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A dynamic pore-scale network model for two-phase imbibition

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ABSTRACT

Pore-scale network modeling serves as an efficient tool for the simulation of multiphase flow in porous media, like carbon dioxide sequestration, enhanced gas/oil recovery and transport in fuel cell. To overcome the limitations of existing dynamic networks, we develop an alternative model for imbibition that accounts for the complex physical process of frontal displacement, film swelling, and snap off. The novelty of this model is that the outlet boundary is permeable to both wetting and non-wetting fluids before all the displaced phase is trapped. Instead of solving the nonlinear system of film pressure equations with conventional algorithms, a scale factor is employed to iteratively adjust the solutions estimated independently by mass conservation and the Young–Laplace equation until they are consistent with each other. To guarantee the effectiveness and accuracy, we also provide strategies for the selection of two significant considerations: scale factor and time-step size. This method is employed to study the effects of displacement rate and contact angle on waterflooding performance, relative permeabilities, as well as residual saturation. We believe this model can be further used to describe the distribution of slickwater in shale gas systems after hydraulic fracturing and predict water saturation based on the pore-scale topology of reservoirs.

1. Introduction

Fully understanding the transport phenomena and mechanisms of multi-phase flow in various natural or artificial porous media systems are of great theoretical and practical interest (Pan et al., 2004). Significant industrial examples include the enhancement of gas/oil recovery from conventional or continuous hydrocarbon accumulations (Amiri et al., 2015; Hatzignatiou et al., 2013; Wang et al., 2013; Min et al., 2015), the capture and sequestration of carbon dioxide to reduce atmospheric greenhouse gas emissions (Ellis and Bazylak, 2012; Ju et al., 2013; Kazemzadeh et al., 2015; Ren et al., 2011, 2014; Tao et al., 2013), as well as the protonic and water transport in polymer electrolyte membrane fuel cells (Xing et al., 2013). Stemming from its inherent multiscale character, large amounts of investigations have been implemented on the pore scale to precisely describe the complex physical and chemical processes. Several effective approaches therefore have been proposed, like micromodel experiments (Armstrong and Wildenschild, 2012; Buchgraber et al., 2012; Li et al., 2014; Mohammadi et al., 2013), network modeling (Blunt et al., 2013; Feng et al., 2012; Xu et al., 2014), and direct simulations using computational fluid dynamics (CFD) techniques: lattice Boltzmann (LB) (Ghassemi and Pak, 2011; Gunde et al., 2013), level set method (LSM) (Prodanović et al., 2013; Amiri et al., 2015), volume-of-fluid (VOF) (Raeini et al., 2012), and etc.

Based on the topologically representative network with idealized properties, pore network modeling, to some extent, not only exhibits great superiority on the computational efficiency over the exorbitant direct simulation methods, but also outweighs expensively phenomenological experiments. Hence, during the last few decades, network modeling has been employed as an efficient tool for the simulation of multiphase flow at the pore scale (Blunt et al., 2013).

The system of pore network modeling can be mainly divided into two types: quasi-static displacement by capillary pressure and dynamic drive with considering other forces (Al-Gharbi and Blunt, 2005). On the basis of percolation theory (Wilkinson and Willemsen, 1983), quasi-static models presume that pore-scale fluid configuration and displacement sequence are only

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dependent on capillary force while ignoring the dynamic effect caused by viscous forces. In these models, the final static position of fluid–fluid interfaces is deterministic and one meniscus advances during each time step (Al-Gharbi and Blunt, 2005; Idowu and Blunt, 2010; Mogensen and Stenby, 1998). Using a representative topology structure, transport properties of porous media, such as relative permeabilities and capillary force, can be predicted through the quasi-static assumption (Al-Futaisi and Patzek, 2003; Bryant and Blunt, 1992; Dixit et al., 1999; Dury et al., 1998; Øren et al., 1998; Øren and Bakke, 2003; Nasri and Dabir, 2014; Zhao et al., 2010).

However, the applicability of purely capillary-controlled displacement is very limited, and the approximation is inappropriate under several significant circumstances. A large number of experimental observations (Avraam and Payatakes, 1995) and numerical simulations (Al-Gharbi and Blunt, 2005; Idowu and Blunt, 2010; Mogensen and Stenby, 1998) have demonstrated that quasi-static models should be restricted to low values (below 10^{-4}–10^{-3}) of the capillary number (Ca) (Dullien, 1992; Blunt and Scher, 1995) defined by

$$Ca = \frac{\mu v}{\sigma} \tag{1}$$

The capillary number represents the ratio of viscous force to capillary pressure. If Ca is very small, then the effect of viscous forces can be negligible. That is why the assumption of quasi-static displacement can reproduce a few experiments with lower flow rates (Blunt et al., 2002). If the viscous pressure drops can be comparable to the capillary forces, i.e., under the situations of large viscosity (flows involving polymers and gels), high velocity (fracture and near wellbore flow), and low interfacial tension (surfactant flooding and near-miscible injection), both capillary and viscous effects are responsible for the multiphase flow at the pore scale (Blunt et al., 2002; Lenormand et al., 1998). Thus quasi-static models are invalid to simulate the fluid distributions and interface movements for large Ca.

Even though various definitions for capillary number have been proposed in previous publications, we still use the expression defined by Eq. (1) in order to be consistent with the cited references. Based on the scale and fluid properties, Jamaloei et al. (2010a, 2012) summarized the different definitions of Ca, and classified them into three different forms:

$$N_{c_1} = \frac{\mu v}{\phi\sigma \cos\theta} \tag{2}$$

$$N_{c_2} = \frac{\mu v}{\sigma \cos\theta} \tag{3}$$

$$N_{c_3} = \frac{\mu_{app} v}{\sigma \cos\theta} \tag{4}$$

The values calculated by Eqs. (2)–(4) are termed pore-scale capillary number, Newtonian-fluid capillary number, and apparent capillary number, respectively. The difference between Eqs. (2) and (3) lies in the introduction of porosity. The mathematical descriptions of Eqs. (3) and (4) are exactly the same except that the viscosity of Newtonian fluid is used in Eq. (3), while the apparent viscosity for chemical solutions, e.g., the displacing fluids of surface-polymer flooding (SPF) and surfactant flooding (SF), is adopted in Eq. (4). Taking into account that the spatial dimensions for a typical pore-scale model are always very small, it is reasonable to assume the porosity and contact angle are constant for this network. Therefore, if we use other Ca forms, the idea that quasi-static models can only be applied to low values of Ca is still valid. The only difference is that the threshold value (below 10^{-4}–10^{-3}) is greater than our results because Ca obtained from Eqs. (2)–(4) are equal to our definitions divided by $\phi\cos\theta$ or $\cos\theta$.

Viscous forces are explicitly incorporated within dynamic network models, in which the transient pressure response and interface positions are computed at each time step with many fluid menisci moving simultaneously (Al-Gharbi and Blunt, 2005; Mogensen and Stenby, 1998). Taking into account more sophisticated principles, dynamic models are able to capture the behaviors of interface more precisely, such as the movements of disconnected oil ganglia (Valavanides and Payatakes, 2001) and the phenomena of viscous fingering (Aker et al., 1998). Thus plenty of dynamic network models have been established and employed to investigate the relationship between the displacement performance and different controlling factors, like capillary number, viscosity ratio, as well as flow rate during drainage and imbibition (Aker et al., 1998; Blunt and King, 1991; Dias and Payatakes, 1986; Hughes and Blunt, 2000; Joekar-Niasar et al., 2010a, 2010b; Knudsen and Hansen, 2002; Koplik and Lasseter, 1985; Lux and Anguy, 2012; Mogensen and Stenby, 1998; Mohanty and Salter, 1983; Singh and Mohanty, 2003; Toubou et al., 1987; Valavanides and Payatakes, 2001; Vizika et al., 1994).

The key feature that distinguishes a dynamic network model from a quasi-static one is involved in the pressure computation. Under quasi-static approximation, the pressure difference at the fluid–fluid interface is the capillary force given by Young–Laplace equation, thus the displacement is simulated without solving the pressure distribution (Mogensen and Stenby, 1998, 1999). However, in dynamic network models, due to the capillary pressure, the system of equations obtained based on the rationale of volume conservation and Poiseuille's law is nonlinear (Lenormand et al., 1988; Toubou et al., 1987). According to Mogensen and Stenby (1998), more than 80% of the total CPU-time is spent on the solution of these nonlinear equations. Thus, a few simplified assumptions have been proposed to avoid complex calculations in dynamic models.

Lenormand et al. (1988) and Toubou et al. (1987) directly solved the nonlinear problem using a relaxation technique instead of substituting a sequence of linear problems for it (Mohanty and Salter, 1983; Koplik and Lasseter, 1985). Dias and Payatakes (1986) simulated ganglion motion through a network of spherical chambers connected by long cylindrical tubes with sinusoidally varying area. Blunt and King (1991) represented the porous media as an isotropic 2D Delaunay or 3D Voronoi network, and assumed that the throats had resistance to Poiseuille flow but no volume, whereas the pores contained all the two-phase fluids with ignoring the capillary pressure drop. Considering the pores as volumeless joining points, Aker et al. (1998) developed a dynamic network model to simulate primary drainage in a 2D lattice of throats, in which the local capillary pressure was given as a function of the interface location. Then this model was extended to study interfacial area and its relation to capillary pressure (Held and Celia, 2001), the competition of gravity, capillary and viscous forces (Løvoll et al., 2005), as well as the local capillary pressure effect that originated from inherent mineral surface heterogeneity (Ellis and Bazylak, 2012). Gao et al. (2013a, 2013b) proposed a rule-based pore-scale dynamic network model for air sparging—an *in situ* soil/groundwater remediation technology. They used the Biconical Abscissa Asymmetric CONcentric (BACON) bonds to represent the typical topology of soil (Gao et al., 2012). In order to estimate the conductance of each bond, an effective viscosity obtained from the saturation-weighted viscosity of individual phase was introduced.

However, all these models neglected the flow of wetting layer through the roughness and crevices of pore spaces—a significant mechanism to understand imbibition (Al-Gharbi and Blunt, 2005; Blunt et al., 2002; Idowu and Blunt, 2010). Several researchers took into account wetting film by keeping the conductance fixed and disallowing simultaneous filling of multipores (Dullien, 1992;