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A lattice Boltzmann investigation of steady-state fluid distribution, capillary pressure and relative permeability of a porous medium: Effects of fluid and geometrical properties

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ABSTRACT

Simulations of simultaneous steady-state two-phase flow in the capillary force-dominated regime were conducted using the state-of-the-art Shan–Chen multi-component lattice Boltzmann model (SCMC-LBM) based on two-dimensional porous media. We focused on analyzing the fluid distribution (i.e., WP fluid-solid, NP fluid-solid and fluid-fluid interfacial areas) as well as the capillary pressure versus saturation curve which was affected by fluid and geometrical properties (i.e., wettability, adhesive strength, pore size distribution and specific surface area). How these properties influenced the relative permeability versus saturation relation through apparent effective permeability and threshold pressure gradient was also explored. The SCMC-LBM simulations showed that, a thin WP fluid film formed around the solid surface due to the adhesive fluid-solid interaction, resulting in discrete WP fluid distributions and reduction of the WP fluid mobility. Also, the adhesive interaction provided another source of capillary pressure in addition to capillary force, which, however, did not affect the mobility of the NP fluid. The film fluid effect could be enhanced by large adhesive strength and fine pores in heterogeneous porous media. In the steady-state infiltration, not only the NP fluid but also the WP fluid were subjected to the capillary resistance. The capillary pressure effect could be alleviated by decreased wettability, large average pore radius and improved fluid connectivity in heterogeneous porous media. The present work based on the SCMC-LBM investigations elucidated the role of film fluid as well as capillary pressure in the two-phase flow system. The findings have implications for ways to improve the macroscopic flow equation based on balance of force for the steady-state infiltration.

1. Introduction

The steady-state infiltration through porous media (i.e., the simultaneous flow of two immiscible fluids at the dynamic equilibrium) is commonly encountered in natural and industrial processes, such as, non-aqueous-phase liquid (NAPL) migration (Oostrom and Lenhard, 1998; Fagerlund et al., 2006) and enhanced oil recovery (Liu and Zhang, 2015; Yu et al., 2015). The flow pattern features the competition between local drainage and local imbibition associated with breakdown and coalesce of fragmented fluid clusters, and the spatiotemporally invariant fluid saturation, fluid flux, capillary pressure and interfacial area at the statistical equilibrium (Avraam and Payatakes, 1995a,b,1999; Tallakstad et al., 2009a,b; Erpelding et al., 2013). Modelling of such two-phase flow process at the macroscale relies on the typical constitutive relationships, including relative permeability ($k_{r\sigma}$) and capillary pressure (p_c) as function of fluid saturation (s_w) as defined below (Li et al., 2017b; Bear and Cheng, 2010)

$$k_{r\sigma}(s_w) = \frac{k_\sigma}{k_{sat}}, \tag{1}$$

$$p_c(s_w) = p_n - p_w, \tag{2}$$

where, $\sigma = $ w, n denotes wetting phase (WP) or non-wetting phase (NP) fluid; and k_σ, k_{sat} and p_σ are effective permeability in the extended two-phase Darcy equation, intrinsic permeability and fluid pressure, respectively. These two equations provide an averaged representation of fluid and geometrical properties inside a representative elementary volume (REV) of the given solid-WP fluid-NP fluid system. However, they are not truly constitutive, in the sense that, $k_{r\sigma}(s_w)$ relation and $p_c(s_w)$ curve are both strongly hysteretic with respect to the flow conditions (i.e., steady-state infiltration or transient displacement) (Li et al., 2017b; Dana and Skoczylas, 2002; Tsakiroglou et al., 2007; Ramstad et al., 2012), and the

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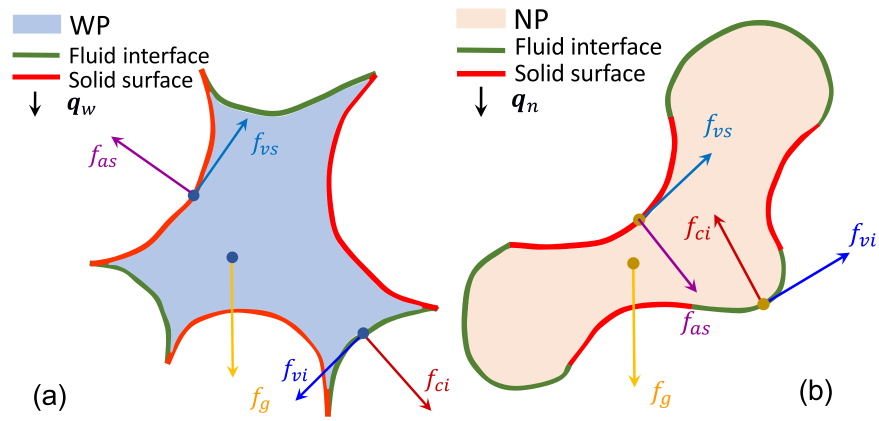

Symbol	Description
f_g	Gravity
f_{vs}	Viscous force at solid surface
f_{vi}	Viscous force at fluid interface
f_{as}	Adhesive force at solid surface
f_{ci}	Capillary force at fluid interface

Fig. 1. Representation of interfacial areas and pore scale forces for the WP (a) and NP (b) fluid packets, drawn from the configuration of two immiscible fluids inside a REV. For simplicity, the gravity is indicated as the flow driver.

capillary number (Li et al., 2017b; Constantinides and Payatakes, 1996; Henderson et al., 1997; Huang and Lu, 2009). In practice, it is questionable either to apply the $k_{r\sigma}(s_w)$ relation measured in the steady-state infiltration to predict the transient displacement behavior, or to utilize the $p_c(s_w)$ curve acquired from the displacement experiment for the steady-state flow analysis (Li et al., 2017b).

Film fluid around the solid surface and capillary pressure have been identified as important factors in controlling the $k_{r\sigma}(s_w)$ relation in the capillary force-dominated regime (Hao et al., 2008; Dou et al., 2014). As the focus of this study, both factors are intrinsic to the two-phase flow system in the coupled thermo-hydrodynamic steady-state infiltration. Longmuir (2004) suggested that, the adhesive interaction between fluid molecules in the pore and solid particles at the surface is capable of generating a WP fluid film around the solid surface, which reduces the WP fluid mobility (the degree of easiness for the fluid movement) and makes the fluid behave in a non-Newtonian way at the macroscale. Benzi et al. (2006) observed that, the repulsive fluid-solid interaction compelled the fluid particles to be away from the solid surface, and the fluid density and viscosity drop rapidly near the solid wall causing the apparent slippage behavior. To account for the macroscale effects of capillary force on the two-phase fluid flow, Hassanizadeh and Gray (1993a,b) proposed an advanced two-phase flow theory by introducing the fluid-fluid interfacial area as a new independent state variable. The proposed Darcy equation included gradients of fluid saturation and fluid-fluid interfacial area as the driving forces. The interfacial areas can be determined through the image analysis technique and calculated as follows (Chen et al., 2007; Porter et al., 2010),

$$A_{nw}(s_w) = \frac{(A_n + A_w - A_s)}{2},\ A_{ws}(s_w) = A_w - A_{nw},\ A_{ns}(s_w) = A_n - A_{nw}, \tag{3}$$

where, A_s, A_w, and A_n denote the specific surface areas of solid grains, WP fluid and NP fluid, respectively; and A_{nw}, A_{ws} and A_{ns} represent the fluid-fluid, WP fluid-solid and NP fluid-solid interfacial areas, respectively.

The two-phase flow process during the steady-state infiltration can be supposed to be the result of an interplay between gravity and adhesive, capillary, and viscous forces at the pore scale. As shown in Fig. 1, the individual WP and NP fluid packets in the two-phase flow system may form connected pathways or isolated in the form of bridges or ganglion. As given by the extended two-phase Darcy equation (Bear and Cheng, 2010), the stationary solid exerts viscous force on the two flowing fluids tangentially on the fluid-solid interfacial area. Adhesive or repulsive force is imposed by the solid surface to the adjacent fluids normally (Longmuir, 2004; Benzi et al., 2006). On the fluid-fluid interfacial area, both normal capillary resistance to the flow of two neighboring fluid packets (Hassanizadeh and Gray, 1993a,b) and tangential viscous coupling between the two flowing fluids occur. In the capillary force-dominated regime, viscous coupling process is not significant; and hence adhesive, capillary and viscous forces dissipate almost all the input energy through the interfacial areas. At the dynamic equilibrium where the macroscopic state variables reach the steady state (Bear and Cheng, 2010; Benzi et al., 2006; Berga et al., 2013; Chen et al., 2007,2017; Constantinides and Payatakes, 1996), a new macroscopic flow equation based on balance of force with consideration of the interfacial areas and the local parametrized pore scale forces can be potentially established.

Nevertheless, so far attention has rarely been paid to how fluid and geometrical properties determine the interfacial areas, the film fluid and the capillary pressure at the steady state. On the other hand, a large volume of literature concerned with the steady-state relative permeability subject to these properties have been published in the past few decades.

As the wettability increased, the WP relative permeability at each saturation decreased (Li et al., 2005; Hao and Cheng, 2010; Landry et al., 2014) due to the WP fluid in contact with more solid surface, while the NP relative permeability increased for the sphere-pack porous medium (Li et al., 2005) and carbon paper gas diffusion layer (Hao and Cheng, 2010) but decreased for the bead-pack system (Landry et al., 2014). The different behaviors of the NP relative permeability under the varying wettability could be attributed to two opposing mechanisms. With increased wettability, less NP fluid-solid interfacial area with less viscous resistance dominated the packing spheres (Li et al., 2005) and gas diffusion layer (Hao and Cheng, 2010), whereas more disconnected NP fluid with larger capillary resistance was dominant in the packing beads (Landry et al., 2014). Furthermore, the rock wettability can be altered by the distribution of brine and oil. As a result, the effect of mixed wettability on the relative permeabilities of two immiscible fluids becomes more complex (Landry et al., 2014). When evaluating the data of fluid flux versus pressure gradient for saturated clays, Swartzendruber (1962) was surprised to find a few positive pressure gradient intercepts of the fitted lines for the soils with more clay content. Subsequently, Miller and Low (1963) and Prada and Civan (1999) observed the threshold pressure gradient in clay and sandstone, respectively, below which the fluid could not flow. The nonlinear flow phenomenon was supposed to be due to reduced film fluid mobility and macroscale non-Newtonian fluid flow behavior caused by the adhesive fluid-solid interaction (Longmuir, 2004). Further, Hao et al. (2008) and Dou et al. (2014) suggested that, the threshold pressure gradient phenomenon in the two-phase flow process resulted from two aspects, film fluid effect and capillary resistance, offering a complete interpretation for the dependence of the $k_{r\sigma}(s_w)$ relation on capillary number (Li et al., 2017b; Constantinides and Payatakes, 1996; Henderson et al., 1997; Huang and Lu, 2009).