Research Article

A Study on the Electrical Characteristics of Fractured Gas Hydrate Reservoirs Based on Digital Rock Technology

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The electrical characteristics of fractured gas hydrate reservoirs were investigated through the diffusion-limited aggregation model, digital rock technology, and the finite element method. The results show that the fracture and gas hydrate have a significant effect on the electrical characteristics of rock partially saturated with gas hydrate, where the matrix pore and fracture mixed gas hydrate form a dual-porosity system. Due to the fracture and gas hydrate effect, the electrical characteristics of fractured gas hydrate reservoirs cannot be described well by traditional Archie equations. The resistivity index vs. water saturation curve of fractured gas hydrate reservoirs shows a nonlinear relationship for different gas hydrate pore habits (pore-filling, cementing, and grain-coating types), and this curve consists of two parts with different gas hydrate saturation exponents for pore-filling and cementing gas hydrate and presents a curve without a fixed water saturation exponent for grain-coating gas hydrate. Fractured gas hydrate reservoirs with different fracture apertures, different gas hydrate pore habits, and saturation features will lead to macroscopic electrical anisotropy. The results of theoretical analysis and numerical simulation show that the electrical anisotropy coefficient of fractured gas hydrate reservoirs is a function of gas hydrate saturation. The function curve consists of three segments with the turning point for pore-filling and cementing gas hydrate, and this curve can be divided into two parts through the turning point. The findings of this study can help for a better understanding of the electrical characteristics of fractured gas hydrate reservoirs, which have great significance for the exploration and development of gas hydrate resources.

1. Introduction

The electrical characteristics of reservoir rocks play an important role in the exploration and development of oil and gas resources [1–4]. Up to now, extensive research has been conducted on the electrical characteristics of rocks with intergranular porosity, achieving relatively good research results, mainly focused on the electrical characteristics of rocks with approximately homogeneous features in conventional oil and gas reservoirs [5–8], and did not pay much attention to fractured gas hydrate reservoirs [9–11], which consist of porous layers and fractured layers and mixed with gas hydrate that distribute in different pore habits [12–15]. However, gas hydrate, which was considered one of the most promising clean energy, is mainly distributed in deep-sea sediments and terrestrial permafrost [16–18]. The macroscopic distribution of gas hydrate mainly includes pore-type and fracture-type in terrestrial permafrost. Due to the presence of fractures and gas hydrates and the influence of reservoir anisotropy, reservoir parameter calculation for fractured gas hydrate reservoirs is still difficult through adopting traditional Archie’s equations. Fractured gas hydrate reservoirs with different fracture apertures and gas hydrate pore habits will lead to macroscopic electrical anisotropy. Pore structure and gas hydrate pore habits suffer from the influence of the heterogeneity and anisotropy of fractured reservoirs [14]; therefore, the analysis of the real nature of the electrical properties of rocks faces unique difficulties. In order to fully analyze the electrical properties of heterogeneous rocks in fractured gas hydrate reservoirs, digital rock technology is a very effective method and means, which can quantitatively calculate and analyze the fracture factors and gas hydrate
pore habits on electrical characteristics. Many numerical simulation methods were used to investigate the electrical characteristics, such as the percolation network model and network model [19–21], whereas these models do not take the complex pore geometry into consideration. With the development of computer technology, the calculation of rock physical properties via actual microscopic pore structure information has been widely used [22, 23]. Jiang et al. [24] and Zhan et al. [25] investigated the electrical characteristics of Fontainbleau and Berea sandstone through digital rock technology, but only for rocks with simple homogeneous features. Zhao et al. [26] constructed a fractured digital rock and investigated the electrical characteristics. Dong et al. [27] have used digital rock technology and diffusion-limited aggregation model to construct pore-type gas hydrate digital rock and analyze the electrical characteristics. Nevertheless, there are relatively few studies on the electrical characteristics of fractured gas hydrate formations.

The overall structure of this article is as follows. First, we briefly summarize some existing digital rock construction methods and introduce the methods of constructing fracture-type digital rocks. Then, the diffusion-limited aggregation model for simulating the distribution of gas hydrate is discussed. Finally, the correlation between resistivity index, gas hydrate pore habits and saturation, and electrical anisotropy of fractured gas hydrate formation is investigated.

2. Fractured Digital Rock Construction

At present, there are many methods to reconstruct three-dimensional digital rocks. There are two different kinds of methods, such as numerical simulation methods [28–31] and physical experimental methods [32, 33]. Numerical simulation methods can be used to obtain the structural information from two-dimensional rock images and then reconstruct digital rock. The numerical reconstruction methods generally include the simulated anneal method and multipoint geologically statistical method. Physical experimental means use high precision laboratory instruments to reconstruct digital rocks, which would include focused ion beam scanning, X-ray computerized tomography, and nuclear magnetic resonance imaging. The characterization of internal structure and pore space distribution characteristics of the rock model constructed by physical experiment is much more accurate than numerical simulation methods. In this investigation, X-ray CT technology, as the main physical experimental method to obtain the real microscopic structure of rock samples, was used to construct a digital rock model. The rock sample was from a gas hydrate field in China. One rock sample (S1) without fractures and gas hydrate was scanned by X-ray CT with a resolution of 3.341 μm. The corresponding three-dimensional digital rock can be reconstructed through the processes of reconstruction and filtration. A digital rock model with the size of 300 × 300 × 300 voxels was segmented for fractured gas hydrate reconstruction and electrical characteristic simulation, and the porosity is 20.41%. Figure 1(a) shows the digital rock model of sample S1, where the blue and green component represent rock matrix and pore space.

Fractured gas hydrate reservoirs have complex pore structures, and the large number of distributed fractures and the complex pore habits of gas hydrate make the electrical characteristics much more complicated. The rock sample without any fractures is designed to eliminate potential interferences with resistivity results from fractures that may already exist. Fractured digital rock can be constructed by superimposing the fracture model and matrix digital rock. The fractures in the fracture model were flat and have smooth surfaces. Figure 1(b) shows the fractured digital rock, and the fracture aperture is 10 voxels (i.e., 33.41 μm).

3. Method and Theory

3.1. Method to Pore-Scale Gas Hydrate Formation and Distribution

Gas hydrate distribution characteristics have an important influence on the formation of a conductive path. Therefore, the most important task is to determine the distribution of gas hydrates in different pore habits and saturation. Hu et al. [34] used high-resolution X-ray CT apparatus to obtain the in situ distribution information of gas hydrate in pore-scale; the results show that the pore habits of gas hydrate are complicated and mainly present three types, that is, pore-filling, cementing, and grain-coating [35]. Yang et al. [36] adopt microscopic X-ray CT to observe gas hydrate-bearing sediments and obtain the spatial distribution information of free gas, formation water, gas hydrate, and rock grains. There are some methods proposed to simulate gas hydrate distribution, including computational HBS models [37], diffusion-limited aggregation model [27], and other methods. The concept of diffusion-limited aggregation model was introduced and improved by Meakin and Stanley, Paterson, and Witten and Sander [38–41], which is a conceptual model that can describe the process of irreversibly attaching solid particles to each other and forming aggregates. The clusters generated through this model have fractal characteristics [42]. Extensive research has shown that there is a certain equivalence relationship between this model and various physical processes that follow the Laplace equation, and this model has achieved good application effects in the description of some physical phenomena [43].

In this paper, the location and conditions of gas hydrate are effectively simulated through the diffusion-limited aggregation model. Randomly generate particles from selected positions, which can improve calculation efficiency and ensure that the shape of the cluster is not affected. With the growth of gas hydrate clusters, some new point sources will be generated. When the particles attach to the gas hydrate clusters, they stop randomly walking and exist in the final position [44]. Once the cluster growth conditions reach a certain predetermined limit, the growth process of gas hydrate will stop. In three-dimensional space, particles can randomly walk in the direction consistent with the definition of pore space connectivity depending on probability [45]. Isotropic or anisotropic conditions can be achieved through changing the probability of randomly walking particles in different directions. Combined with the gas hydrate pore habits, different gas hydrate digital rock models can be constructed.
by using the diffusion-limited aggregation model. For the detailed process of constructing gas hydrate digital rocks with different pore habits and saturation, please refer to the published article [27].

In order to verify the actual application effect, we applied the diffusion-limited aggregation model to the two-dimensional rock pore space. Figure 2(a) shows an original two-dimensional image of porous rock. The diffusion-limited aggregation model is applied to pore space, and the results of different gas hydrate distribution types are shown in Figures 2(b)–2(d), where the red component in the three figures is gas hydrate.

3.2. Method to Electrical Characteristic Simulation. Garboczi [46] and Sasaki [47] determined the finite element method to study the electrical characteristics of digital rocks, which can calculate the performance of porous media in which information is stored in two-dimensional or three-dimensional digital matrices. For electrical characteristics, a variational formulation of the linear electrical conductivity equations is imposed. For specific microstructure, according to the applied electric fields and the conductivity tensors of the solid composition of the material and the fluid phase, the final voltage distribution should maximize the total energy dissipated, the gradient of the energy relative to the voltage is zero, and the calculation formula is as follows:

$$\frac{\partial E_n}{\partial u_m} = 0,$$

where $E_n$ is the energy of the system and $u_m$ is the voltage at the $m^{th}$ node in a pixel.

The numerical simulation results based on the finite element method match the experimental test results well, which proves that this method is a powerful tool for exploring the electrical characteristics of digital rocks [48]. In this investigation, the scale of the digital rock used to study the electrical characteristics of fractured gas hydrate reservoirs suffers the influence of pore throat structure and gas hydrate pore habits are $300 \times 300 \times 300$ voxels.

4. Results and Discussions

In this investigation, digital rock with the voxel size of $300 \times 300 \times 300$ is used to study the electrical characteristics of fractured gas hydrate reservoirs. The diffusion-limited aggregation model is used to determine the distribution of gas hydrate and formation water in pore space at different gas hydrate pore habits and saturation. In the process of resistivity simulation, the electrical conductivity of rock skeleton and gas hydrate is set as $\sigma_m = 0$ and $\sigma_h = 0$, and formation water is set as $\sigma_w = 1$.

4.1. Gas Hydrate Distribution Has a Dominant Impact. Gas hydrate distribution has a dominant impact on the electrical properties of rock. The diffusion-limited aggregation model is used to simulate the distribution of gas hydrate in fractured rock pore space. Figure 3 shows gas hydrate distribution simulation results in fractured rock with a fracture aperture of 10 voxels. The pore habits are pore-filling, cementing, and grain-coating types, and corresponding gas hydrate saturation is 43.13%, 41.78%, and 42.24%, respectively.

The electrical characteristics of rock suffer from the influence of gas hydrate saturation. The diffusion-limited aggregation model is adopted to simulate different gas hydrate saturation in the pore space of fractured rock. Figure 4 shows grain-coating gas hydrate distribution simulation results at different saturation in fractured rock with a fracture aperture of 20 voxels. The corresponding gas hydrate saturation is 24.01%, 54.64%, and 78.30%, respectively.

4.2. Fracture Apertures Have a Dominant Impact. Fracture apertures influence the gas hydrate distribution, which means that fracture apertures have a dominant impact on the electrical properties. Digital image processing technology is used to construct fractured digital rock with different fracture apertures, and the diffusion-limited aggregation model is used to simulate the distribution of gas hydrate in pore space. Figure 5 shows fractured gas hydrate digital rock with different fracture apertures. The fracture apertures are 10 voxels, 20 voxels, 30 voxels, and 40 voxels, and the corresponding gas hydrate saturation is 60.98%, 59.76%, 60.67%, and 59.64%, respectively.
4.3 Effect of Fracture on Electrical Properties of Fractured Gas Hydrate Rock.

The saturation exponent in the Archie formula is a vital parameter for calculating water saturation. Referring to this concept, we take it to apply into gas hydrate reservoir. In order to study the effect of fractures on the resistivity index, we construct a set of fractured gas hydrate digital rock with different fracture apertures, and the fracture aperture and gas hydrate saturation affect total porosity. The correlation between resistivity index and gas hydrate saturation was analyzed based on digital rock and finite element method. The resistivity index can be calculated through the Archie formula [49], as shown in

\[ RI = \frac{R_s}{R_0} = b \frac{S_w}{S_w^m}, \]  

Figure 2: Illustration of gas hydrate distribution numerical simulation results in two-dimensional. (a) The original rock image, gas hydrate distribute in (b) cementing type, (c) grain-coating type, and (d) pore-filling type, where the blue, green, and red components represent rock matrix, pore, and gas hydrate.

Figure 3: Gas hydrate distribution in fractured digital rock with a fracture of 10 voxels. (a) Pore-filling type, (b) grain-coating type, and (c) cementing type, in which the blue, green, and red components represent rock matrix, formation water, and gas hydrate.
where $R_t$ is the real resistivity of the rock saturated with both formation water and gas hydrate, $R_0$ is the resistivity of the rock fully saturated with formation water, $S_w$ is water saturation, $n$ is water saturation exponent, and $S_h$ (i.e., $1 - S_w$) is gas hydrate saturation.

Figure 6 shows the curve of resistivity index vs. water saturation of fractured gas hydrate rock consisting of porous layers and fractured layers with different apertures in different gas hydrate pore habits. This curve change rule is the same for the fixed gas hydrate pore habits, and the difference in RI value is relatively small for cementing and pore-filling gas hydrate. On the contrary, the difference in the RI – $S_w$ curve is relatively large for grain-coating gas hydrate. The reason is that the cementing and pore-filling gas hydrate can view that the rock particles suspended in pore fluid have no influence on the pore structure. However, grain-coating

Figure 4: Grain-coating gas hydrate distribute in fractured digital rock with a fracture aperture of 20 voxels at different gas hydrate saturation.

Figure 5: Grain-coating gas hydrate distributions in fractured digital rock with different fracture apertures. The fracture apertures are (a) 10 voxels, (b) 20 voxels, (c) 30 voxels, and (d) 40 voxels, respectively.
gas hydrate, which has great effect on the effective pore structure, then presents in the RI – $S_w$ curve that the RI value has great difference.

4.4. Effect of Gas Hydrate on Electrical Properties of Fractured Gas Hydrate Rock. A set of fractured gas hydrate digital rock with different gas hydrate pore habits and saturation was constructed to investigate the influence of gas hydrate on the resistivity index. Figure 6 shows the relationship between resistivity index and water saturation of fractured gas hydrate rock consisting of porous layers and fractured layers with different fracture apertures in different gas hydrate pore habits. This curve (Figures 6(a) and 6(c)) consists of two linear segments with different slopes (water saturation exponent) for cementing and pore-filling gas hydrate. The first segment with the lower slope at a high-value range of water saturation should correspond to fracture, and the second with a higher slope at a low range of water saturation corresponds to the

![Graphs showing RI vs. $S_w$ for different fracture apertures and gas hydrate habits.](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2021/1365284/5382878/1365284.pdf)

**Figure 6**: RI vs. $S_w$ plot for fractured gas hydrate rock with different fracture apertures in different gas hydrate pore habits: (a) cementing type, (b) grain-coating type, (c) pore-filling type, and (d) different gas hydrate pore habits with fracture aperture of 10 pixels.
rock matrix, and the RI – $S_w$ curve (Figure 6(b)) presents a curve without a fixed water saturation exponent for grain-coating gas hydrate.

4.5. Electrical Anisotropy of Fractured Gas Hydrate Rock. In this part, a rock matrix that is homogeneous and isotropic in all directions was constructed and then superimpose fractures with different fracture apertures and gas hydrate with different pore habits and saturation. The electrical anisotropy of fractured gas hydrate reservoir rock is caused by the presence of fractured and gas hydrate. The coefficient of electrical anisotropy is defined as

$$\lambda = \sqrt{\frac{R_V}{R_H}}$$  \hspace{1cm} (3)$$

where $R_V$ is vertical resistivity and $R_H$ is horizontal resistivity. Figure 7 is the cross plot of the anisotropy coefficient versus

![Figure 7: Electrical anisotropy versus fracture apertures for different gas hydrate pore habits: (a) cementing type, (b) grain-coating type, (c) pore-filling type, and (d) different gas hydrate pore habits with fracture aperture of 10 pixels.](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2021/1365284/5382878/1365284.pdf)
fracture apertures for different gas hydrate pore habits. The electrical anisotropy curve can be divided into three segments for cementing and pore-filling gas hydrate. As for cementing gas hydrate, the coefficient of electrical anisotropy present increases and decreases and then increases with the decrease of water saturation using two points. As for pore-filling gas hydrate, the coefficient of electrical anisotropy present increases gradually with the increasing of water saturation. However, in the middle range of water saturation, the value almost keeps constant. By contrast, the electrical anisotropy curve can be divided into two segments for grain-coating gas hydrate; the first segment was at a high range of water saturation, the value increases rapidly, and in the second segment, the value increases more and more quickly with the decrease of water saturation.

5. Summary and Conclusions

In this paper, fractured digital rocks are constructed via the physical experimental method. The diffusion-limited aggregation model is used to simulate the distribution of gas hydrate in pore space, and the electrical properties of fractured gas hydrate rock are studied using the finite element method. According to our results, the following conclusions were drawn:

(1) The rock fracture and gas hydrate pore habits have a great influence on the electrical properties of partially gas hydrate saturated rock, where the fracture and matrix pore form a dual-porosity system, and the gas hydrate distribution complicated the electric conductive system

(2) The $RI - S_{w}$ curve of fractured gas hydrate rock shows a nonlinear relationship for different gas hydrate pore habits, and this curve of dual-porosity fractured gas hydrate rock consists of two linear segments with different water saturation exponents for cementing and pore-filling gas hydrate

(3) The $RI - S_{w}$ curve presents a curve without a fixed water saturation exponent for grain-coating gas hydrate, this phenomenon is caused by the presence of fractures and gas hydrate, and the electrical behavior of a fractured rock partially saturated with gas hydrate cannot be described by the Archie formula well. Owing to the presence of fractures, there is a significant difference in the resistivity of fully saturated rock measured in different directions

Nomenclature

- $E_{n}$: The energy of the system
- $\mu_{m}$: The voltage at the $m^{th}$ node in a pixel
- $RI$: Resistivity index
- $R_{v}$: The real resistivity of the rock saturated with formation water and gas hydrate
- $R_{h}$: The resistivity of the rock fully saturated with formation water
- $S_{w}$: Water saturation
- $n$: Water saturation exponent
- $S_{h}$: Gas hydrate saturation
- $\lambda$: The coefficient of electrical anisotropy
- $R_{v}$: Vertical resistivity
- $R_{h}$: Horizontal resistivity

Data Availability

All data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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