International Communications in Heat and Mass Transfer 85 (2017) 53–61

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Relative permeability of two immiscible fluids flowing through porous media determined by lattice Boltzmann method

Huawei Zhao[a,b,*], Zhengfu Ning[a,b], Qinjun Kang[c], Li Chen[d], Tianyi Zhao[a,b]

[a] State Key Laboratory of Petroleum Resources and Engineering in China University of Petroleum, Beijing 102249, PR China
[b] Ministry of Education Key Laboratory of Petroleum Engineering in China University of Petroleum, Beijing 102249, PR China
[c] Computational Earth Science Group (EES-16), Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[d] Key Laboratory of Thermo-fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaoting University, Xi'an, Shaanxi 710049, PR China

ARTICLE INFO

Keywords:
Lattice Boltzmann method
Two phase flow
Relative permeability

ABSTRACT

This article applied the multiple relaxation time multicomponent/multiphase pseudopotential lattice Boltzmann model to simulate two immiscible fluids flow in 2D porous media, and analyzed the effects of capillary number (*Ca*), viscosity ratio (*M*) and wettability on the relative permeability curves. Simulation results indicate that the nonwetting phase (NWP) relative permeability increases with increasing *Ca*; while the effect of *Ca* on the wetting phase (WP) relative permeability depends on the wettability. When $M > 1$, the NWP relative permeability increase with increasing *M* in a strong wetting condition because of the lubricating effect. The amplitude of the NWP relative permeability may even exceed the single phase permeability. However, the exact value of the amplitude and where it occurs depends on *M* and the structure of the porous media. The WP relative permeability is insensitive to *M*. When the porous media converts from strong wetting condition to neutral wetting condition, the NWP relative permeability decreases while the WP relative permeability increases.

1. Introduction

Two immiscible fluids flowing through porous media is a common environmental phenomenon and is of significant importance for many industrial problems, such as enhanced oil recovery, geological carbon dioxide sequestration, and fuel cells [1–3]. The relative permeability is the key descriptor of the flows of the two phase fluids. During the early years, the flows of the two phase fluids were believed to be uncoupled, and a simple extension of the single phase Darcy's law was made to obtain the relative permeability curves. However, researchers were soon afterwards aware that viscous coupling effect, which was a result of the monument transfer between the two fluids, played a vital role during the two immiscible fluids flow [4–6]. And it is now widely accepted that the relative permeability curves, rather than a simple result of saturation, are functions of many parameters including capillary number, viscosity ratio, and wettability.

Historically, laboratory experimental methods were first and widely used to determine the relative permeability curves of the two phase flow. For example, Dullien and Dong measured the relative permeability curves of sand packs by two sets of co-current steady state experiments [7]. External force was applied to one phase each time, and the relative permeability curves were calculated based on the recorded oil and water velocity. Bentsen and Manai estimated the permeability coefficients by a combination of co-current and countercurrent flow experiments [8]. Until now, experimental methods are still general choices for the study of two phase flow [9,10]. However, the relative permeability experiment is a time consuming process; the experiment sometimes fails to reflect the real subsurface conditions; and the heterogeneity between experimental porous media may affect the analysis of the flow controlling factors. In recent years, benefited by the evolution of the computational capacities, some numerical simulation methods emerged, among which the pore network modeling has great potential applications [11]. Zhao et al. used pore network modeling to study the oil recovery by water flooding in sandstones and carbonates, and discussed the effect of initial water saturation, contact angle distribution and oil wet fraction [12]. Gharbi and Blunt used the pore network modeling method to study the relative permeability curves of carbonate samples, and discussed the impact of wettability and connectivity on the relative permeability curves [13]. However, the pore network method is based on displacement and transport equations, which fail to unveil the underlying microscopic dynamics. Besides, the accuracy of the modeling is highly related to the extracted network.

The lattice Boltzmann (LB) method emerged in the late 1980s, and

Abbreviations: LB, lattice Boltzmann;; MRT, multiple relaxation time; MCMP, multicomponent multiphase; WP, wetting phase; NWP, nonwetting phase

* Corresponding author at: School of Petroleum Engineering, China University of Petroleum, Beijing 102249, PR China.
E-mail address: h.w.zhao2013@gmail.com (H. Zhao).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.04.020

Nomenclature

$\mathbf{f}^{\sigma}$	density distribution function
$\mathbf{f}^{\sigma(\mathrm{eq})}$	equilibrium density distribution function
$\mathbf{e}$	discrete velocities
$\mathbf{u}^{\mathrm{eq}}$	equilibrium velocity
ρ_{σ}	density
$\mathbf{M}$	transformation matrix
$\mathbf{S}$	diagonal relaxation matrix
υ_{σ}	viscosity
$\mathbf{F}^{\sigma}$	total force
$\mathbf{F}_{\mathrm{f}}^{\sigma}$	fluid-fluid interaction force
$\mathbf{F}_{\mathrm{ads}}^{\sigma}$	fluid-solid interaction force
$\mathbf{F}_{\mathrm{b}}^{\sigma}$	external body forces
$g_{\sigma\bar{\sigma}}$	fluid-fluid interaction strength
$g_{\sigma\mathrm{w}}$	fluid-solid interaction strength
$K_{\mathrm{r,nw}}$	nonwetting phase relative permeability
$K_{\mathrm{r,w}}$	wetting phase relative permeability
Ca	capillary number
M	viscosity ratio
θ	contact angle

has become an effective numerical tool to simulate and investigate a broad class of flows, including the two phase flow [14–16]. By now, there are four types of LB multiphase models, which are the color model proposed by Rothman and Keller (also called R-K model) [17,18], the pesudopotential model proposed by Shan and Chen (Shan-Chen model) [19,20], the free energy model introduced by Swift et al. [21], and the kinetic theory based model proposed by He et al. (He-Shan-Doolen model) [22]. There have been some studies investigating the multiphase flow using different multiphase models based on different pore structures. Langaas and Papatzacos simulated concurrent and countercurrent flows in a uniform pore space geometry using the free energy model and studied the effects of capillary pressure, viscosity ratio under different wettability [23]. Kang et al. simulated displacement of a two-dimensional (2D) immiscible droplet in a channel using the pseudopotential model, and discussed fingering controlling factors [24,25]. Li et al. used a multiple relaxation time (MRT) pseudopotential model to simulate two phase flow in a 3D porous medium and discussed the impacts of capillary number, viscosity ratio, wettability and fluid-fluid interfacial area on the relative permeability curves [26]. Huang and Lu simulated co-current and counter-current flow in a simplified 2D porous medium using one component/two phase pseudopotential model [27]. Dou and Zhou discussed the relative permeability affecting factors in both homogenous and heterogeneous 2D porous media [28]. All these studied have deepened the understanding of viscous coupling in two phase immiscible flows.

In this study, lattice Boltzmann simulation of two immiscible fluids flowing through 2D porous medium has been conducted. The applied lattice Boltzmann is the multicomponent multiphase (MCMP) pseudopotential model with a MRT collision operator. The 2D porous medium structure was extracted from a computer tomography image of a tight sandstone sample. After validating the model by three benchmarks (i.e., Laplace law, contact angle, and flow in 2D channel), the two immiscible fluids flowing through the porous media were simulated. And the effects of the capillary number (Ca), viscosity ratio (M), and wettability (θ) on the relative permeability curves were discussed.

2. Methodology

The MCMP pseudopotential model was used for the simulations in this study. And a MRT collision operator was added to increase the stability of the simulations [29]. The standard LB equation using the MRT collision operator with a force term is expressed as

$$\mathbf{f}^{\sigma}(\mathbf{x}+c\mathbf{e}\delta_t,t+\delta_t)-\mathbf{f}^{\sigma}(\mathbf{x},t)=-(\mathbf{M}^{-1}\mathbf{S}^{\sigma}\mathbf{M})(\mathbf{f}^{\sigma}(\mathbf{x},t)-\mathbf{f}^{\sigma(\mathrm{eq})}(\mathbf{x},t))+\left[\mathbf{M}^{-1}\left(\mathbf{I}-\frac{\mathbf{S}^{\sigma}}{2}\right)\mathbf{M}\right]\overline{\mathbf{F}}^{\sigma}(\mathbf{x},t) \tag{1}$$

Where $\mathbf{f}^{\sigma}(\mathbf{x},t)$ is the density distribution function of the component σ at position $\mathbf{x}$ and time t. $c=\delta_x/\delta_t$is the lattice speed with δ_x and δ_t being the lattice spacing and time step respectively. $\mathbf{e}$ are the discrete velocities, and $\mathbf{f}^{\sigma(\mathrm{eq})}(\mathbf{x},t)$ is the equilibrium density distribution function. The discrete velocities for a D2Q9 model are given by

$$\mathbf{e}=\begin{pmatrix}0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1\\ 0 & 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1\end{pmatrix} \tag{2}$$

And the equilibrium distribution function $f_i^{\sigma(\mathrm{eq})}(\mathbf{x},t)$ is written as

$$f_i^{\sigma(\mathrm{eq})}=\rho_{\sigma}\omega_i\left[1+\frac{3}{c^2}(\mathbf{e}_i\cdot\mathbf{u}_{\sigma}^{\mathrm{eq}})+\frac{9}{2c^4}(\mathbf{e}_i\cdot\mathbf{u}_{\sigma}^{\mathrm{eq}})^2-\frac{3}{2c^2}|\mathbf{u}_{\sigma}^{\mathrm{eq}}|^2\right] \tag{3}$$

In which, ω_i is the weight factor with $\omega_0=4/9$, $\omega_{1-4}=1/9$ and $\omega_{5-8}=1/36$.

In the MCMP model, the equilibrium velocity is calculated as

$$\mathbf{u}^{\mathrm{eq}}=\sum_{\sigma}s_{\rho}^{\sigma}\rho_{\sigma}\mathbf{u}_{\sigma}\Big/\sum_{\sigma}s_{\rho}^{\sigma}\rho_{\sigma} \tag{4}$$

Where ρ_{σ} and $\mathbf{u}_{\sigma}$ are the density and velocity of component σ, and are calculated as

$$\rho_{\sigma}=\sum_i f_i^{\sigma},\ \rho_{\sigma}\mathbf{u}_{\sigma}=\sum_i\mathbf{e}_i f_i^{\sigma}+\frac{\delta_t}{2}\mathbf{F}^{\sigma} \tag{5}$$

$\mathbf{M}$ is a transformation matrix, and for the detailed value of $\mathbf{M}$ one is referred to [30]. $\mathbf{S}$ is a diagonal relaxation matrix, and is expressed as

$$\mathbf{S}^{\sigma}=\mathrm{diag}[s_{\rho}^{\sigma},s_{e}^{\sigma},s_{\varepsilon}^{\sigma},s_{j}^{\sigma},s_{q}^{\sigma},s_{j}^{\sigma},s_{q}^{\sigma},s_{\upsilon}^{\sigma},s_{\upsilon}^{\sigma}] \tag{6}$$

Where s_{ρ}^{σ} corresponds to conserved mass, and s_j^{σ} corresponds to conserved moments. They are both taken 1. s_e^{σ}, s_{ε}^{σ} and s_q^{σ} correspond to non-conserved moments and can be adjusted independently to improve the accuracy and stability of the MRT model. In this study, following [31], the three parameters are taken as: $s_e^{\sigma}=0.6$, $s_{\varepsilon}^{\sigma}=1.54$, and $s_q^{\sigma}=1.2$. s_{υ}^{σ} is the dimensionless relaxation time, and is related to viscosity υ_{σ} as

$$\upsilon_{\sigma}=c_s^2\left(\frac{1}{s_{\upsilon}^{\sigma}}-\frac{1}{2}\right)\delta_t \tag{7}$$

Where c_s^2 is the lattice sound speed $\left(c_s^2=\frac{c^2}{3}\right)$.

The force term $\overline{F}_i^{\sigma}$ in Eq. (1) follows Guo's force scheme, and is defined as [30,32]

$$\overline{F}_i^{\sigma}=\frac{\mathbf{F}^{\sigma}\cdot(\mathbf{e}-\mathbf{u}^{\mathrm{eq}})}{\rho_{\sigma}c_s^2}f_i^{\sigma(\mathrm{eq})} \tag{8}$$

Where $\mathbf{F}^{\sigma}$is the total force acting on component σ, and is composed of three parts

$$\mathbf{F}^{\sigma}=\mathbf{F}_{\mathrm{f}}^{\sigma}+\mathbf{F}_{\mathrm{ads}}^{\sigma}+\mathbf{F}_{\mathrm{b}}^{\sigma} \tag{9}$$

Where $\mathbf{F}_{\mathrm{f}}^{\sigma}$ is the fluid-fluid interaction force, $\mathbf{F}_{\mathrm{ads}}^{\sigma}$ is the fluid-solid interaction force, and $\mathbf{F}_{\mathrm{b}}^{\sigma}$ are other possible external forces such as gravitational force. For the MCMP model, the fluid-fluid interaction force between components σ and $\bar{\sigma}$ is defined as

$$\mathbf{F}_{\mathrm{f}}^{\sigma}(\mathbf{x})=-g_{\sigma\bar{\sigma}}\psi_{\sigma}(\mathbf{x})\sum_{i=1}^{N}w(|\mathbf{e}_i|^2)\psi_{\bar{\sigma}}(\mathbf{x}+\mathbf{e}_i)\mathbf{e}_i \tag{10}$$

Where $g_{\sigma\bar{\sigma}}$ represents the interaction strength between different components. In this study, we set $g_{\sigma\sigma}$ and $g_{\bar{\sigma}\bar{\sigma}}$ as zero, and take $g_{\sigma\bar{\sigma}}=g_{\bar{\sigma}\sigma}=0.65$ to separate the two phase and maintain a moderate