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Investigation on permeability of shale matrix using the lattice Boltzmann method

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A B S T R A C T

Permeability is an important parameter for the measurement of fluid transport capacity in a porous medium. Therefore it is necessary to be able to predict permeability in shale-gas reservoirs. However, predicting permeability of shale matrix is challenging because of the effects of surface diffusion and gas slippage in nanoscale pores. This paper presents a lattice Boltzmann model for gas flow in shale matrix under shale-gas reservoir conditions. The model can take into account the effects of surface diffusion, gas slippage, and a non-ideal gas. The present model, in which the diffuse-bounce-back boundary scheme is proposed to deal with the curved walls in the shale matrix, is an extension of that by Ren et al. [Transp. Porous Med. 106(2), 285-301 (2015)]. Simulations are conducted to study the intrinsic permeability and apparent permeability of shale matrix. It is found that for shale matrix with a small average pore size, the intrinsic permeability is noticeably lower than the apparent permeability. When the average pore size is less than 10 nm, the Klinkenberg correlation is unable to describe the relationship between the apparent permeability and intrinsic permeability. However, when the average pore size is larger than 50 nm, the Klinkenberg correlation can describe the relationship quite accurately. In particular, it is demonstrated that the classic Klinkenberg correlation is not applicable to shale-gas reservoirs but is suitable for low-permeability gas reservoirs and coalbed methane reservoirs.

1. Introduction

Shale gas has enormous potential for increasing total gas production and thus much attention has been paid to shale-gas reservoirs in recent years. Pores in the shale matrix are nanoscale pores in which surface diffusion and gas slippage occur simultaneously under shale-gas reservoir conditions (Kang et al., 2011). Therefore, classical simulation methods based on a continuous medium hypothesis may not be applicable to shale-gas reservoirs. Recently, interest in using new methods to study shale-gas transport mechanisms has grown strikingly.

The lattice Boltzmann method (LBM) is considered a promising method to simulate microscale gaseous flow (Aidun and Clausen, 2010). Recently, some researchers have applied the LBM to study gas flow in kerogen pores. Fathi et al. (2012) proposed a modified Klinkenberg correlation without the effect of surface diffusion based on a lattice Boltzmann (LB) simulation. Fathi and Akkutlu (2013) developed an LB model to study gas flow in a kerogen pore with the effects of both surface diffusion and gas slippage, but their LB model may lead to some numerically discrete effects. Zhang et al. (2014) used the LBM to investigate the effect of gas slippage in a nano-capillary. Most recently, Ren et al. (2015) presented an LB model to simulate gas flow in a kerogen pore with the effects of surface diffusion, gas slippage, and a non-ideal gas. However, all the above studies focused on gas flow in a simple kerogen pore and their results cannot be used directly to simulate gas flow in a porous medium.

The shale matrix is the major component in shale-gas reservoirs and therefore understanding gas transport in the shale matrix is very important for accurately simulating shale-gas production. In practice, permeability is commonly used to measure fluid transport capacity in a porous medium. It is therefore necessary to predict the permeability of the shale matrix. Because the shale matrix has extremely low permeability and porosity, it is

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difficult to measure the physical properties of shale matrix accurately using experimental methods (Cui et al., 2009). The intrinsic permeability is the measured liquid permeability, which only depends on the porous structure. The apparent permeability is the measured gas permeability, which truly reflects the gas seepage capacity in a porous medium. Recently the LBM has been applied to study the intrinsic permeability and apparent permeability of shales (Chen et al., 2013, 2015). However, most of the LBM studies on apparent permeability only consider the effect of gas slippage and neglect the effect of surface diffusion. The resulting simulations cannot reflect actual apparent permeability under shale-gas reservoir conditions.

In this study, we extend our previous LB model for a simple kerogen pore (Ren et al., 2015) to an LB model for a porous medium. This model can take the effects of surface diffusion, gas slippage, and a non-ideal gas into account. The model can be used to predict the apparent permeability of shale matrix at low cost and aid in understanding the intrinsic permeability and apparent permeability of the shale matrix.

2. Lattice Boltzmann model

To simulate gas transport in the shale matrix under shale-gas reservoir conditions, the pore-scale lattice Boltzmann model presented by Ren et al. (2015) is considered here

$$f_i(\mathbf{r}+\mathbf{c}_i\delta_t, t+\delta_t) - f_i(\mathbf{r},t) = -\frac{\chi}{\tau_e}\left[f_i(\mathbf{r},t) - f_i^{(eq)}(\mathbf{r},t)\right] + \delta_t J_i, \tag{1}$$

where

$$\tau_e = \sqrt{\frac{6}{\pi}}\frac{L}{\delta_x}Kn\Psi(Kn)(1+0.5b\rho\chi)^2 + \frac{1}{2}\chi, \tag{2}$$

$$J_i = -\left(1-\frac{\chi}{2\tau_e}\right)f_i^{(eq)} b\rho\chi(\mathbf{c}_i - \mathbf{u})\cdot\frac{\partial}{\partial \mathbf{r}}\ln\left(\rho^2\chi\right) + F_i, \tag{3}$$

$$f_i^{(eq)} = \omega_i\rho\left[1 + \frac{\mathbf{c}_i\cdot\mathbf{u}}{c_s^2} + \frac{(\mathbf{c}_i\cdot\mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u}\cdot\mathbf{u}}{2c_s^2}\right], \tag{4}$$

$$F_i = \left(1-\frac{\chi}{2\tau_e}\right)\omega_i\left[\frac{\mathbf{c}_i - \mathbf{u}}{c_s^2} + \frac{(\mathbf{c}_i\cdot\mathbf{u})\mathbf{c}_i}{c_s^4}\right]\cdot\left[\mathbf{F} + \frac{\partial}{\partial \mathbf{r}}\left(a\rho^2\right)\right], \tag{5}$$

and where f_i is the density distribution function, $\mathbf{c}_i$ is the discrete velocity at site $\mathbf{r}$ and time t, $f_i^{(eq)}$ is the equilibrium distribution function, δ_t is the time step, δ_x is the lattice spacing, ρ is the gas density, $\mathbf{u}$ is the macroscopic velocity, L is the characteristic pore size, τ_e is the effective relaxation time, and $Kn = \lambda/L$ is the Knudsen number with λ representing the mean free path of gas molecules, $\mathbf{F}$ is the external force, a is related to the averaged force potential due to intermolecular attraction, and $\Psi(Kn)$ is the correction function. The correction function is expressed by Guo et al. (2006) as:

$$\Psi(Kn) = \frac{2}{\pi}\arctan\left(\sqrt{2}Kn^{-3/4}\right), \tag{6}$$

where χ is the pair correlation function, which is given by Chapman and Cowling (1970) as:

$$\chi = 1 + \frac{5}{8}b\rho + 0.2869(b\rho)^2 + 0.1103(b\rho)^3 + 0.0386(b\rho)^4, \tag{7}$$

where $b = 2\pi d^3/(3\,m)$ with d and m representing the diameter and mass of a single molecule, respectively. For a two-dimensional nine-velocity (D2Q9) lattice structure, the weight coefficients ω_i are $\omega_0 = 4/9$, $\omega_{1-4} = 1/9$, $\omega_{5-8} = 1/36$; $c_s = c/\sqrt{3}$ is the lattice sound speed; $\mathbf{c}_i$ is the discrete velocity, which is given by

$$\mathbf{c}_i = \begin{cases} (0,0), & i=0, \\ (\cos[(i-1)\pi/2], \sin[(i-1)\pi/2])c, & i=1-4, \\ (\cos[(2i-9)\pi/4], \sin[(2i-9)\pi/4])\sqrt{2}c, & i=5-8, \end{cases} \tag{8}$$

where $c = \sqrt{(3RT)}$with R and T representing the gas constant and system temperature, respectively.

The density and velocity are defined as follows

$$\rho = \sum_i f_i, \tag{9a}$$

$$\rho\mathbf{u} = \sum_i \mathbf{c}_i f_i + \frac{\delta_t}{2}\left[\mathbf{F} + \frac{\partial}{\partial \mathbf{r}}\left(a\rho^2\right) - bc_s^2\frac{\partial}{\partial \mathbf{r}}\left(\rho^2\chi\right)\right]. \tag{9b}$$

The pressure p and kinematic shear viscosity ν are given respectively by:

$$p = \rho RT(1 + b\rho\chi) - a\rho^2, \tag{10}$$

$$\nu = RT\left(\frac{\tau_e}{\chi} - \frac{1}{2}\right)\delta_t. \tag{11}$$

The mean free path for ideal gas can be expressed as (Cercignani, 1990)

$$\lambda = \frac{\mu}{\rho}\sqrt{\frac{\pi}{2RT}}, \tag{12}$$

where $\mu = \rho\nu$ is the dynamic viscosity.

3. Boundary conditions for porous media

Because of the complicated phenomena taking place at the solid surface under shale-gas reservoir conditions, it is critical to choose an appropriate boundary condition for simulating gas flow in the shale matrix. Ren et al. (2015) used the bounce-back/specular-reflection (BSR) boundary condition to simulate gas flow in a kerogen pore. However, the BSR boundary condition is not suitable for gas flow with curved walls owing to the inclusion of specular reflection. To simulate gas flow in a shale matrix, this study uses an approximation to deal with the curved walls in a porous medium. First, as shown in Fig. 1, the physical boundary is approximated by a zigzag ghost boundary. These zigzag boundaries have been proven to be reasonable when the lattice is fine enough (Ladd and Verberg, 2001; Dünweg and Ladd, 2009). Then, the diffuse-bounce-back (DBB) scheme is used to obtain the unknown distribution function at the walls. DBB can be expressed by:

$$f_i = rKf_i^{(eq)}\left(\rho_w, \mathbf{u}_{surface}\right) + (1-r)f_{\bar{i}}', \quad \left(\mathbf{c}_i - \mathbf{u}_{surface}\right)\cdot\mathbf{n} > 0, \tag{13}$$

where $f_{\bar{i}}' = f_{\bar{i}} - \chi(f_{\bar{i}} - f_{\bar{i}}^{(eq)})/\tau_e + \delta_t J_{\bar{i}}$ is the post-collision distribution function with $\mathbf{c}_{\bar{i}} = -\mathbf{c}_i$, r is the combination coefficient, $\mathbf{n}$ is the inward unit normal, ρ_w is the gas density at the wall, and $\mathbf{u}_{surface}$ is the adsorbed-gas velocity. K is defined as follows: