Numerical Study on Seepage Characteristics of Hydrate-Bearing Sediments: A Pore-Scale Perspective

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Abstract. Natural gas hydrate is one of the most promising energy resources. The permeability of hydrate-bearing sediments (HBS) is a critical parameter that affects gas production efficiency. In this study, by carrying out two-dimensional seepage models of HBSs with uniformly round particles, the effect of factors including pore habit, hydrate saturation, and particle size on the permeability of HBS is investigated. Two pore habits, seven hydrate saturations, and three matrix particle sizes were considered to complete the numerical simulation. The results show that the permeability of HBSs decreases with increasing hydrate saturation and decreasing matrix particle size because of the formation of smaller flow channels. The pore-filling HBSs present a considerable reduction of permeability at low hydrate saturation than that of grain-coating HBSs. This can be attributed to the fact that hydrates formed in the center of pores restrict fluid flow more than those on the surface of particles. As a result, the permeability assumes a zero value at hydrate saturation close to 68%, though it is supposedly only possible at 100%. This discrepancy may account for the variations of pore spaces between the two-dimension and three-dimension, the ignorance of heterogeneity in HBSs, and the shapes of hydrates and soils. For coarse-grained HBSs, models developed to account for features as pore geometry can capture the primary trend of HBSs permeability and reveal its seepage characteristics.

1. Introduction

Natural gas hydrate is considered one of the most promising energy resources since the organic carbon in hydrates is twice as rich as all fossil fuels [1,2]. Therefore, this property of natural gas hydrate has received substantial interest. Its formation conditions are characterized by high pressure and low-temperature environments within marine and permafrost regions, with extensive distribution channels worldwide [3]. However, many challenges confront its recovery from hydrate-bearing sediments (HBS), safety, and economic feasibility [4].

One of the most critical parameters, permeability, controls the fluid movement within the porous media, determined by a long list of factors, e.g., grain size, specific surface area, porosity, and pore geometry [5,6]. These parameters affect mass transfer, reservoir deformation, and gas production efficiency [7]. Especially the complicated pore structures of HBSs make the internal flow behaviors more difficult to understand [8]. Previous research has revealed the seepage characteristics of HBS, focusing on the visualization of pore structures combining with various measurement methods. Kneafsey et al. [9] investigated hydrate and fluid distribution of HBSs by micro-focus X-ray computed tomography (CT) during permeability measurements. Mahabadi et al. [10] utilized a pore network
model simulation combined with CT technology to identify seepage characteristics of sediments from the Mallik site. CT technology and the lattice Boltzmann method were also carried out to study the relationship between permeability and hydrate saturation of Xenon HBSs [11]. Ji et al. [12] implemented nuclear magnetic resonance (NMR) combined with the equivalent seepage capacity method to study the effect of heterogeneous distribution of methane hydrate on the permeability of porous media. With the development of visualization technology, the pore structures of porous media could be quantitatively obtained. Moreover, the combination of this method and flow tests or numerical simulations provides convenience to permeability measurements. However, more specific pore space characteristics need to be fully measured by indirect imaging techniques or direct methods, providing complete microstructure information to study seepage characteristics in HBSs.

In this study, several different two-dimensional numerical models of HBS were implemented to study the effect of hydrate saturation, pore habit, and matrix particle size on the permeability of HBSs. In addition, it aims to get a better understanding of the seepage characteristics insides HBSs from a pore-scale.

2. Numerical models
In this study, commercial CFD software was used for the numerical simulations. Fluent is a widely accepted numerical method with multiple models to solve various problems. The permeability of HBSs was calculated by using the finite volume method to work out the Navier-Stokes equations of laminar flow conditions.

2.1 Basic assumption
Several assumptions of numerical simulations were set up as follows: 1) Both soil particles and hydrate particles are assumed to be round and distributed uniformly. 2) The soil and hydrate particles are assumed to be static, and hydrates will not decompose or reform during the fluid transportation process. 3) The entire process is simulated using laminar flow, which is suitable to calculate permeability by Darcy’s Law.

2.2 Modeling process
The particles were arranged with equal size and distributed uniformly to avoid the effects of anisotropy and heterogeneity. The length (L) between adjacent soil particles is three times longer than the radius of soil particles \( r_p \), as shown in Figure 1. The radius of hydrate particles \( r_h \) is calculated specifically for different hydrate saturations.

![Figure 1. The unit of numerical models of hydrate-bearing sediments (HBS): (a) pore-filling; (b) grain-coating.](image)

The whole specimen was assumed to be \( 9 \times 4.5 \) mm. The porosity and hydrate saturation were calculated using the ratio of surface area. According to the relationship between hydrate particle radius
and hydrate saturation, seven hydrate saturations were considered in numerical models. In addition, coarse-grained sediments are mainly studied and easily verified. Therefore, three distinct particle size matrices were implemented to accomplish the numerical simulation: coarse sand, medium sand, and fine sand, respectively. In addition to two pore habits, 39 numerical models were constructed, as shown in Table 1.

| Pore habit       | Particle Size(mm) | Hydrate saturation (%) |
|------------------|-------------------|------------------------|
| Pore-filling     | 1 0 10 20 30 40 50 60 |                        |
|                  | 0.5 0 10 20 30 40 50 60 |                        |
|                  | 0.25 0 10 20 30 40 50 60 |                        |
|                  | 1 10 20 30 40 50 60     |                        |
| Grain-coating    | 0.5 10 20 30 40 50 60   |                        |
|                  | 0.25 10 20 30 40 50 60  |                        |

### Verification

The results presented in Figure 2(a) were obtained using Darcy’s Law. $K$ is the effective permeability, defined as the permeability of single-phase flow tests through HBSs. When the hydrate saturation is 0, the effective permeability is referred to as the absolute permeability. The normalized permeability ($K_n$) represents the ratio of the effective permeability to the absolute permeability. Figure 2 (b) demonstrates a comparison between numerical data and existing models, including the parallel capillary tube model and the Kozeny grain (KG) model. The decreasing trend observed for normalized permeability of HBS is almost the same as that of the existing models. Both pore habits are more in line with the corresponding trends while closer to the KG model. Notably, the discrepancy between numerical data and existing models gradually increases with the increasing hydrate saturation. When the hydrate saturation exceeds 67% in the two-dimensional model, the entire fluid channel between pores gets utterly blocked, with no connections available. Yet, this phenomenon happens for a three-dimensional pore space when the hydrate saturation is within the range of 90%–100%. Section 4 covers a detailed discussion of these trends.

![Figure 2](image-url)
3. Results

3.1 Pore habits

Two pore habits, pore-filling and grain-coating are critical for understanding the effect of permeability in HBSs. The normalized permeability of both pore-filling and grain-coating hydrate decreases with increasing hydrate saturation and eventually reaches zero, as shown in Figure 2(b). When hydrates form in the center of pores, they congest more flow channels than when on the exterior surface of grains. Thus, the result of a hydrate saturation of 30% will be discussed in Figure 3. The inlet pressure of pore-filling hydrate tends to be massive when the velocity of two pore habits are assumed to be equal, as shown in Figure 3(a) and (b). Thus, the same hydrate saturation presents different pressure distributions depending on the pore habits under consideration. In addition, Figure 3(c) to (f) illustrate the velocity contour and vector images, clearly indicating the seepage characteristics under identical hydrate saturation levels but different pore habits. The two hydrate distributions caused significant differences in flow paths. The formation of pore-filling hydrate obstructs the original flow path, thus resulting in a split, with fluid covering almost all pore channels of the porous media. In contrast, the grain-coating hydrate maintains the original flow path and hardly expands the flow to both sides. As a result, the pore channels gradually diminish as the hydrate grows, and the flow velocity increases in the constriction created.

![Figure 3](image_url)

**Figure 3.** Numerical results of different pore habits of HBSs (S_h = 0.3). Pressure contours: (a) Pore-filling; (b) Grain-coating. Velocity contours: (c) Pore-filling; (d) Grain-coating. Velocity vectors: (e) Pore-filling; (f) Grain-coating.
3.2 Hydrate saturation

In general, the permeability of HBSs gradually decreases with increasing hydrate saturation. The reason that more hydrate formations block fluid flow is attributed to this phenomenon. Only the pressure contours will be presented in this section. It can be observed from Figure 4 that as the hydrate saturation gradually increases, the inlet pressure also increases, and the pressure drop becomes more significant, which coincides greatly with the trend of decreasing permeability. The inlet pressure of pore-filling hydrate is much larger than that of grain-coating, which presents lower permeability as analyzed above.

![Pressure contours of HBSs. Pore-filling: (a) S_h = 0.1; (c) S_h = 0.3; (e) S_h = 0.5. Grain-coating: (b) S_h = 0.1; (d) S_h = 0.3; (f) S_h = 0.5.](image)

**Figure 4.** Pressure contours of HBSs. Pore-filling: (a) S_h = 0.1; (c) S_h = 0.3; (e) S_h = 0.5. Grain-coating: (b) S_h = 0.1; (d) S_h = 0.3; (f) S_h = 0.5.

3.3 Matrix particle size

The particle-matrix size is a less prominent factor when studying the influence of the permeability in HBSs. This is because the physical properties of the particle-matrix size determine the porous media characteristics. Thus, clayed sediments have different pore characteristics, e.g., larger specific surface area, higher capillary force [13], which control the growth trend and distribution of hydrate, altering the permeability of the porous media. Nevertheless, the permeability of all matrix sizes still obeys the common reduction trend, as shown in Figure 2. Moreover, the permeability of HBSs with the smallest particle size is still the smallest in most cases among two pore habits and six-hydrate saturations. Figure 5 only presents the numerical results of hydrate-free sediments (S_h = 0). It is observed that the inlet pressure with the smallest particle size is the largest, representing the smallest measure of
permeability. Also, the flow paths are not directly affected regardless of the matrix particle size. The essential difference is the size of the pore channels. Small particle size suggests a small pore size. The permeability is inherently affected by pore size wherever hydrates form.

Figure 5. Numerical results of different matrix particle sizes of hydrate-free sediments. Pressure contour: (a) $d_p = 1$; (c) $d_p = 0.5$; (e) $d_p = 0.25$. Velocity contour: (b) $d_p = 1$; (d) $d_p = 0.5$; (f) $d_p = 0.25$.

4. Discussions

4.1 Pore space
The discrepancy between the results of numerical models and existing theoretical models became more apparent with increasing hydrate saturation, as shown in Figure 2 (b). The normalized permeability of numerical models reached zero at around 68% hydrate saturation, even though the theoretical saturation level for this to happen is 100%. The reason for this is the limitation of two-dimensional pore space. Hydrates formed in the center of pores or on the surface of grains will obstruct flow channels and continually intensify the effect as hydrates accumulate. When hydrate saturation reaches 68%, the main flow channels will be blocked entirely, and the permeability will be zero. Although some pore spaces in the two-dimensional numerical models still exist, they are mainly ineffective in accommodating fluid flow. The same blockage effect will be observed for three-dimensional models when the hydrate saturation exceeds 68%.
4.2 Anisotropy and heterogeneity
The hydrates and soil particles are distributed uniformly in numerical models, different from the microstructure of gas hydrate reservoirs. The intricate pore structures of soil make inherent seepage characteristics elusive. Moreover, the nucleation and growth of hydrates in pores exhibit great randomness [14], leading to the heterogeneous distribution of hydrates. Both non-uniformly distributed soil and hydrate particles could result in scattered permeability measurements and unexpected predictions [8]. Existing research ensures homogenous assumptions in the flow tests, theoretical models, and numerical simulations [15,16]. Thus, finding it extra challenging to explain the abnormal discrepancy. Therefore, CT and NMR technology are necessary to visualize and measure pore structures of reservoirs.

4.3 Irregular particle shapes
The soil and hydrate particles were assumed to be round in these numerical models, though the shape of soil particles exhibit a plethora of varying shapes in reality. In addition, hydrate morphology equally presents some level of variability, such as lenses, nodules, chunks, veins, etc., [17]. Different shapes represent different roughness and specific surface area, which may affect contact angle, capillarity, location of water-gas interface, further leading to inconsistent flow characteristics. The category of particles, determining hydrophilicity and hydrophobicity, also has a connection with the shape. The round shape simplifies the calculation process and ignores its effect on the permeability of HBSs, disregarding a wide variety of permeability results.

5. Conclusions
In this study, the pore-scale numerical models of HBSs were constructed, and the effect of three influencing factors on the permeability of HBSs was studied to reveal seepage characteristics. The key findings are as follows:
(1) The permeability of HBSs decreases with the increasing hydrate saturation and reducing particle-matrix size. Therefore, hydrate formations constrict flow channels, and fine-grained sediments inherently present the smallest flow channels.
(2) The pore-filling HBSs show a more significant permeability reduction at low hydrate saturation than grain-coating HBSs since the hydrates formed in the center of pores block pore channels more significantly in HBSs.
(3) The results of numerical models agreed well with existing theoretical models but presented an apparent discrepancy with increasing hydrate saturation. The difference between the two-dimensional and three-dimensional pore spaces, the unaccounted-for effect of heterogeneity in HBS, and the irregular shapes of particles may be responsible for this divergence.

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