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Effect of hydrate on permeability in porous media: Pore-scale micro-simulation

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ABSTRACT

The permeability variation caused by hydrate dissociation will affect the further exploitation of hydrate resources during the development of natural gas hydrate. To study the effect of hydrate on seepage characteristics in hydrate-bearing sediments, the micro-flow simulation was carried out by the lattice Boltzmann method. The effect of factors related to the pore-scale distribution of mineral particle and hydrate on permeability variation was analyzed in the two-dimensional porous media. Results show that the mineral particles arrangement has no effect on permeability variation for the two-dimensional homogeneous porous media, the permeability variation is sensitive to the hydrate-formation habit and hydrate-distribution morphology in the pore center. The concept of "control seepage channel" is proposed through comparative analysis of velocity field distribution. It controls the change characteristics of permeability. Based on the control seepage channel size and the control seepage channel tortuosity, a new model is presented to measure the permeability in porous media with gas hydrate. Considering two hydrate-formation habits: grain-coating and pore-filling, the relationships between relative permeability and hydrate saturation are proposed to describe permeability variation. The relationship of pore-filling case agrees well with the experimental results. It shows that hydrate grows mainly in the pore center under the experimental conditions.

1. Introduction

Natural gas hydrates are crystalline solids in which the gas molecules are trapped in water molecule structure under certain conditions [1]. The natural gas hydrate deposited mainly in ocean floor sediments and permafrost regions is a potential unconventional resource [2]. The global natural gas hydrate inventory which was estimated at a workshop in 2008 is likely to be in the range of 1000–10,000 GtC [3]. For comparison, the global inventory of other fossil fuels including oil, natural gas and coal was estimated to be around 5000 GtC [4]. Its order of magnitude is the same with the natural gas hydrate inventory alone. A significant amount of research has been conducted by many countries and regions because of high energy density and huge reserves in hydrate-bearing sediments [5]. However it is difficult to exploit cost-effectively the natural gas hydrate. In-situ dissociation of hydrate is considered an important development method for commercial recovery of natural gas in hydrate-bearing sediments [6]. It includes depressurization [7], thermal stimulation [8], inhibitor injection [9], CO_2 replacement [10] and so on. In any of the above methods, the permeability of hydrate-bearing sediments is an important factor for estimating gas deliverability [2]. It has an important influence on mass transfer and thermal transmission [11].

The change of pore structure caused by the hydrate dissociation results in the permeability variation in the process of natural gas hydrate development. It will affect the further exploitation of hydrate resources. Many researchers have studied on the change characteristics of permeability in porous media with gas hydrate through experiment methods [5,12–17]. Kleinberg et al. [18] measured the relative permeability to water in methane hydrate-bearing sandstones using NMR method. Liu et al. [19] used the gas injection method to measure gas phase permeability of methane hydrate-bearing clayey sediments. Li et al. [20] measured the water effective permeability of unconsolidated quartz sands using the water injection method. However it is difficult to accurately measure permeability in that the pore space integrity cannot generally be maintained [21] and the reformation or dissociation of hydrate cannot be avoided [22].

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Previously, many kinds of theoretical or semi-empirical models were proposed to calculate the relative permeability in porous media with gas hydrate, for example, the parallel capillary model derived from the simplest model of a porous media consisting of a bundle of straight, parallel cylindrical capillaries [18], Kozeny grain model on the basis of Kozeny-Carman equation and the formation conductivity [23]. According to above models, people developed other calculation models including the sinusoidal pore model [14], Masuda model [24], Sakamoto model [22], the hybrid model [25] and so on. The starting point of these models is the capillary theory. They ignore the microscopic analysis of some influencing factors, for example, the hydrate-distribution morphology in the pore center. The two-dimensional model can help to understand the seepage characteristic of fluid from microcosmic angle. Compared to the three-dimensional model, it is more easily and clearly used to analyze related mechanism problems. Therefore, it is necessary to conduct microscopic studies on the change characteristics of permeability in hydrate-bearing sediments on the basic of two-dimensional model.

In view of the difficulty of microcosmic experiments in porous media with gas hydrate, it is necessary to carry out the micro-flow simulation study. Micro-flow simulations that need to be carried out at the pore scale in hydrate-bearing sediments mainly include two aspects: the pore network model [26–28] and the lattice Boltzmann method (LBM) [29–32]. The pore-network model simulation is well applied in flow simulation in hydrate-bearing sediments [33,34]. But some information on hydrate-distribution morphology is lost in that the pore network model simplifies the porous media. Kang et al. [30] studied on the effect of capillarity on permeability reduction by lattice Boltzmann flow simulation. LBM has been a valid method for the micro-flow simulation study. Therefore, the microscopic simulation was carried out by the lattice Boltzmann method in this study. In consider of the hydrate saturation, the mineral particles arrangement, the hydrate-formation habit and the hydrate-distribution morphology in the pore center, the effect of hydrate on permeability variation of two-dimensional porous media was analyzed. Based on factorial analysis, a new model of permeability in hydrate-bearing sediments was proposed to analyze experimental results.

2. Model and method

2.1. Porous media model

Fig. 1 shows four kinds of two-dimensional porous media including two homogeneous models (Model 1 and Model 2) and two etched models (Model 3 and Model 4). The round particles are arranged homogeneously in tilted 45° square array in the Model 1, as shown in Fig. 1(a). The size of Model 1 is 160×320. The round particles are arranged homogeneously in square array in the Model 2, as shown in Fig. 1(b). The size of Model 2 is 169×338. In the Model 1 and Model 2, the particle radius (r) is 20, the particle spacing (l) is $40\sqrt{2}$, the porosity without hydrate (ϕ_0) is 0.61. The size of etched models is 200×480. The porosity without hydrate (ϕ_0) of Model 3 (Fig. 1(c)) and Model 4 (Fig. 1(d)) is 0.53 and 0.59.

2.2. Flow simulation

Lattice Boltzmann method (LBM) which originates from the lattice gas automata method is a numerical approach in computational fluid dynamics. The discrete Boltzmann equation is solved to simulate the kinetic of microscopic fluid particles [35]. In this study, the lattice Bhatnagar-Gross-Krook model (LBGK) is used to calculate the permeability, as shown in Eq. (1).

$$f_i(\mathbf{x}+\mathbf{e}_i\Delta t, t+\Delta t) - f_i(\mathbf{x},t) = \frac{f_i^{eq}(\mathbf{x},t) - f_i(\mathbf{x},t)}{\zeta} \tag{1}$$

where $f_i(\mathbf{x},t)$ is particle distribution function at lattice node $\mathbf{x}$ and time t, f_i^{eq} is equilibrium distribution function, $\mathbf{e}_i$ is the discrete velocity, the subscript i represents the lattice directions around the node, ζ is relaxation time, and Δt is time step which is 1.

The equilibrium distribution function is determined as a discretization of the Maxwell–Boltzmann equilibrium distribution [36], as shown in Eq. (2).

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

where ρ is macroscopic local fluid density, w_i is weight factor in the i th direction, $\mathbf{u}$ is macroscopic local fluid velocity, and c_s is speed of sound which is $1/\sqrt{3}$. The relaxation time is a function of fluid kinematic viscosity (i.e. $v = c_s^2(\zeta - 0.5)\Delta t$).

In this study, the discrete velocity model is D2Q9 [36]. The lattice directions around the node are shown in Fig. 2(a). The weight factor w_i and discrete velocity $\mathbf{e}$ are defined as follows:

$$w_i = \begin{cases} 4/9 & i = 0, \\ 1/9 & i = 1,\ 3,\ 5,\ 7, \\ 1/36 & i = 2,\ 4,\ 6,\ 8. \end{cases} \tag{3}$$

$$\begin{aligned} \mathbf{e} &= [\mathbf{e}_0,\ \mathbf{e}_1,\ \mathbf{e}_2,\ \ldots,\ \mathbf{e}_8] \\ &= \begin{bmatrix} 0 & 1 & 1 & 0 & -1 & -1 & -1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & -1 & -1 & -1 \end{bmatrix} \end{aligned} \tag{4}$$

The macroscopic quantities such as fluid density (ρ) and pressure (P) are computed using the following relations:

$$\rho = \sum_i f_i \tag{5}$$

$$P = c_s^2 \rho \tag{6}$$

The bounce-back scheme is used to simulate flow over a stationary no-slip boundary for migrating fluid particles toward a solid voxel. To simulate single-phase flow driven by pressure difference, Pressure boundary condition is adopted at the inlet and outlet to generate constant pressure difference. The solid voxel walls is adopted to seal boundary planes which is parallel to flow direction as shown in Fig. 2(b). When flow reaches steady state, permeability can be evaluated by Darcy's law. The criterion of steady flow is shown in Eq. (7).

$$\frac{\sqrt{\sum_{i,j}\{[u_x(i,j,t+\Delta t) - u_x(i,j,t)]^2 + [u_y(i,j,t+\Delta t) - u_y(i,j,t)]^2\}}}{\sqrt{\sum_{i,j}[u_x(i,j,t+\Delta t)^2 + u_y(i,j,t+\Delta t)^2]}} < 10^{-6} \tag{7}$$

where u_x and u_y denote the flow velocity of x and y direction, respectively.

2.3. Permeability calculation

Based on Darcy's law, the equation for calculating the water permeability by the lattice Boltzmann method is shown in Eq. (8).

$$k^L = \frac{q\rho_w(\zeta - 0.5)\Delta t L}{\rho_{out} - \rho_{in}} \tag{8}$$

where ρ_w is the fluid average density, *in* and *out* denote respectively the inlet and outlet, ρ_{in} and ρ_{out} denote respectively the fluid density at inlet and outlet, L is the length of model, and q is the rate of flow which is computed using the following relation: