Chemical Engineering Science 161 (2017) 57–66

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Pore-scale simulation of effects of coal wettability on bubble-water flow in coal cleats using lattice Boltzmann method

Jie Yi, Huilin Xing *

School of Earth Sciences, University of Queensland, Brisbane, QLD 4072, Australia

HIGHLIGHTS

- Bubble-water flow dynamics were investigated by lattice Boltzmann method.
- Coal wettability affects the bubble-water flow behaviours especially in narrow throats.
- The influences of bubble size on bubble-water flow were investigated and discussed.

ARTICLE INFO

Article history:
Received 21 September 2016
Received in revised form 3 December 2016
Accepted 6 December 2016
Available online 9 December 2016

Keywords:
Pore-scale
Coal wettability
Bubble-water flow
Coal cleat
Lattice Boltzmann

ABSTRACT

We study the effects of coal wettability on gas bubble/water two-phase flow behaviour in micro-cleats of the coal seam gas reservoir using a free energy based two-phase lattice Boltzmann model. The model is validated by comparison with analytical results and published results, and good agreement is achieved in general. Then we use this model to simulate bubble-water flow in both smooth capillary and a capillary with a narrow throat to systematically study the influences of contact angle, capillary pressure and bubble size on the flow behaviour. The simulation results indicate that both the bubble size and contact angle have significant impacts on the flow capacity of bubble and water, especially in a channel with a narrow throat. A decrease in water flow rate is observed when larger bubbles occur, and the water flow rate increases when the gas wettability becomes stronger. The bubble flow dynamics significantly influence the drainage of water and the further gas production.

1. Introduction

Coal seam gas (CSG), any naturally occurring gas trapped in underground coal seams by water and ground pressure, is regarded as a clean energy but also a major factor restricting coal mine safety (e.g. gas burst). Efficient gas drainage from extremely low permeable coal seam is crucial for resource utilisation, mining safety and environment protection. It is commonly agreed that the face/butt cleats (i.e. fractures in coal) are the main pathways for gas flowing into the wellbore. Since the cleat systems of most coal seams are initially saturated with water, the gas/water two-phase flow becomes a critical issue in CSG recovery (Wang et al., 2011), carbon dioxide (CO_2) enhanced CSG recovery and carbon storage in coal seams (Mavor et al., 2004).

Several studies have been done to understand the two-phase flow physics in coal seams (Clarkson et al., 2011; Kalam et al., 2012; Karacan, 2013; Zhang et al., 2015). However, most of them are either based on laboratory core flooding experiment data or field data, and they cannot explain the factors controlling the multiphase flow at pore scale (Dawe et al., 2011; Ofori et al., 2010; Shen et al., 2011). To fill this knowledge gap, a detailed research of gas/water two-phase flow behaviours in coal seams at pore scale is essential.

Fluid flow capacity in coal seams depends on many factors including the effective stress, the geometry of the cleat, the flow pattern, the cleat network connectivity and the wettability of coal (Han et al., 2010; Nicholl et al., 2000; Su et al., 2001). Among them, the coal wettability and fluid flow patterns have attracted increasing attentions during the last decade. The contact angle of the fluid interface with the coal surface is commonly used to quantify the coal wettability. The contact angle in the coal-water-CO_2 system with different pressures, coal rank and ash content has been studied (Kaveh et al., 2011; Sakurovs and Lavrencic, 2011). Saghafi et al. (2014) measured the contact angles of CO_2 and CH_4 bubbles in water with coal from the Sydney Basin at different pressures. Later, Mahoney et al. (2015) used a microfluidic Cleat Flow Cell (CFC) instrument to investigate the effect of rank and lithotype on coal wettability. However, difficulties still exist to provide an in-depth understanding of the influences of coal wettability on gas/water

* Corresponding author.
E-mail address: h.xing@uq.edu.au (H. Xing).

http://dx.doi.org/10.1016/j.ces.2016.12.016
0009-2509/

flow at pore scale. Since most of the previous researches are confined to experimental work based on sessile drop experiments or wetting of particles, the gas water two-phase flow dynamic across coal cleats with different wetting properties has not been explored in detail. Also, with the premise that the coal cleats are initially saturated with water, and gas diffuses from the low permeable matrix into cleats during the production, one can imagine that the diffused gas has to form some discontinuous gas bubbles before gathering into the continuous phase. Li et al. (2012) has pointed out that the gas bubble can restrict fluid flow at bottlenecks in the cleat network, and it is necessary to identify the bubble water flow dynamics use an appropriate method. In the last decade, pore-scale modelling technique has developed rapidly and has become a powerful predictive tool in oil and gas industry. With a strong theoretical background, the lattice Boltzmann method (LBM) has made rapid progress since its appearance. It has become a numerically efficient technique for multiphase flow simulation (Aidun and Clausen, 2010; Ghosh et al., 2012; Gunstensen et al., 1991; He et al., 1999; Huang et al., 2011a; Shan and Chen, 1993; Swift et al., 1995; Wang et al., 2016a) involving complex geometries (Ramstad et al., 2010; Wang et al., 2016b).

Research has also been done towards LBM simulation of multiphase flow with large density ratio. The free energy model developed by Swift et al. (1995) is one of the most commonly used models for multiphase flow with a low-density ratio. Based on this model, Inamuro et al. (2004) proposed an improved multiphase LBM that can tolerate high density, but it must solve a Poisson equation, which significantly reduces its efficiency. Later, Lee and Lin (2005) developed another LB model, but the LB equation for the interface cannot be completely recovered to the Cahn-Hilliard (CH) equation. Then, a revised lattice Boltzmann equation to recover the CH equation is proposed by Zheng et al. (2006), which has relatively high efficiency and stability. However, this model is proved to be restricted to density-matched binary fluids (Fakhari and Rahimian, 2010). Recently, a modified new model considering the local density variation is developed by Shao et al. (2014).

Researchers have also attempted to use LBM to simulate interfacial dynamics in porous materials, where fluid/solid interactions significantly influence the mass transport (Wang et al., 2016c). Dong et al. (2011) studied the viscous fingering phenomena and found that the finger pattern changes with wettability. Ghassemi and Pak (2011) investigated the effects of various factors on relative permeability of porous media and found that the relative permeability of wetting phase is not affected by the pore geometry. Dou and Zhou (2013) reported an improved lattice Boltzmann model and applied it to investigate the influence of capillary number on relative permeability.

Although LBM has been well used to study multiphase flow for the last decade, the dynamic behaviours of bubble-water flow at pore-scale still need to be further addressed. In this paper, the LB model developed by Shao et al. (2014) and the partial wetting boundary condition (Briant, 2002) are applied to simulate bubble-water flow in coal cleats at pore-scale. The influences of coal wettability and capillary pressure on gas-water two-phase flow behaviours in a coal cleat are investigated. The paper is organised as follows: the extended LB model is introduced in Section 2, the validation and the numerical simulation analysis are carried out in Section 4 and finally a brief conclusion is presented in Section 5.

2. Mathematical model

2.1. Governing equations

The generalized Navier-Stokes equations (Takada et al., 2001; Zheng et al., 2006, 2008) for an incompressible viscous fluid system and the interfacial capturing equation (Jacqmin, 1999) (Cahn-Hilliard equation) can be described as:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{u}) = 0, \tag{1}$$

$$\frac{\partial (n\boldsymbol{u})}{\partial t} + \nabla \cdot (n\boldsymbol{u}\boldsymbol{u}) = -\nabla \cdot \boldsymbol{P} + \mu \nabla^2 \boldsymbol{u} + \boldsymbol{F}, \tag{2}$$

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \boldsymbol{u}) = \theta_M \nabla^2 \mu_\phi, \tag{3}$$

where $\boldsymbol{P}$ is the pressure tensor, $\boldsymbol{u}$ is the velocity vector, μ is the dynamic viscosity, F is the external force, θ_M is the mobility, and μ_ϕ is the chemical potential. ϕ and n are defined as:

$$n = \frac{\rho_L + \rho_G}{2}, \phi = \frac{\rho_L - \rho_G}{2}, \tag{4}$$

where ρ_G is the density of gas phase, ρ_L is the density of liquid phase.

In Eq. (2), the term $\nabla \cdot \boldsymbol{P}$ is related to the surface tension force and can be expressed as,

$$\nabla \cdot \boldsymbol{P} = \phi \nabla \mu_\phi + \nabla (n c_s^2), \tag{5}$$

where c_s is the speed of sound.

The chemical potential μ_ϕ can be derived from the free-energy function (Zheng et al., 2006), and it satisfies:

$$\Psi = \int dV \left[\psi(\phi) + \frac{k}{2} (\nabla \phi)^2 + \frac{n \ln n}{3} \right], \tag{6}$$

where k is a coefficient that is related to the interface layer thickness and the surface tension. For homogeneous system, the bulk free-energy density per unit mass $\psi(\phi)$ is chosen as a double-well form (Zheng et al., 2006)

$$\psi(\phi) = \frac{\partial \psi}{\partial \phi} = A\left(\phi^2 - \phi^{*2}\right)^2, \tag{7}$$

where $\phi^* = \frac{\rho_L - \rho_G}{2}$ is the initial order parameter which is related to the equilibrium state, and it distinguishes the gas-liquid two-phase flow.

The coefficients A and k are defined as,

$$A = 3\sigma/(4W\phi^{*4}), \tag{8}$$

$$k = 3W\sigma/(8\phi^{*2}). \tag{9}$$

2.2. Lattice Boltzmann method

The modified lattice Boltzmann equation (Zheng et al., 2006) using probability distribution function g_i to explain Eq. (3) can be expressed as:

$$g_i(\boldsymbol{x} + \boldsymbol{e}_i \delta t, t + \delta t) = g_i(\boldsymbol{x}, t) + (1 - q)[g_i(\boldsymbol{x} + \boldsymbol{e}_i \delta t, t) - g_i(\boldsymbol{x}, t)] + \Omega_i, \tag{10}$$

with

$$\Omega_i = \frac{g_i^{eq}(\boldsymbol{x}, t) - g_i(\boldsymbol{x}, t)}{\tau_\phi}, \tag{11}$$

where g_i^{eq} is the equilibrium distribution function, the distribution function g_i is used to compute the order parameter, $\boldsymbol{e}_i$ is the lattice velocity (the value of the lattice velocity depends on lattice velocity model), τ_ϕ is the dimensionless relaxation time, δt is the lattice time step and q is a constant coefficient. When q is set to one, the Eq. (10) will reduce to conventional lattice Boltzmann equation. The value of q is determined by Zheng et al. (2006)

$$q = \frac{1}{\tau_\phi + 0.5}. \tag{12}$$