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# Relative permeability of two-phase flow in three-dimensional porous media using the lattice Boltzmann method

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ABSTRACT

The three-dimensional (3D) multi-relaxation-time (MRT) pseudopotential lattice Boltzmann model (LBM) which is able to handle high density ratio is employed to simulate two-phase flow in sphere-packed porous media. The effects of driving force, wettability, phase saturation, porosity and solid sphere distribution on the two-phase flow pattern as well as the relative permeability are investigated. The results show that the relative permeabilities of nonwetting phase and wetting phase increase with the driving force. As the wettability of porous media changes from strongly wet to neutrally wet, the relative permeability of the nonwetting phase reduces while the relative permeability of the wetting phase increases. With the increase of nonwetting saturation, the relative permeability of nonwetting phase increases but the relative permeability of wetting phase decreases. In addition, the heterogeneity of porous media can affect the steady state two-phase distribution pattern and the relative permeability significantly. The relative permeabilities of nonwetting phase and wetting phase in porous media of higher porosity are larger than the relative permeabilities with lower porosity. The present work demonstrates that the 3D MRT pseudopotential lattice Boltzmann model is an effective tool for understanding the transport mechanism of two-phase flow in porous media.

## 1. Introduction

The immiscible two-phase flow in porous media occurs commonly in nature and is of significance for many industrial issues, such as enhanced oil recovery and coalbed methane recovery, carbon dioxide storage, fuel cell, biological flow process, contaminant transport and groundwater remediation (Chen et al., 2013; Dai et al., 2014; Durucan et al., 2013; Gharbi and Blunt, 2012; Kang et al., 2010). The immiscible two-phase flow in porous media is a very complex process and is controlled by a number of factors such as relative permeability, which is a key parameter for immiscible two-phase flow in porous media. In the early years, the two-phase flow was believed to be uncoupled, and a simple extension of Darcy's law was made to obtain the relative permeability. However, researchers were soon afterwards aware that the viscous coupling effect plays an important role during the two immiscible fluids flow (Avraam and Payatakes, 1999; Ayub and Bentsen, 1999; Bentsen, 1998). The existence of viscous coupling between the two phases makes the simple extension of Darcy's law highly questionable. Now, it is widely accepted that the relative permeability depends on many flow parameters including phase saturation, viscosity ratio, driving force, wettability and pore structure.

Traditionally, the relative permeability was determined experimentally using different measurement methods. Theodoropoulou et al. (2005) experimentally investigated the unsteady immiscible displacement of a fluid by another fluid on glass-etched pore networks, and they found that the relative permeability of nonwetting phase increases as the flow pattern changes from compact displacement to viscous fingering or from viscous to capillary fingering, while the relative permeability of wetting phase increases as the flow pattern changes from compact displacement or capillary fingering to viscous fingering. Aggelopoulos and Tsakiroglou (2008) performed rate-controlled transient immiscible displacement experiments on two disturbed soil columns. They revealed that the capillary pressure and relative permeability curves depend not only on the pore space morphology but also on the experimental procedure and flow dynamics. Tsakiroglou et al. (2007) investigated transient and steady-state relative permeabilities from two-phase flow experiments in glass-etched planar pore networks. Their results showed that the transient and steady-state relative permeabilities in strong and intermediate wettability systems are different. Until now, experimental methods are still general choices for the study

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of two-phase flow in porous media, however, experiments are tedious, time consuming and expensive.

An alternative approach to derive transport properties of porous media and thus enrich experimental measurement is the numerical simulation method. Gharbi and Blunt (2012) studied the impact of wettability and connectivity on waterflood relative permeability for a set of carbonate samples with different pore structures using pore network modeling. They found that both connectivity and wetting state of the porous media affect the relative permeability. Xu et al. (2016) analyzed the impact of different displacement pressure gradients on the two-phase oil-water relative permeability, and they established an empirical correction model based on the water-wet core flooding experiments. Janetti et al. (2017) illustrated the role of complex micro-scale pore geometry and wettability on oil and water relative permeability within elementary cells through diffusive-interface formulation. They found that the relative permeability varies linearly with phase saturation in the regular elementary cells, while the relative permeability curves vary in a highly non-linear fashion with phase saturation in the random elementary cells due to the occurrence of stagnant flow regions. Xu et al. (2013) proposed a fractal model to study the two-phase flow of immiscible fluids in unsaturated porous media, and they found that the multiphase fluid flow process is governed by saturation and capillary pressure as well as geometrical parameters of porous media. By using a diffuse-interface representation and adaptive refinement of finite elements at the interface, Ahmadlouydarab et al. (2012) developed a highly accurate computational toolkit for simulating interfacial flows and found that the relative permeability is a complex function of geometry and flow parameters of the system.

The lattice Boltzmann method is a recently developed effective computational fluid dynamic method for simulating fluid flow in porous media. One of the advantages of the lattice Boltzmann method is that it can be used for large-scale simulations of complex fluids in various specific cases and boundary conditions (Liu et al., 2015; Ma et al., 2018; Wang et al., 2015; Yan et al., 2011). Huang and Lu (2009) used single-relaxation-time (SRT) Shan-Chen single-component multiphase lattice Boltzmann model to study the two-phase flow in 2D porous media. They found that concurrent relative permeability is usually larger than the countercurrent one because of the drag-force effect in countercurrent flow. Dou and Zhou (2013) also used single-relaxation-time (SRT) Shan-Chen model to analyze the steady-state immiscible two-phase flow in 2D porous media. Their results showed that the relative permeability has different responses to the variation of capillary number and viscosity ratio in the homogeneous and heterogeneous porous media. Li et al. (2005) employed the three-dimensional lattice Boltzmann method to investigate the complex behavior of two-phase flow with density ratio of unity in porous media, and they found that the relative permeability strongly depends on the fluid-fluid interfacial area. Ramstad et al. (2012) applied single-relaxation-time lattice Boltzmann method to obtain relative permeability from digitized microstructure images of Bentheimer and Berea sandstone under water-wet conditions. The density ratio was also set to unity and the results showed that the unsteady-state relative permeability for the drainage is fundamentally different from the steady-state situation where transient effects have vanished.

Although researchers have numerically investigated the immiscible two-phase flow in porous media, most of the existing works are from two-dimensional point of view, and the density ratio of the two phases is limited to small. The aim of the present paper is to apply a 3D high density ratio multi-relaxation-time (MRT) pseudopotential lattice Boltzmann model for the investigation of immiscible two-phase flow in sphere-packed porous media. To the authors' best knowledge, there are no such studies in the literature that address the relationship between various factors and the relative permeability for immiscible two-phase flow in complex porous media with the 3D high density ratio MRT pseudopotential lattice Boltzmann model. Specifically, the effects of driving force, wettability, phase saturation, porosity and solid sphere distribution on two-phase flow and the relative permeability are investigated systematically. The present work demonstrates that the 3D high density ratio MRT pseudopotential lattice Boltzmann model is effective to simulate the two-phase flow in complex porous media. The results also help to understand the transport mechanism of two-phase flow in porous media that underlies the relative permeability.

The rest of this paper is organized as follows. Firstly, a brief introduction is given to the 3D large density ratio MRT pseudopotential lattice Boltzmann model. Secondly, the 3D large density ratio MRT pseudopotential lattice Boltzmann model is validated. Thirdly, the two-phase flows in 3D porous media are systematically investigated under the effects of driving force, wettability, phase saturation, porosity and solid sphere distribution. Finally, a brief conclusion is drawn.

## 2. Method

In this study, we employ the multi-relaxation-time (MRT) collision due to its superiority over single-relaxation-time (SRT) in numerical stability and suppression of spurious velocity (Huang et al., 2014; Liu et al., 2014; Salimi and Taeibi-Rahni, 2015; Yu and Fan, 2010). The evolution equation of the D3Q19 lattice Boltzmann model using the MRT collision operator with a force term can be written as (McCracken and Abraham, 2005)

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta_t, t+\delta_t) = f_\alpha(\mathbf{x}, t) - \sum_\beta \Omega_{\alpha\beta}\left(f_\beta(\mathbf{x}, t) - f_\beta^{eq}(\mathbf{x}, t)\right) + S_\alpha(\mathbf{x}, t) - \frac{1}{2}\sum_\beta \Omega_{\alpha\beta} S_\beta(\mathbf{x}, t) \tag{1}$$

where $f_\alpha$ is the density distribution function along the $\alpha$th direction, $f_\beta^{eq}$ is the equilibrium distribution function, $\Omega_{\alpha\beta}$ is the collision matrix in the velocity space, $\delta_t$ is the time step, and $\mathbf{e}_\alpha$ ($\alpha$ = 0, 1, ...,18) is the particle velocity in the $\alpha$th direction given by

$$[\mathbf{e}_0, \mathbf{e}_1, ..., \mathbf{e}_{18}] = \begin{bmatrix} 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 & 1 & -1 & 1 & -1 \end{bmatrix} \tag{2}$$

$S_\alpha$ is the forcing term in the velocity space given by (Zhang et al., 2017)

$$S_\alpha = w_\alpha\left[\frac{\mathbf{e}_\alpha - \mathbf{u}}{c_s^2} + \frac{\mathbf{e}_\alpha\cdot\mathbf{u}}{c_s^4}\mathbf{e}_\alpha\right]\cdot\mathbf{F} \tag{3}$$

where $\mathbf{u}$ is the velocity, $c_s = c/\sqrt{3}$ is the lattice sound speed and $c = \delta_x/\delta_t$. The weighting factors are $w_0 = 1/3$, $w_\alpha = 1/18$ for $\alpha = 1-6$ and $w_\alpha = 1/36$ for $\alpha = 7-18$. $\mathbf{F} = \mathbf{F}_f + \mathbf{F}_s + \mathbf{F}_b$ is the total force on each particle, including the fluid-fluid cohesion $\mathbf{F}_f$, the fluid-solid adhesion force $\mathbf{F}_s$ and the body force $\mathbf{F}_b$, which will be described later.

Eq. (1) is projected to the moment space by the transformation matrix $\mathbf{M}$. Thus, Eq. (1) can be transformed to the following form:

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta_t, t+\delta_t) = f_\alpha(\mathbf{x}, t) - \mathbf{M}^{-1}\Lambda(\mathbf{m}(\mathbf{x}, t) - \mathbf{m}^{eq}(\mathbf{x}, t)) + \mathbf{M}^{-1}\left(\mathbf{I} - \frac{\Lambda}{2}\right)\overline{\mathbf{S}}(\mathbf{x}, t) \tag{4}$$

where $\mathbf{m} = \mathbf{M}f$ and $\mathbf{m}^{eq} = \mathbf{M}f^{eq}$ are the moment spaces of the density distribution function and its equilibrium distribution function, respectively. The transformation matrix $\mathbf{M}$ for D3Q19 is