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Numerical investigation on immiscible displacement in 3D rough fracture: Comparison with experiments and the role of viscous and capillary forces

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ABSTRACT

Immiscible fluid-fluid displacement in rough fractures is important in many subsurface processes, including enhanced oil recovery and geological carbon sequestration. Numerous previous works experimentally investigated the dynamics of multiphase flow in fractures, but direct numerical simulation for fluid-fluid displacement in 3D rough fractures and the validation with experiments were rarely reported. Here we perform 3D direct numerical simulations for drainage processes of water displacing oil in a real rough fracture with capillary number $\log_{10}Ca$ ranging from −3 to −5. Comparison between experiments and simulations shows that the simulated results can generally reproduce the dynamic invasion morphologies at the scale of fracture. The discrepancy of the invasion morphologies, however, is observed at the local scale, mainly because the mesh resolution is not small enough compared with the scale of the interface. We then perform quantitative analysis of the simulated results to investigate the role of capillary and viscous forces. We show that Haines Jump events in the flow passage of void neck connecting to a wider void occur in the capillary-dominated flow regime. Statistical analysis of the velocity fields under various flow rate conditions shows that as the effect of viscous force becomes more important and eventually dominates that of capillarity, void-filling toward the outlet is continuously enhanced, with the velocity vector angles being more probably localized in the zone around the bulk flow direction. The direct evidence provided by the 3D numerical simulations improves our understanding of the competition of viscous and capillary forces controlling the immiscible displacement in rough fractures.

1. Introduction

The flow of immiscible fluids through rock fractures is of great interest to many engineering applications, including enhanced oil recovery in fractured reservoirs (Adibhatla and Mohanty, 2008; Austad et al., 2011; Bikkina et al., 2016; Meng et al., 2017; Zhang et al., 2017), geological CO_2 sequestration (de Dios et al., 2017; Ren et al., 2017) and environmental contamination by non-aqueous phase liquid (Ji et al., 2008; Detwiler et al., 2009; Lee et al., 2010; Faisal et al., 2015). Due to their much higher permeability compared with rock matrix, preferential flow paths always occur in fractures. When immiscible fluids are involved, description of such flow behaviors of multiple phases with interfaces is much more complicated. In geological CO_2 sequestration, the presence of fractures in sealing formations may pose a threat of upward migration of CO_2 and brine from deep reservoirs (Miocic et al., 2016). For enhanced oil recovery, the non-compact fluid-fluid displacement during water flooding would significantly reduce the displacement efficiency. Therefore, understanding and controlling the multiphase flow in rock fractures are important for optimizing subsurface fluid management.

The investigation of immiscible fluid-fluid displacements in permeable media can be traced to Hele–Shaw experiment performed over one hundred years ago (Hele–Shaw, 1898). Although it has long been studied, characterization of multiphase flow remains a challenging issue, due mainly to the complex interplay between the capillary and viscous forces (Homsy, 1987; Wong, 1994; Hu et al., 2017b, 2018). The pioneering study in 2D porous media provided a basic understanding that displacement patterns vary from capillary to viscous fingering as the role of viscous force becomes more important and eventually dominates that of capillarity (Lenormand et al., 1988). This interplay of capillary and viscous forces impacting displacement patterns was also recognized for rough fractures, but the crossover zone from capillary fingering to viscous fingering is much narrower than that in porous media due to the differences in the geometry of void spaces (Chen et al., 2017). The light-transmission experiments (Fourar and Bories, 1995; Persoff and Pruess, 1995; Amundsen et al., 1999; Babadagli et al., 2015a, b; Chen et al., 2017, 2018) and computed-tomography (CT) experiments (Bertels et al., 2001; Karpyn et al., 2007) provide evdiences and insights that how fracture-wall geometry together with capillary and viscous forces impacts fluid occupancy and invasion morphology during immiscible

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displacement (Amundsen et al., 1999; Neuweiler et al., 2004; Karpyn et al., 2007; Babadagli et al., 2015b; Yang et al., 2016).

The laboratory-based CT experiment permits 3D visualization of the phase configuration in fractures, but its time resolutions cannot match the actual occurrence of flow events. Consequently, this method can be used only for quasi-static conditions rather than dynamic cases (Bertels et al., 2001; Karpyn et al., 2007; Karpyn and Piri, 2007), unless the synchrotron-based X-ray CT is employed (Berg et al., 2013; Reynolds et al., 2017). On the other hand, the light-transmission experiment can provide real-time imaging of fluids displacement processes (Neuweiler et al., 2004; Bergslien and Fountain, 2006; Chen et al., 2017), but the image of fluid distribution is 2D, hence failing to capture the 3D features of the fluid-fluid interfaces. More importantly, since the experimental observations cannot access to the detailed information of flow behaviors (including the velocity and pressure fields within the whole domain of fracture space), quantitative analysis of fluids displacement only relies on the imaging of dynamic invasion morphology, hence lacking a link to the evolutions of velocity and pressure.

Direct numerical simulation permits access to information on interface advancement in three dimensions as well as on the velocity/pressure fields linking to dynamic invasion morphology, thus improving the understanding of multiphase flow in rough fractures. Numerical investigation of the immiscible flow has been conducted using pore-network models (Joekar Niasar et al., 2009; Raeesi and Piri, 2009; Yuan et al., 2015), computational fluid dynamics (Ferrari et al., 2015; Raeini et al., 2015; Hu et al., 2017a), Lattice Boltzmann methods (Jiang and Tsuji, 2015; Liu et al., 2015), and the smooth particle hydrodynamic methods (Bandara et al., 2011). Most of these numerical studies focused on multiphase flow in 3D porous media and 2D microfluidics, and only a very few of emphases were given to rough fractures (Amundsen et al., 1999; Neuweiler et al., 2004; Yang et al., 2012; Dou et al., 2013). Amundsen et al. (1999) developed an invasion percolation model for predicting the flow patterns of air displacing water in rough-walled plates in the capillary-dominated flow regime. Later on, Neuweiler et al. (2004) verified the invasion percolation model via displacement experiment in a rough fracture and demonstrated the role of the in-plane curvature that would stabilize the displacement front (Glass et al., 1998; Yang et al., 2012). Karpyn and Piri (2007) extended the invasion percolation model to consider the dynamic effect. Dou et al. (2013) employed the Lattice Boltzmann Method to study the wettability effect on the fluid-fluid interface area during immiscible displacement in a 3D self-affine rough fracture. Despite the above efforts, direct numerical simulation for fluids displacement in real 3D rough fractures and the corresponding validation by experiments were rarely reported.

Here we perform direct numerical simulation of the full Navier–Stokes equations with the Volume of Fluid (VOF) method tracking the fluid-fluid interface for modeling the two-phase flow of water displacing oil in a 3D rough fracture. We validate the numerical simulation via experimental results independently documented in our previous study (Chen et al., 2017), with the aim to show that whether the direct numerical simulation can satisfactorily reproduce the fingering flow in rock fractures at various capillary numbers. We then perform quantitative analysis on the role of viscous/capillary forces in controlling displacement pattern by linking 3D displacement front advancement to the pressure variations, and the detailed 3D velocity fields. This study not only provides comparisons between experiments and direct numerical simulations for multiphase flow in a rough fracture, but also improves our understanding of the effect of the competition between capillary and viscous forces on displacement processes.

2. Experiments and simulations

2.1. Overview of experiments

We carried out a series of drainage experiments of water displacing silicone oil in a transparent rough fracture, and the details of the experiments were reported in Chen et al. (2017). The transparent rough fracture is 20 cm in length and 10 cm in width, comprised of two resin replicas that were fabricated from a granite fracture. We used a high-resolution non-contact 3D Laser Scanning method (e.g., Chen et al., 2015) to measure the topography of the fracture surface (Fig. 1a), with a resolution of $\pm 1\ \mu$m in the z direction. After the scanned data were recorded automatically at every 200 μm interval in both the x and y directions, we then reconstructed each square-surface (200 μm × 200 μm) in an anticlockwise order and finally obtained the 3D surface of the full range of the rough fracture, as shown in Fig. 1a'. The light transmission technique (Detwiler et al., 1999) was employed to measure the aperture field of the duplicated fracture (Fig. 1b), with its mean being $\langle b \rangle = 0.660$ mm and the standard deviation being $\sigma_b = 0.123$ mm. The static contact angle of water is $\theta = 134^\circ \pm 4^\circ$. We first fully saturated the fracture with silicone oil and then dyed water was injected via an ISCO pump into the fracture to displace oil at constant flow rates. The water invasion morphology during the drainage processes in the entire fracture was recorded at 10 frames/s with a CCD camera until the invading fluid reached the outlet of the fracture. Experimental results with flow rates $Q = 0.3$, 1, 10, 30 and 100 mL/min and viscosity ratio $M = \mu_i/\mu_d = 1/100$ (μ_i and μ_d are, respectively, the viscosity of the invading and defending fluids) were adopted for comparison. As reported in Chen et al. (2017), independent experiments were conducted and showed good reproducibility of the experimental observations. We use the classic macroscopic capillary number $Ca = \mu_i v_i/\sigma$ to represent the relative effect of viscous force to capillary force, where σ is the interfacial tension, $\sigma = 35.0$ mN/m (Peters and Arabali, 2013), and $v_i = Q/A_c$, A_c is the cross-sectional area of the inlet, $A_c = 23.2$ mm^2. The capillary number Ca in the experiments spans three orders of magnitude, $\log_{10}Ca$ = −5.59, −5.07, −4.07, −3.59, and −3.07. The corresponding displacement patterns include both capillary and viscous fingerings.

2.2. Direct numerical simulation

The water invasion processes in rough fractures can be described by the Navier–Stokes equations (Eqs. (1) and (2)), together with the volume of fluid method (VOF) that tracks the evolution of fluid-fluid interface (Eq. (3)):

$$\frac{\partial(\rho(\alpha)\mathbf{u})}{\partial t} + \nabla\cdot(\rho(\alpha)\mathbf{u}\mathbf{u}) = -\nabla p + \nabla\left[\mu(\alpha)\left(\nabla\mathbf{u} + \nabla^T\mathbf{u}\right)\right] + \boldsymbol{f}_s \quad (1)$$

$$\nabla\cdot\mathbf{u} = 0 \quad (2)$$

$$\frac{\partial\alpha}{\partial t} + \nabla\cdot(\alpha\mathbf{u}) + \nabla\cdot\left(\alpha\cdot(1-\alpha)\mathbf{u}_r\right) = 0 \quad (3)$$

where $\mathbf{u}$ is the fluid velocity, p is the pressure, μ is the viscosity, and $\mathbf{u}_r$ is an artificial compression velocity to limit numerical diffusion (Rusche, 2003; Greenshields, 2015). The variable α represents the volume fraction of fluid within cells, i.e. $\alpha = 0$ for non-wetting phase, $\alpha = 1$ for wetting phase, and $0 < \alpha < 1$ for the fluid-fluid interface. Consequently, the density $\rho(\alpha)$ and the viscosity $\mu(\alpha)$ can be written as $\rho(\alpha) = \rho_w\alpha + \rho_{nw}(1-\alpha)$ and $\mu(\alpha) = \mu_w\alpha + \mu_{nw}(1-\alpha)$, respectively, where the subscripts w and nw denote the wetting and non-wetting phases, respectively. $\boldsymbol{f}_s$ represents the contribution of momentum from the surface tension at the fluid-fluid interface, expressed as (Ferrari and Lunati, 2013):

$$\boldsymbol{f}_s = -\sigma\cdot\nabla\cdot\left(\frac{\nabla\alpha}{\|\nabla\alpha\|}\right)\cdot\nabla\alpha \quad (4)$$

We employ the multiphase-flow solver (interFoam) included in the open-source library OpenFOAM (Greenshields, 2015) to directly solve the governing equations (Eqs. (1)–(3)) for the drainage processes in the 3D rough fracture. In simulations, the initial time step is set as 2.0×10^{-5} s with automatic adjustment based on the Courant–Friedrichs–Lewy (CFL) number. The Maximum Courant number and the Maximum Alpha Courant number are both set as 1.0. The wettability