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Effect of flow and fluid properties on the mobility of multiphase flows through porous media

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HIGHLIGHTS

- 3D fully resolved pore-scale simulations of multiphase flow using a VOF-IBM method.
- Validation test cases for multiphase porous media flows with wettability effects.
- Water flooding simulations through regular single and random multi-pore structures.
- Effect of capillary number, contact angle and viscosity ratio on the mobility of flow.

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ABSTRACT

In this paper we quantify the effect of capillary number (Ca), contact angle (θ) and viscosity ratio (M) on the mobility of multiphase flow through porous media. The focus is mainly on oil-water flows through porous rocks observed during the water flooding process. Simulations are performed using a finite volume method employing a staggered grid formulation. Interactions between fluids and complex solid boundaries are resolved by a direct forcing, implicit and sharp interface immersed boundary method (IBM). The fluid-fluid interface is tracked by a mass conservative sharp interface volume of fluid (VOF) method. IBM and VOF are coupled by imposing the contact angle as a boundary condition at the three phase contact line. Our methodology has been verified/validated for several test cases including multiphase Poiseuille flow in a channel, a viscous finger in a channel and mesh convergence of the contact force. Two types of porous structures are considered: (i) a repeated single pore and (ii) a random multi-pore arrangement. Temporal evolution of phase pressure difference and oil saturation have been studied as viscous fingers penetrate the pores. We observed that the residual oil saturation for different capillary numbers shows exactly the opposite trend for the single and multi pore arrangement. The residual oil saturation for multi-pore shows a well defined linear trend with $\log Ca$, θ and $\log M$.

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1. Introduction

Multiphase flow through porous media is a subject of significant interest among several scientific communities and industries. Examples include underground water flows (Høst-Madsen and Jensen, 1992), enhanced oil recovery (EOR) (Alvarado and Manrique, 2010), fluidized bed reactors (Pyle, 1972), microfluidics devices (Stone et al., 2004), soil remediation (Mulligan et al., 2001; Kumpiene et al., 2008) and many more.

The oil recovery process is generally carried out in multiple stages. In the primary stage, oil flows out of the porous rocks automatically due to its own natural pressure. Gradually, this natural flow decreases/stops due to rock pressure normalization. A lot of oil still remains trapped inside the porous rocks after the primary recovery due to capillary effects. To recover this residual oil variety of secondary and ternary (EOR) processes are used e.g. water flooding (Sheng, 2014; Jerauld et al., 2006), surfactant or polymer flooding (Shah, 2012; Keshtkar et al., 2016; De et al., 2017), thermal recovery (Prats, 1982; Zhu, 2011), gas injection, etc. Water flooding is one of the most common secondary oil recovery processes in which a high pressure water is used to displace the oil out of the porous rocks. This paper focuses on direct numerical simulations (DNS) of oil-water flow through porous media. To perform these simulations the following challenges need to be resolved efficiently: (i) oil-water interface tracking, (ii) modeling of the interactions between fluid (oil or water) and porous media and (iii) wettability effects at three phase contact lines.

Numerical simulations of multi-fluid interfaces are especially challenging because of the requirements of mass conservative

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interface advection and accurate computation of interfacial tension forces. A wide range of numerical methods has been developed and successfully tested for this purpose and an overview is presented by Scardovelli and Zaleski (1999). Frequently applied methods are front-tracking (Tryggvason et al., 2001), level-set (Sussman et al., 1994), volume of fluid (Hirt and Nichols, 1981; Youngs, 1982), Lattice-Boltzmann (Chen and Doolen, 1998) and phase field (Singer-Loginova and Singer, 2008). The Volume of fluid (VOF) method is used for the present simulations as it has a sharp interface representation and is the most mass conservative method among all multi-fluid interface tracking/capturing methods. Immersed boundary methods (IBM) (Mittal and Iaccarino, 2005) use non-body conforming structured (mostly Cartesian) computational grids to resolve fluid-solid interactions. Main advantage of IBM is the ease of grid generation, discretization of the Navier-Stokes equations and computer code implementation. IBM uses simple data structures due to structured grids which increases computational efficiency and decreases computational time. IBM can be categorized into two types: (i) continuous forcing approach where an explicit forcing function is used to apply the no-slip boundary condition at solid boundaries and (ii) direct forcing approach where the no-slip boundary condition is applied at the level of the discretized momentum equation. Present IBM is direct forcing, 2nd order accurate and implicit which sharply resolves fluid-solid interactions. There are other methods available to model fluids-solid interactions but they either require calibration of the geometry (Lattice-Boltzmann method) or produce a diffuse interface (level-set method). Three phase contact line dynamics plays a major role in wetting-dewetting phenomena when a multi-fluid interface comes in contact with a solid boundary. The contact line motion is determined by the microscopic physico-chemical interactions of the interface with substrate and it can drastically alter the bulk flow (Snoeijer and Andreotti, 2013). The effect of contact line dynamics at the macroscopic length scale can be represented by an apparent contact angle which may also depend on surface topology, surface roughness or contact line hysteresis. For fully-resolved numerical simulations, this effect can be incorporated by imposing a single/static (Renardy et al., 2001) or a dynamic (Saha and Mitra, 2009) value for the apparent contact angle as a boundary condition at three-phase contact line. A review on multiphase flow simulations with moving contact line is presented by (Sui et al., 2014).

Accurate and efficient simulations of heterogeneous oil reservoir flow poses many challenges (Gerritsen and Durlofsky, 2005): (i) length scale of the reservoir (kilometers) compared to that of pores (micrometers) (ii) presence of many phases in flow e.g. gas pockets, water, soil particles, oil (iii) uncertain rock properties and (iv) inter-solubility of fluid phases. Usage of coarse-scale models offers one option to model multiphase flow through oil reservoirs where a grid cell is (many fold) larger than the finest scale of the porous media. Effects of fine-scale interactions e.g. wettability, pore size distribution, pore arrangement are imposed in a volume averaged manner as a source term for coarse-scale simulations. Although coarse-scale models can simulate flow through heterogeneous reservoirs, a lot of work is still required in coarse-graining of multiphase flows with wettability effects and material transport. Recently, fully resolved fine-scale simulations of (a small part of) oil reservoirs have attracted many technologists and researchers. These simulations can accurately model wettability and material transport which may further help in developing upscaling models. The Lattice-Boltzmann method (Yiotis et al., 2007; Huang and Lu, 2009; Huang et al., 2009) is the most common technique used for fully resolved simulations. Pores are typically modeled by randomly arranging multiple solid unit squares/cubes in 2D/3D and the oil-water flows through the voids between them. Even though the Lattice-Boltzmann method is computationally fast because of being fully explicit, it is unable to strictly enforce continuity of velocity and shear-stress at the fluid-fluid interface. Very few attempts have been made to simulate pore-scale multiphase flow with wettability effects using VOF. Lv and Wang (2015) used the VOF method to simulate hot water flooding process through a single 2D pore and quantified the residual oil for the flooding at different temperatures. Ferrari and Lunati (2013) simulated multiphase flow through a 2D porous bed consisting of multiple cylindrical particles to link capillary pressure and total surface energy. Both of these papers use body-fitted unstructured grid for simulations in CFD software packages e.g. Fluent or OpenFOAM.

In this paper, we present simulations of multiphase flow through 3D porous media with wettability effects on a non-body fitted Cartesian computational grid using a coupled IBM-VOF method developed in-house. First, we will introduce the governing equations and the implementation details for the individual methods (IBM or VOF) and then for the IBM-VOF coupling in brief. Further, we will present some verification/validation test cases specifically pertaining to the oil-water flows through the porous media. Finally, we will simulate multiphase flows with wettability effects through a single and multi pore structures to quantify its mobility.

2. Numerical methodology

The mass and momentum conservation equations for unsteady, incompressible, Newtonian, multiphase flow can be expressed in a single field formulation as follows,

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \mathbf{F}_\sigma \tag{2}$$

where $\boldsymbol{\tau} = \mu\left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right]$ is the fluid stress tensor. $\mathbf{F}_\sigma$ is the volumetric interfacial tension force which acts in the vicinity of the fluid-fluid interface. ρ and μ are local phase averaged density and dynamic viscosity, respectively computed from the following equations:

$$\rho = F\rho_1 + (1 - F)\rho_2 \tag{3}$$

$$\frac{\rho}{\mu} = F\frac{\rho_1}{\mu_1} + (1 - F)\frac{\rho_2}{\mu_2} \tag{4}$$

where the two different immiscible fluids are denoted by subscripts 1 and 2. F is the local phase fraction which shows the fractional amount of a particular fluid present in a certain computational cell. In our study, $F = 1$ for a computational cell means that it is fully occupied by fluid 1. Advection of F is governed by the following equation:

$$\frac{DF}{Dt} = \frac{\partial F}{\partial t} + \mathbf{u} \cdot \nabla F = 0 \tag{5}$$

The volume of fluid (VOF) method is used for the numerical solution of Eq. (5) using geometrical advection. A finite volume methodology with pressure-velocity coupling on a staggered Cartesian computational grid is used to discretize of Eqs. (1) and (2). No-slip boundary conditions at non-body fitting solid boundaries are applied by a sharp interface immersed boundary method (IBM). IBM and VOF are coupled by imposing the contact angle as a boundary condition at the three phase contact line. Our IBM, VOF and IBM-VOF coupling are described with all necessary implementation details and verification/validation test cases in Das et al. (2016), Van Sint Annaland et al. (2005) and Patel et al. (2017), respectively. Here we will only outline them for completeness.

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