Study on pore network model of porous media hydrate permeability

Qingge Zhang
School of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao, Shandong, 266590, China
Corresponding author’s e-mail: 201882040046@sdust.edu.cn

Abstract: Considering the influence of hydrate on fluid flow in porous media, the relationship between hydrate saturation and absolute permeability of porous media is studied by using pore network model. The absolute permeability of hydrate free porous media is calculated and the convergence is studied. The absolute permeability of hydrate bearing porous media is calculated, the phase equilibrium migration is studied, and the pore network model of hydrate porous media system is calculated. The results show that: (1) when the throat number in the pore network model is greater than 3000, the calculation result is relatively stable; (2) under the condition that the throat diameter follows the log-normal distribution, the permeability decreases faster with the increase of the standard deviation; (3) the calculation results of the network model are consistent with the experimental data, which proves its feasibility to a certain extent.

1. Introduction
Pore and throat are the main places and channels for fluid storage and seepage in porous media. Some scholars[1-3] have tried to use the pore network model to study the formation and distribution of hydrate in porous media, but the influence of hydrate on fluid flow in porous media has not been considered in these studies. In this chapter, we will try to use the pore network model to study the relationship between hydrate saturation and absolute permeability of porous media.

The pore network model is to use the model network to replace the complex pore space in porous media. The parameters describing pore network space mainly include network dimension, pore throat radius, pore throat length, coordination number, pore throat ratio, shape factor, pore throat distribution law and other property parameters.

2. Calculation of absolute permeability of hydrate free porous media
2.1. capillary pore network model to simulate fluid flow
It is assumed that the porous medium is completely saturated by a fluid, the fluid in the capillary is Newtonian fluid, and the fluid flow is laminar flow, and the following formula is guaranteed.

\[ Re = \frac{\bar{v}D_n}{\rho} \leq Re_{crit} = 2300 \] (1)

Where \( \bar{v} \) is the average velocity of the fluid in the capillary, and \( \rho \) is the density of the fluid. If the above formula holds, the pressure drop in the tube can be calculated by an equation.
\[ \Delta P = \frac{Q}{g} \]  

The conductivity between nodes is calculated by the following formula, where \( g \) is the radius of capillary:

\[ g = \frac{\pi r^4}{8 \mu l} \]  

(3)

Assuming that the fluid in porous media is incompressible and the volume is conserved at the nodes, the following equation can be obtained:

\[ \sum_j Q_{ij} = 0 \]  

(4)

The volume conservation equations are established for each node in the network structure. The following formula can be obtained by using matrix structure

\[ G\Delta P = b \]  

(5)

Where \( G \) is a sparse matrix containing the conductivity between nodes, \( \Delta P \) is the vector of pressure between nodes determining the flow direction, \( b \) is the vector representing the source term. By solving equation (5) of conjugate gradient method, the pressure of each node in pore network structure can be determined. Fig.1 shows the pore network structure.

![Fig.1 Three-dimensional cubic lattice of node dimensions of \( N_x \times N_y \times N_z \) together with a unit cell node \((i_x, j_y, k_z)\)](image)

2.2. Convergence research

In order to ensure that the three-dimensional cubic pore network model used in this study can accurately simulate the fluid flow in porous media, it is necessary to use different size scale models to study the convergence. In this study, the model adopts three, five, eight, ten, twelve, fourteen and sixteen connection keys in each direction.
Fig. 2 Convergence study of permeability for different porosities and sizes of the models, mean diameter, $\lambda=22.5\mu m$, standard deviation $\xi=0.9\mu m$

It can be seen from Fig. 2 that, regardless of the porosity, satisfactory calculation results can be obtained only when the number of connecting throats is more than 3000.

When the throat diameter obeys log-normal distribution, the generation of random number is closely related to the validity of the model. In order to meet the needs of the model, Marsaglia[4] proposed the verification of the pseudo-random number generation model. In this study, the random number generator in Matlab was used to generate the random number from the log-normal distribution. Fig. 3 shows the permeability obtained by different calculation times under the same distribution law. It can be seen that the results of several calculations are basically consistent.

Therefore, the model size in this calculation simulation uses the pore network model with 12 connecting throat in each direction and 4752 in total.

3. Calculation of absolute permeability of hydrate bearing porous media

3.1. Phase equilibrium migration

The influence of pore size on the phase equilibrium of methane hydrate can be calculated by Kelvin-Clapeyron[5] equation.

$$T_{shift} = T - T_{eq} = -\frac{2\gamma T_{eq} \cos \theta}{r \rho_s L}$$

(6)
Where $T$ is the hydrate formation temperature in porous media, $T_{eq}$ is the phase equilibrium temperature without porous media, $\gamma$ is the interface energy between the primary phase and the generated phase, $\theta$ is the wetting angle between the primary phase and the generated phase, $r$ is the equivalent radius of hydrate generated in the pore, $\rho$ is the density of hydrate generated, and $L$ is the latent heat of hydrate formation or decomposition.

Equation (6) can be used to calculate the influence of pore size of porous media on the phase equilibrium conditions of methane hydrate. In the formula calculation, $\gamma$ is the interface energy between hydrate and water phase, the size is 26.7mJ/m$^2$. In the capillary model, the wetting angle is 0°, the hydrate density is 0.91g/cm$^3$, and the decomposition latent heat of hydrate is 436.7kJ/kg. Fig.4 shows the relationship between pore size and phase equilibrium temperature shift of methane hydrate. It can be seen from the figure that when the pore diameter is larger than 600 A, the hydrate formation temperature shifts by 0.2%, that is, about 0.615k.

The modified Kelvin-Clapeyron equation describes the temperature excursion of hydrate phase equilibrium in porous media with single pore size. The actual pore size of porous media is not single, but random. Combining equation (6) with the distribution of pore size, the temperature excursion under different equilibrium pressure and different hydrate saturation can be calculated. Fig.5 shows the migration of methane hydrate saturation and equilibrium temperature in porous media with an average pore size of 550A and a log-normal distribution. Light lines in the figure are the offset lines of equilibrium temperature in porous media.

![Fig.4 Sensitivity of equilibrium shift with capillary radius size for capillaries larger than 600A, the shift is about 0.2%, or 0.5K at the ice point](image)

![Fig.5 Pressure-composition phase diagram for hydrate of average pore radius 550A](image)
3.2. Pore network model calculation of hydrate porous media system
The formation mode and growth characteristics of hydrate in porous media not only affect the formation process of hydrate and change the structure of porous media, but also affect the decomposition behavior of hydrate. Masoumeh[6] observed hydrate formation in the center of porous media through experiments, which proved the rationality of the above hypothesis. Based on this, the equivalent diameter can be used to calculate the flow characteristics of fluid through annular pores.

Fig. 6 The permeability variation curve with hydrate saturation for different ξ value

In the hypothesis, it is considered that the hydrate generated in the pore leads to the decrease of the cross-sectional area of the fluid flowing through the pore to 1/50 of the original value. The purpose of this assumption is to prevent the pore from being completely blocked in the calculation process, resulting in the calculation results not converging. In order to verify this hypothesis, 1/1000, 1/100 and 1/25 are selected as the cross-sectional area decline rates of fluids to study the variation characteristics of permeability. Fig.6 shows the curve of permeability changing with hydrate saturation in four cases. It can be seen from the figure that the permeability curves of the four cases are basically coincident, indicating that our hypothesis is feasible.

4. Conclusion
(1) The three-dimensional cubic pore network structure is established to calculate the permeability of porous media. When the throat number in the pore network model is greater than 3000, the calculation result is relatively stable.
(2) In the pore network model structure used in this study, under the condition that the throat diameter obeys log-normal distribution, the permeability decreases faster with the increase of standard deviation.
(3) The calculated results of the network model are in good agreement with the experimental data, which proves its feasibility to a certain extent.

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