase is a key parameter in pore-network models to relate the flow rate of a phase to pressure gradient.

Several studies have been performed to quantify and establish correlations for hydraulic conductances by relating them to pore geometry, contact angle and interface rheology. Ransohoff and Radke [30] employed a finite-element method to model the flow of a wetting phase along corners of predominantly gas-occupied noncircular capillaries. They quantified the relationship between the average velocity of the wetting phase in a corner, $\overline{u}$, and the pressure gradient within the phase, ∇p, as a dimensionless flow resistance, β,

$$\beta = -\frac{R_l^2}{\mu \overline{u}} \nabla p, \tag{1}$$

where R_l is the radius of interface curvature. They reported the computed dimensionless flow resistance for different pore geometries, contact angles and interfacial shear viscosities. Zhou et al. [31] established approximate analytical solutions to relate the dimensionless flow resistance, β, to pore and interface geometry for oil flow along sandwiched layers and water flow along corners of predominantly gas-occupied noncircular capillaries. Futaisi and Patzek [32] employed a high-resolution finite-element method in conjunction with a projection-pursuit regression approach to determine analytical correlations for three-phase hydraulic conductances in angular capillaries. However, none of theses models take into account the existence of viscous coupling between the flowing fluids and simply assume that conductances are independent of viscosity ratio, i.e. uncoupled flow of the fluids.

This assumption may adversely affect the accuracy of pore-network models when used to predict macroscopic flow properties such as relative permeabilities. Therefore, it is important to establish reliable hydraulic conductance correlations that respect the existence of viscous coupling between the two fluids and incorporate them into pore-network models. To do so, one can perform direct numerical simulations on various two-phase fluid configurations in single micro-scale capillaries to calculate generalized mobilities of each fluid, stabilized by capillary forces. Then, this information can be exploited to find mathematical expressions which can be incorporated into two-phase pore-network models in the form of hydraulic conductivities.

In this work, we first solve two-phase flow through square, triangular and star-shaped pore geometries with uniform and nonuniform wettability conditions using a volume-of-fluid finite-volume based numerical method. Then, we employ an approach similar to Dehghanpour et al. [23] to obtain simple parametric scaling models for the hydraulic conductance of centre, layer and corner flows as a function of the geometry and viscosity ratio. Finally, we find appropriate parameters for each model by fitting against general mobilities that are obtained from the numerical simulations.

2. Pore-scale modelling and validation

In this section, we first give a brief description of the direct numerical simulation approach used to model two-phase flow at the pore level. Then, the accuracy of the model in capturing the viscous coupling effects is validated for a square capillary tube for which a semi-analytical solution is available [14].

2.1. Numerical model

The following single set of Navier-Stokes equations is solved to describe an isothermal, incompressible, immiscible flow of two Newtonian fluids:

$$\nabla \cdot \mathbf{u} = 0, \tag{2}$$

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) - \nabla \cdot \mathbb{T} = -\nabla p + \mathbf{F} + \mathbf{f}_c, \tag{3}$$

where $\mathbf{u}$ is the velocity vector, $\mathbb{T} = \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$ is the viscous stress tensor, ρ is the local density, μ is the local dynamic viscosity, p is pressure, $\mathbf{F}$ is any body force and $\mathbf{f}_c$ is the capillary force computed based on a contour-level surface force model; see Shams et al. [21] for more details.

Since the two fluids are modelled as one single-fluid continuum system, the fluid-fluid interface is treated as a discontinuity in fluid properties using an indicator function, α. Therefore, the fluid properties of the system such as density and dynamic viscosity are calculated proportional to the indicator function,

$$\begin{aligned} \rho &= \alpha \rho_1 + (1-\alpha)\rho_2, \\ \mu &= \alpha \mu_1 + (1-\alpha)\mu_2, \end{aligned} \tag{4}$$

where the subscripts 1 and 2 denote the first and second phases, respectively. The indicator function, α, represents the volume fraction of one of the fluids in each computational cell. If the cell is