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Direct pore-to-core up-scaling of displacement processes: Dynamic pore network modeling and experimentation

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S U M M A R Y

We present a new dynamic pore network model that is capable of up-scaling two-phase flow processes from pore to core. This dynamic model provides a platform to study various flow processes in porous media at the core scale using the pore-scale physics. The most critical features of this platform include (1) the incorporation of viscous, capillary, and gravity pressure drops in pore-scale displacement thresholds, (2) wetting-phase corner flow in capillary elements with angular cross-sections, (3) adjustments of corner interfaces between wetting and non-wetting phases based on changes in local capillary pressure, (4) simultaneous injection of wetting and non-wetting phases from the inlet of the medium at constant flow rates that makes the study of steady-state processes possible, (5) heavy parallelization using a three-dimensional domain decomposition scheme that enables the study of two-phase flow at the core scale, and (6) constant pressure boundary condition at the outlet. For the validation of the dynamic model, three two-phase miniature core-flooding experiments were performed in a state-of-the-art micro core-flooding system integrated with a high-resolution X-ray micro-CT scanner. The dynamic model was rigorously validated by comparing the predicted local saturation profiles, fractional flow curves, relative permeabilities, and residual oil saturations against their experimental counterparts. The validated dynamic model was then used to study low-IFT and high-viscosity two-phase flow processes and investigate the effect of high capillary number on relative permeabilities and residual oil saturation.

1. Introduction

Multiphase flow in porous media occurs in many natural and artificial processes such as subsurface flow of hydrocarbons and brine, geologic storage of CO_2, non-aqueous phase liquids (NAPL) migration in soil, reactive transport, and water removal in gas diffusion layer (GDL) of proton exchange membrane (PEM) fuel cells. Understanding the displacement and transport processes relevant to multiphase flow systems and predicting the associated macroscopic properties are crucial for design and prediction of performance of these processes (Dullien, 1992; Sahimi, 2010).

In petroleum and environmental engineering contexts, multiphase flow in porous rocks has been studied extensively using experimental and numerical techniques at multiple scales. Large-scale continuum models (e.g. reservoir models) generally solve mass conservation partial differential equations over grid blocks of the medium that are larger than (or equal to) Representative Elementary Volume (REV) of that medium. These models read as input multiphase flow functions such as relative permeabilities. These functions are manifestation of many pore-scale phenomena, and they inform the numerical solvers of mass conservation equations about the underlying displacement physics. Pore-scale investigations are often used to develop improved understanding of fundamental phenomena relevant to a given process and predict the pertinent flow and transport properties. These physically-based properties are then used to inform the larger-scale continuum models.

The pore-scale models can be categorized into direct and network models. In direct models, multiphase flow is simulated directly in the pore space structure that is mapped using an imaging technique or created by a process-based reconstruction method, e.g., sedimentation simulation. Direct models include Lagrangian particle-based (mesh-free) methods, such as moving particle semi-implicit (MPS) (Koshizuka et al., 1995; Premože et al., 2003; Ovaysi and Piri, 2010, 2011), smoothed particle hydrodynamics (SPH) (Gingold and Monaghan, 1997; Zhu et al., 1999; Tartakovsky and Meakin, 2005), and Lattice Boltzmann (Inamuro et al., 2004; Li et al., 2005), and mesh-based methods, e.g., finite element (Fourie et al., 2007). These models use accurate representation of the pore space. However, due to irregular fluid–solid boundaries and deformability of fluid–fluid interfaces, direct

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models are computationally expensive and may not be suitable for studying multiphase flow at the core scale. In the second group of pore-scale models, i.e., network models, the pore space is represented by a network of idealized pores and throats. Pore-scale displacements are carried out in the pore network to simulate multiphase flow (Øren et al., 1998; Patzek, 2001; Blunt et al., 2002; Piri and Blunt, 2005a,b).

Pore network modeling was first introduced in the 1950s by Fatt (1956a,b,c) who used a network of real resistors to calculate relative permeability and capillary pressure for a drainage process. Network modeling, since its introduction, has evolved enormously. Today, one can map the pore space of a rock sample with high-resolution imaging techniques and extract an equivalent pore network (Dong and Blunt, 2009). Our knowledge of the pore-scale displacement physics has also improved dramatically due to micro-fluidics and other types of experiments. Pore network models can be divided into quasi-static and dynamic. The majority of the previously-developed network models are quasi-static in which the pore-scale displacements take place based on their threshold capillary pressure. These models have had significant success in modeling two- and three-phase flow in porous media under capillary-dominated conditions (Øren et al., 1998; Patzek, 2001; Øren and Bakke, 2003; Valvatne and Blunt, 2004; Piri and Blunt, 2005a,b). However, quasi-static models do not include the effects of viscous and gravity forces, and therefore, cannot be used to study cases in which capillary-dominated assumptions do not apply. Viscous and gravity forces become significant during many subsurface flow processes, such as enhanced oil recovery (EOR) methods of polymer and surfactant flooding, and high velocity flow regimes that are encountered in naturally and hydraulically induced fractures as well as near well-bore areas (Lake, 1989; Sahimi, 2010). In these cases, the combined effects of capillary, viscous, and gravity forces determine the flow behavior in porous media. In dynamic network models, on the other hand, viscous and in some cases gravity forces are taken into account. These models can be used to study the cases in which viscous or gravity forces are relevant. However, due to various reasons, such as difficulties in implementing the complex pore-scale physics and the computational costs associated with these models, the previously-developed dynamic models lack some of the critical capabilities to successfully simulate dynamic two-phase flow processes at the core scale.

Tables 1 and 2 list the previously-developed dynamic pore network models along with their largest network size, phenomena studied, and validation techniques. A comprehensive review of dynamic pore network models of two-phase flow in porous media can be found elsewhere, see, Joekar-Niasar and Hassanizadeh (2012) and Aghaei (2014). Here, we discuss the characteristics and predictive capabilities of each previously-developed model. We then present an overview of the dynamic model developed under this study and explain the critical relevance of its capabilities within the context of direct up-scaling.

Koplik and Lasseter (1985) developed the first dynamic network model to study the effects of microscopic pore structure on macroscopic phenomena. They stated the computational difficulties associated with dynamic pore network modeling as the limiting constraint in selecting the network size. Lenormand et al. (1988), Blunt and King (1991), and Lee et al. (1995) developed models in which the pores contained all the fluid and the pressure drops took place exclusively in the throats. Lenormand et al. (1988) performed drainage simulations at various capillary numbers and viscosity ratios and identified three distinct flow patterns. Blunt and King (1991) ran drainage simulations in two- and three-dimensional random networks and calculated relative permeabilities based on local flow rates and pressure drops. The model developed by Lee et al. (1995) was a parallel model that was used to perform water-flooding and miscible-flooding simulations in networks as large as 524,288 pores. This model was later extended by Kamath et al. (1996) and Xu et al. (1999) who were able to to reproduce recoveries in a fully *miscible* core-flooding experiment in a dolomite sample.

van der Marck et al. (1997) extended the model introduced by Lenormand et al. (1988) by allowing up to two menisci in pore throats. Mogensen and Stenby (1998) developed a model in which the corner flow and snap-off displacements were incorporated. Aker et al. (1998) developed a model with hourglass-shaped throats to study time dependencies of pressure distribution and fluid front in drainage processes. Later, Knudsen and Hansen (2002) modified this model by adding biperiodic boundary conditions. Dahle and Celia (1999) introduced a new interface tracking method in which fluids could form compartments that were separated by fluid–fluid interfaces. Hughes and Blunt (2000) used the wetting-phase viscous pressure drop to perturb the order of displacements. This quasi-dynamic model was used to study the effect of the capillary number during imbibition. Constantinides and Payatakes (2000) studied the effects of wetting layers on disconnection of the non-wetting phase during imbibition. Thompson (2002) created random pore networks with converging–diverging geometry for throats to study drainage and imbibition in fibrous materials. Singh and Mohanty (2003) introduced a new method for handling the corner flow in which the wetting phase was removed from the layers in proportion to the local capillary pressure drop. Nordhaug et al. (2003) extended the model developed by Blunt and King (1991) to study interfacial velocities and areas. Løvoll et al. (2005) studied drainage of a high-viscosity wetting phase and stabilizing effect of gravity using a dynamic pore network model and glass beads experiments.

Al-Gharbi and Blunt (2005) incorporated layer swelling and snap-off displacements in a dynamic model and used it to study the effects of capillary number and viscosity ratio in drainage in

Table 1
Previously-developed dynamic pore network models.

Study	Largest network size[a]	Phenomena studied	Validation techniques
Koplik and Lasseter (1985)	100	Effect of N_c on trapping	N/A
Lenormand et al. (1988)	10,000	Flow regimes	Micro-models
Blunt and King (1991)	80,000	Drainage K_r	Buckley-Leverett
Lee et al. (1995)	524,288	Imbibition K_r, S_{or}, P_c	N/A
Kamath et al. (1996)	262,144	Saturation profiles, recoveries	Unsuccessful core-flooding
Xu et al. (1999)	131,072	Saturation profiles, recoveries	Recoveries in miscible flooding
van der Marck et al. (1997)	2,401	Pressure field in drainage	Micro-models, viscosity ratio of one
Mogensen and Stenby (1998)	3,375	Trapping, S_{or}	N/A
Aker et al. (1998)	4,800	Pressure field in drainage	Glass beads, viscosity ratio of one
Dahle and Celia (1999)	8,381	P_c in drainage	N/A
Hughes and Blunt (2000)	16,384	K_r, flow patterns	Micro-models

[a] Maximum number of pores.