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Construction of Dual Pore 3-D Digital Cores with a Hybrid Method Combined with Physical Experiment Method and Numerical Reconstruction Method

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Abstract In order to further improve the accuracy of digital core modeling, a new hybrid method was proposed to construct the dual pore 3-D digital core with high precision. First of all, 3-D macro-pore digital cores were constructed by micro-CT. Secondly, based on the high-resolution 2-D scanning electron microscopy images of rock cores, micro-pore digital cores were constructed by simulated annealing method. And then, a superposition method was used to construct the digital core which could describe different pore characteristics. Finally, pore structures of digital cores were compared, and lattice Boltzmann method was used to analyze the percolation properties. The results show that the carbonate dual pore digital core constructed by the new hybrid method has a high accuracy, which can capture the pore properties of both macro-pore and micro-pore, and whose permeability simulation results are in good agreement with the experimental measurements. In addition, the new hybrid method is not only accurate and reliable, but also high efficient and economic, and can be applied to all kinds of reservoir modeling.

Keywords Hybrid method · Dual pore digital core · Micro-CT · Simulated annealing method · Lattice Boltzmann method

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1 Introduction

At present, we can study the micro-seepage of fluid in porous media based on the digital core platform, and the method of constructing digital cores is mainly divided into two categories: physical experiment method and numerical reconstruction method (Adler et al. 1990; Thovert et al. 2001; Thovert and Adler 2011). Physical experiment method (Lmberopoulos and Payatakes 1992; Dunsmuir et al. 1991; Tomutsa et al. 2007), as the name suggests, is a way to construct 3-D digital cores by using a variety of rock physical experiment equipment, such as high magnification optical microscope, nuclear magnetic resonance (NMR), scanning electron microscopy and CT scanner and so on. The method often directly or indirectly obtain 2-D images of the cores, and then use image processing and mathematical methods to reconstruct 2-D images of different sections into 3-D digital cores (Qu 2014). According to the difference of rock physical experiments, physical experiment method is mainly divided into sequence imaging method (Vogel and Roth 2001), focus scanning method (Fredrich et al. 1995), NMR method (Westphal et al. 2005) and X-ray CT scanning method (Arns 2002; Coenen et al. 2004). Numerical reconstruction method (Liu et al. 2009; Joshi 1974; Hazlett 1997; Arns et al. 2003) is mainly based on the petrophysical information, such as casting slice, rock particle size data, effective grain shapes and so on, to extract the key information of constructing digital cores by image analysis and mathematical statistics method, etc., and then use mathematical algorithms for 3-D modeling. According to the difference of algorithms, numerical reconstruction method is mainly divided into random method and process method. And different random methods select different statistical characteristics as reconstruction constraint functions, so random method can be subdivided into Gauss field method, simulated annealing method, multiple point geostatistics method and the sequential indicator simulation method and so on (Zhao 2009). However, one of the most commonly used methods includes X-ray CT scanning method and simulated annealing method.

X-ray CT scanning method can obtain 3-D digital cores which reflect real rock pore structure characteristics, and this method has advantages of high accuracy, no damage to the sample, visual image, etc. According to different CT scanning resolution, it can be roughly divided into micro-CT and nano-CT. The advantage of micro-CT is that the size of digital cores is larger, which can reflect the macro-pore information of the rock. The disadvantage is that the micro-pore cannot be identified, whose size is smaller than the scanning resolution, resulting in part of the pore loss. The advantage of the nano-CT is able to reflect the micro-pore information of the cores, and the disadvantage is that the sample preparation is difficult and scanning is cost. What is more, because the size of digital cores is smaller, when the rocks have strong heterogeneity, it will result in poor representation (Qu 2014).

The simulated annealing method is based on statistical thermodynamics theory and selects modeling reference functions as input data to construct digital cores (Thovert et al. 2001). Moreover, the method developed early and has become mature, has been widely used in the field of digital cores. Furthermore, the data of reconstruction are easy to acquire, the process is simple and fast, and the results have a wide applicability. However, there are also some differences in pore structures between the digital cores and the real cores.

As for this kind of reservoir rocks which are same as carbonate rocks whose pore space is complex, pore size distribution is wide, and heterogeneity is strong, because the sample size is so small, the constructed digital cores cannot reflect the fractures and holes. Therefore, it is very important to establish the multi-scale 3-D digital cores to study numerical simulation of reservoir rock based on the rock pore information obtained from different resolutions. In view of the shortcomings of existing digital core modeling method, a new hybrid method was proposed to construct the dual pore 3-D digital core with high precision. First of all, 3-D macro-pore digital cores were constructed by micro-CT. Secondly, based on the high-resolution 2-D scanning electron microscopy (SEM) images of rock cores, micro-pore digital cores were constructed by simulated annealing method. And then, a superposition method was used to construct the digital core which could describe different pore characteristics. Finally, pore structures of digital cores were compared, and lattice Boltzmann method was used to analyze the percolation properties.

2 Construction of 3-D Digital Cores of Carbonate Rocks

2.1 Construction of 3-D Macro-Pore Digital Cores by X-Ray CT Scanning Method

Because the 3-D digital cores by X-ray CT scanning method have the same pore structure characteristics as the real cores, the numerical simulation of rock physical characteristics has strong accuracy and reliability based on these models. And the process of building 3-D digital cores with X-ray CT scanning method can be divided into six steps (Sakellariou et al. 2007):

(1) Sample preparation. In order that the specimen cylinder has the proper size.
(2) Sample X-ray CT scanning. After reasonable selection of scanning resolution, the 3-D gray images of the cores are built through the scanning experiment.
(3) Gray image filtering. To eliminate 3-D gray image noise by median filtering method and so on.
(4) Binarization of gray image. For two-phase system of rock skeleton and pore space, the image segmentation technique is adopted to convert the gray image into binary image.
(5) Smoothing processing of binary image. To eliminate isolated rock skeletons.
(6) Representative volume element analysis. To select the best size of 3-D digital cores.

This study used the Xradia XRM-500 CT machine produced by Xradia company of America, whose highest resolution reached 0.7 $\mu m/pixel$, which was suitable for the establishment of various lithology 3-D digital cores. Figure 1 shows a binary image in carbonate rocks by micro-CT (the white represent rock skeleton, the black represent rock pore), and the CT scanning resolution is 1.24 $\mu m/pixel$, and diameter of the sample is about 2.2 mm.

Figure 2 presents a 3-D digital core pore space distribution image obtained by processing CT images, whose physical size is 0.186 mm × 0.186 mm × 0.186 mm and voxel size is 150 × 150 × 150. Compared with the real core porosity of 32.62%, there are 10.48% missing pores because the porosity of the digital core is 22.14%. And the missing pores are less than 1.24 μm.

2.2 Construction of Micro-Pore 3-D Digital Cores by Simulated Annealing Method

In this study, the two-phase (pore space and rock skeleton) isotropic system was reconstructed by using the porosity ϕ_0, two-point probability function $S(r)$ and the linear path function $L(\mathrm{r})$ as the constraint conditions, and ϕ_0, $S(r)$ and $L(\mathrm{r})$ can be obtained by the calculation for core modeling images. $S_r(r)$ and $L_r(\mathrm{r})$ are corresponding to $S(r)$ and $L(\mathrm{r})$, so simulated annealing algorithm is actually to optimize the system until $S_r(r)$, $L_r(\mathrm{r})$ and $S(r)$, $L(\mathrm{r})$ are approximately equal. The modeling process (Zhao et al. 2007) is as follows:

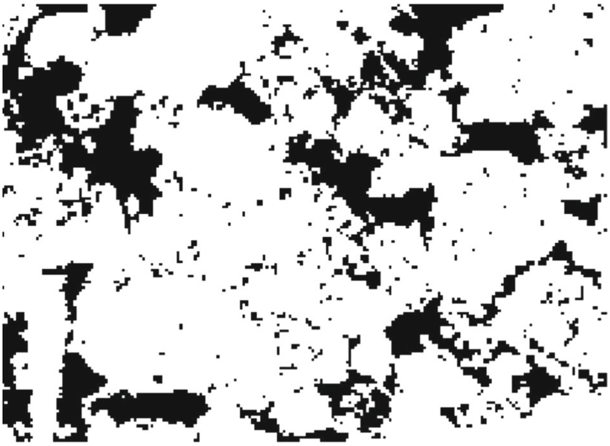
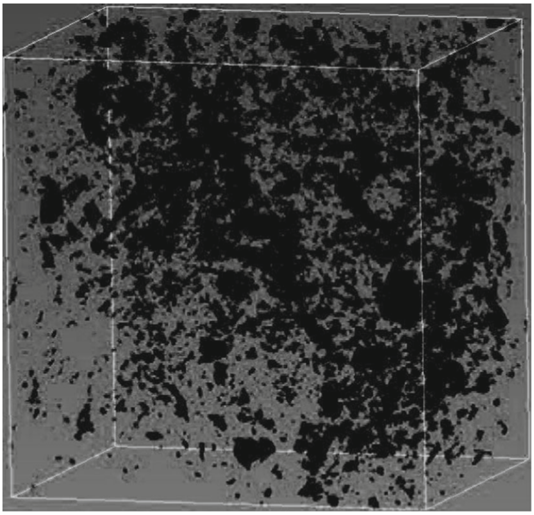


Fig. 1 Low-resolution binary image in carbonate rock at 1.24 μm/pixel

Fig. 2 Pore morphology distribution of low-resolution digital core (physical size is 0.186 mm × 0.186 mm × 0.186 mm, voxel size is 150 × 150 × 150)



Firstly, a 3-D '0, 1' digital core system (0 represents the pore, and 1 represents the rock skeleton) with a porosity of ϕ_0 was randomly generated, and the simulated annealing process was started. The two-point probability function and the linear path function of the system were assumed as $S_r(r)$, L_r(r) in a moment, and the energy of the system E (called the original system) was calculated by the following formula.

$$E = \sum_i \alpha_i \left[S_r(r_i) - S(r_i)\right]^2 + \sum_i \beta_i \left[L_r(r_i) - L(r_i)\right]^2 \tag{1}$$

In the formula, α_i, β_i are the weight values of the function of different independent variables.

Then, one pore point and one skeleton point were randomly selected in the pore space and rock skeleton space, respectively. And through exchanging the position of two points, a new system was generated, whose porosity was consistent with the original system in the whole

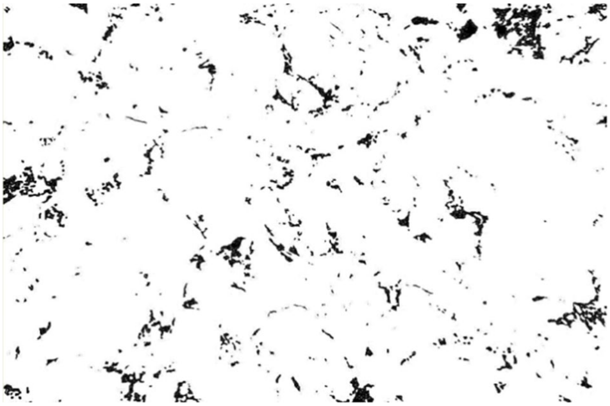
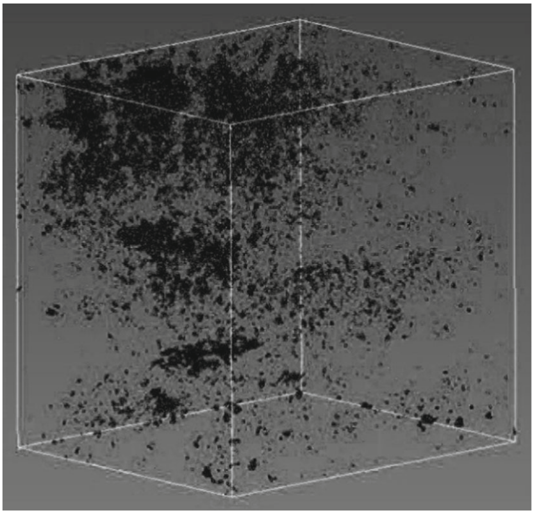


Fig. 3 High-resolution binary image in carbonate rock at 0.31 μm/pixel

Fig. 4 Pore morphology distribution of high-resolution digital core (physical size is 0.186 mm × 0.186 mm × 0.186 mm, voxel size is 600 × 600 × 600)



process of optimization. Secondly, $S_r(r)$, L_r(r) and system energy E' of the new system were calculated. At this time, Metropolis criteria was used to judge whether the new system was accepted. If the new system was accepted, the original system was updated by the new system. Otherwise, the new system was abandoned and the original system was retained. Through the optimization process, the system was continuously optimized.

Based on carbonate core scanning images obtained by scanning electron microscopy, binary images of carbonate cores were generated with image segmentation technology (Zhao 2009). Figure 3 shows a binary image of carbonate core with high resolution (the white represent rock skeleton, and the black represent pore space), whose image phase amplitude is 600 × 400, and resolution is 0.31 μm/pixel and resolution ratio of scanning electron microscope and CT scanning image is 1:4, which is mainly used to describe the characteristics of micro-pores in carbonate rocks.

Figure 4 presents the pore space distribution image of the micro-pore digital core which was constructed by the simulated annealing method, whose physical size is 0.186 mm × 0.186 mm × 0.186 mm and the same as the size of the macro-pore digital core constructed

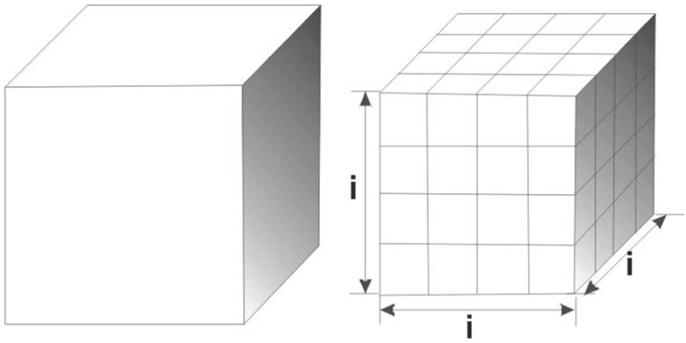


Fig. 5 Schematic diagram of voxel refinement

by micro-CT. In addition, the porosity of micro-pore digital core is 15.25%, the voxel size is $600 \times 600 \times 600$, and the resolution is $0.31\ \mu m/pixel$.

2.3 Construction of Dual Pore 3-D Digital Cores by Superposition Method

The steps of construction of dual pore 3-D digital cores by superposition method (Wang et al. 2012, 2013) were as follows:

(1) Voxel refinement of macro-pore digital cores. As shown in Fig. 5, according to the resolution ratio of i ($i = 4$), the voxel of macro-pore digital core was divided into $i \times i \times i$ voxels, so that the voxel of both macro-pore digital core and micro-pore digital core had the same size.
(2) The pore systems of both digital cores were superimposed, and the pore system I_s of the dual pore digital core was as follow:

$$I_s = I_A \cup I_B \tag{2}$$

In the formula, I_A and I_B represent the pore system of both macro-pore digital core and micro-pore digital core, respectively. Since the data body of the digital cores was characterized by 0 (pore space) and 1 (skeleton space), the superposition operation was as follow:

$$0 + 0 = 0, 0 + 1 = 0, 1 + 0 = 0, 1 + 1 = 1 \tag{3}$$

Figure 6 presents the pore space distribution image of the dual pore digital core of a carbonate rock constructed by superposition method, whose voxel size is $600 \times 600 \times 600$ and resolution is $0.31\ \mu m/pixel$. And compared with the macro-pore digital core and the micro-pore digital core, the porosity of the dual pore digital core is significantly increased, which is closer to the measured porosity (32.62%) of the real core.

3 Digital Core Structure Characteristics

3.1 Two-Point Probability Function and Linear Path Function

Based on the macro-pore digital core (Fig. 2), the micro-pore digital core (Fig. 4) and the dual pore digital core (Fig. 6), the main parameters of the pore structure of digital cores including the connected volume ratio, two-point probability function and linear path function were calculated, respectively.

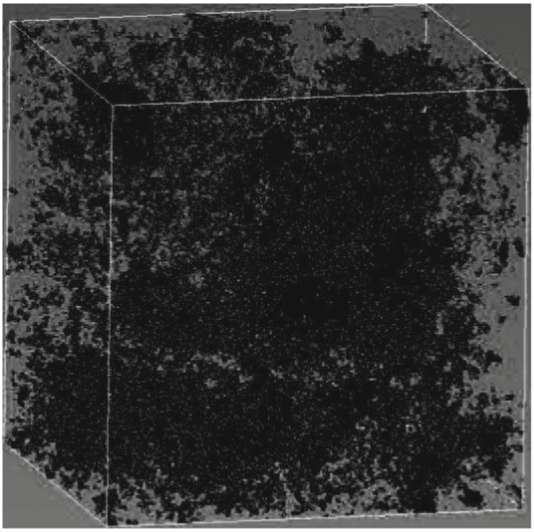


Fig. 6 Pore morphology distribution of dual pore digital core (physical size is 0.186 mm × 0.186 mm × 0.186 mm, voxel size is 600 × 600 × 600)

3.1.1 Two-Point Probability Function

In process of digital core modeling, as to the system with only pore and skeleton phase, the two-point probability function is the probability of two points which are selected randomly in the system and belonged to the same phase. And the pore phase is usually used as the research object, so S(r) is used to represent the probability of two points which are randomly selected in the system and belonged to the pore phase. And its definition is as follows:

$$S(r) = \overline{Z(r) \times Z(r + r_0)} \tag{4}$$

$$Z(r) = \begin{cases} 1 & r \in \text{pore} \\ 0 & r \notin \text{pore} \end{cases} \tag{5}$$

$$\phi = \overline{Z(\mathrm{r})} = S(0) \tag{6}$$

In the formula, r is any point in system, r_0 is distance between any two points in system, "—" indicates statistical average, Z(r) is pore phase function, ϕ is two-phase system porosity. Under normal circumstances, the length of the S(r) curve is intercepted when the curve reaches a stable value or the level of volatility is not large.

3.1.2 Linear Path Function

The linear path function is an important function to describe the connected performance of pore phase in porous media, and its definition is as follow:

$$L(r_1, r_2) = \overline{p(r_1, r_2)},\ p(r_1, r_2) = \begin{cases} 1, & r_x \in \text{pore} \\ 0 & \text{else} \end{cases} \tag{7}$$

In the formula, r_x is any point on line $r_1 r_2$.

In the isotropic system, $L(r_1, r_2)$ depends only on the distance of r, so that the formula can be simplified as $L(r)$. And the system whose pore phase volume fraction is ϕ is content with equation: $L(0) = S(0) = \phi$. In addition, $L(r)$ decreases with the increase of r and even

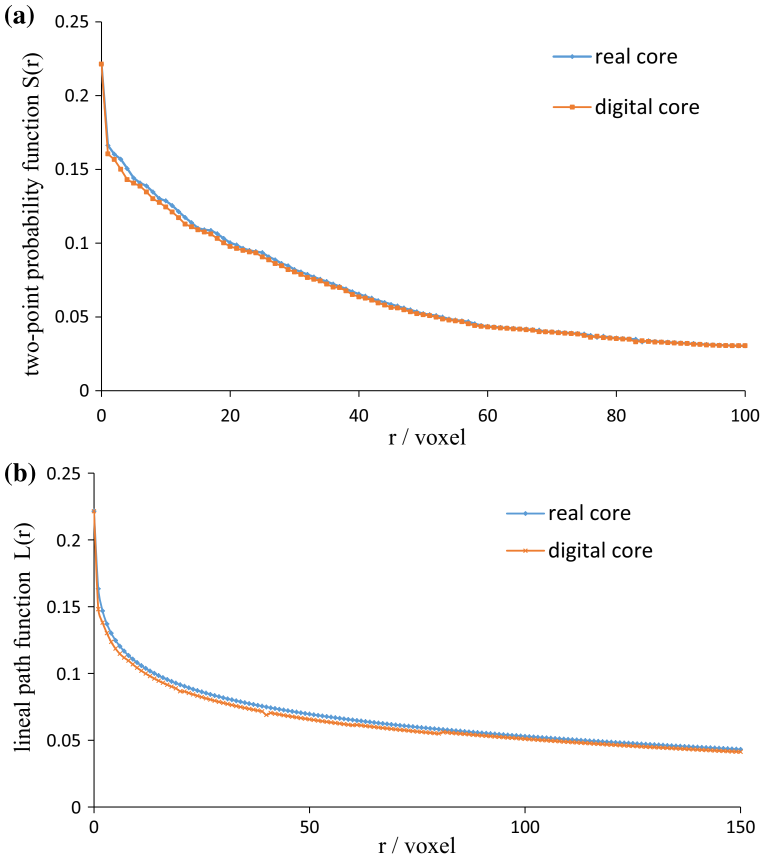


Fig. 7 Two-point probability function and lineal-path function of macro-pore digital core. **a** Two-point probability function. **b** Linear path function

down to 0. The calculation length of $L(r)$ can be selected when the value of $L(r)$ is down to 0.

Figure 7 illustrates the two-point probability function and linear path function curves of the macro-pore digital core by macro-CT, and Fig. 8 illustrates the two-point probability function and linear path function curves of the micro-pore digital core by simulated annealing method. It can be seen that the statistical function of the macro-pore digital core is almost identical to that of the 2-D CT slice analysis, which indicates that micro-CT can truly reflect spatial distribution characteristics and pore morphology of rocks. And the statistical function of the micro-pore digital core is similar to that calculated from the original images by scanning electron microscope, so it also proves that simulated annealing method can well reflect the pore characteristics of rocks.

3.2 Connected Pore Volume Ratio

Connected pore volume ratio f_p (Yeong and Torquato 1998) is expressed as:

$$f_p = V^*/V \tag{8}$$

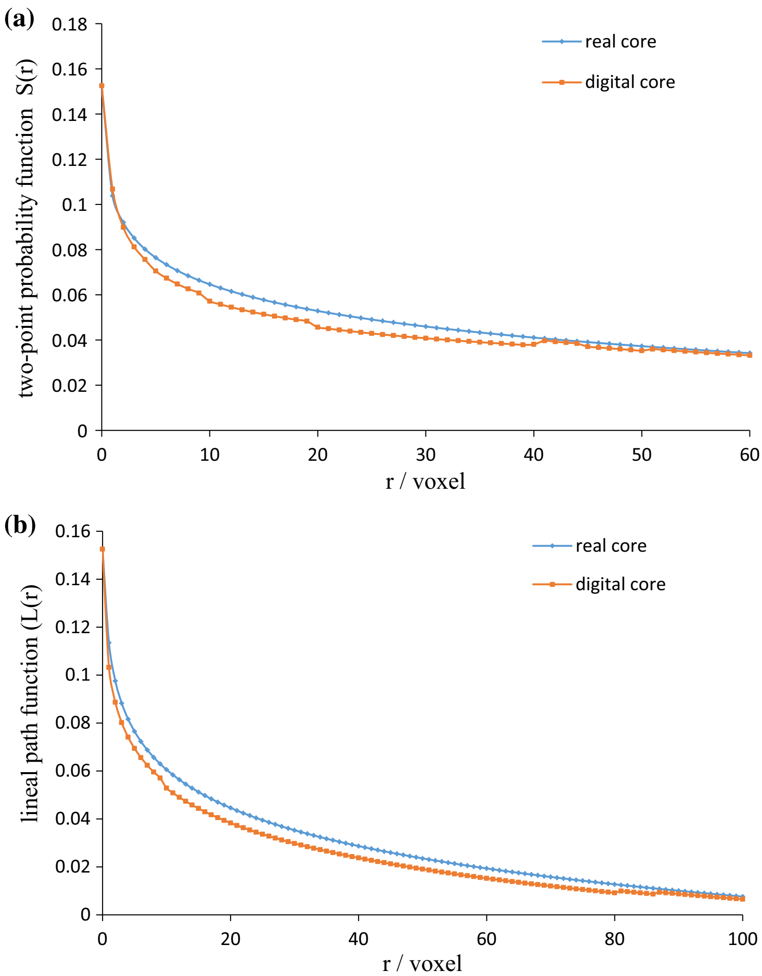


Fig. 8 Two-point probability function and lineal-path function of micro-pore digital core. **a** Two-point probability function. **b** Linear path function

In the formula, V^* is the pore volume of fluid flowing through from one side of core to another side, m^3. V is the total pore volume of core, m^3.

It was calculated that the connected pore volume ratio of the macro-pore digital core, the micro-pore digital core and the dual pore digital core were 79.58, 84.62 and 93.47%. It is seen that although the volume ratio of macro-pore is higher than that of micro-pore, the connected pore volume ratio of the macro-pore digital core is lower than that of the micro-pore digital core, and both of them are lower than that of the dual pore digital core. In general, one of the reason is caused by the strong heterogeneity of carbonate rocks, another is due to the enhancement of connectivity between the isolated macro-pore with addition of micro-pore. And it also proves that in the process of digital core modeling, the micro-pore plays an important role in the connectivity of the whole digital core.

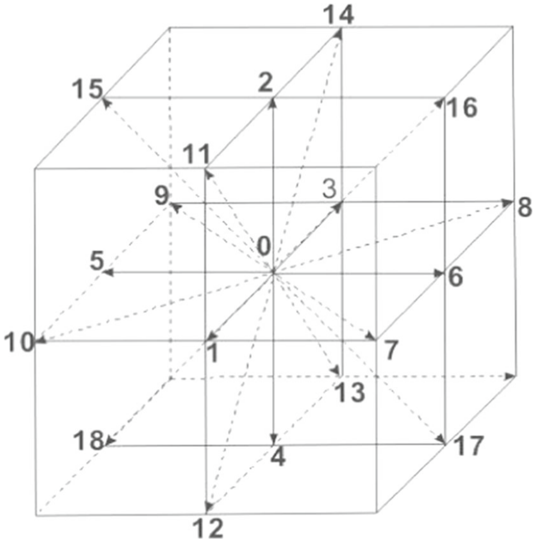


Fig. 9 D3Q19 lattice structure model

4 Seepage Characteristics

Recently, there are two main permeability simulation methods based on digital core: percolation network model and lattice Boltzmann method. Taking into account the practicality and accuracy, this study selected lattice Boltzmann method. At the same time, considering the accuracy and speed of calculation, D3Q19 3-D lattice Boltzmann model was adopted. And the grid structure is shown in Fig. 9 (Yeong and Torquato 1998; Chen and Doolen 1998; Zhang et al. 2015), and the discrete velocity direction is as follow.

$$\vec{e_i} = \begin{cases} (0,0,0),\ i=0; \\ (\pm1,0,0),(0,\pm1,0),(0,0,\pm1), \\ i=1,\ldots,6; \\ (\pm1,\pm1,0),(\pm1,0,\pm1),(0,\pm1,\pm1), \\ i=7,\ldots,18. \end{cases} \tag{9}$$

Evolution equation:

$$f_i(\mathrm{x}+\mathrm{e}_i\Delta \mathrm{t}) = f_i(\mathrm{x},t) - \frac{1}{\mathrm{T}}\left[f_i(\mathrm{x},t) - f_{\mathrm{eqi}}(\mathrm{x},t)\right] \tag{10}$$

Equilibrium distribution function f_{eqi}:

$$f_{eqi} = t_\sigma \rho \left[1 + 3\frac{e_i u}{c^2} + 4.5\frac{(e_i u)^2}{c^4} - 1.5\frac{u^2}{c^2}\right] \tag{11}$$

Macroscopic density and macroscopic velocity are as follows:

$$\rho = \sum_i f_i(x,t) \tag{12}$$

$$\rho u = \sum_i f_i(x,t)e_i \tag{13}$$

In the formula, $f_i(x,t)$ is the particle distribution function along the i direction at the moment of t in the lattice x; T is the relaxation time; $c = \Delta x/\Delta t$ is the lattice velocity; Δx

and Δt represent the grid step and the time step, respectively; the weight coefficient is as follows: $t_\sigma = 1/3, i = 0; t_\sigma = 1/18, i = 1, \ldots, 6; t_\sigma = 1/36, i = 7, \ldots, 18$.

Formulas (9)–(13) constitute the iterative model of lattice Boltzmann method. In the calculation, the direction of fluid flow was first set and the rest surface of digital core were surrounded by a layer of skeleton. In order to ensure the accuracy of the two order calculation, the curve boundary condition between pore and skeleton was adopted (Mei et al. 2013), and the inlet and outlet were put under certain pressure.

By using the lattice Boltzmann method to simulate the seepage process of macro-pore digital core (Fig. 2), micro-pore digital core (Fig. 4) and dual pore digital core (Fig. 6) and to calculate absolute permeability of digital cores, it was calculated that the macro-pore digital core permeability was $1.62 \times 10^{-3}\,\mu\text{m}^2$, and the micro-pore digital core permeability was $0.057 \times 10^{-3}\,\mu\text{m}^2$. Through the comparison of the digital core permeability, it is seen that the difference of pore characteristics of carbonate rocks in different scales is significant, the permeability of micro-pore is very low, and the permeability of macro-pore is much higher than that of micro-pore. Furthermore, the permeability of dual pore digital core is up to $2.46 \times 10^{-3}\,\mu\text{m}^2$, which is not only larger than the permeability of macro-pore digital core and micro-pore digital core, but also higher than the sum of the two. These permeability simulation results show good agreement with the report by Apourvari and Arns (2016). It can be concluded that micro-pore can greatly improve the overall reservoir connectivity in carbonate reservoir with strong heterogeneity. Therefore, it is so important that the hybrid method is applied for construction of dual pore digital cores which can accurately reflect the macro-pore structure characteristics and contain the micro-pore structure information too.

5 Conclusion

In conclusion, by means of CT scanning and simulated annealing method, the dual pore digital core by the hybrid method overcomes the disadvantage of large modeling errors of physical experiment and numerical reconstruction method at single scale, and it not only maintains the core size and macro-pore characteristics but also contains the characteristics of micro-pore structure, which greatly improves the accuracy of digital core modeling. And it also can be seen from the porosity data and the percolation characteristic analysis that the volume ratio of macro-pore is higher and the contribution of permeability is the largest, and the existence of micro-pore can greatly improve the overall connectivity of carbonate reservoir. Therefore, using the hybrid method to establish 3-D digital cores with high precision which not only contain accurate and reliable macro-pore space structure information but also possess micro-pore structure feature is crucial to the rock physics numerical simulation. Moreover, the hybrid method is not only accurate and reliable but also efficient and economic, which overcomes some disadvantages, for example, the construction of micro-pore digital core by nano-CT is time-consuming and high cost, and construction of macro-pore digital core by numerical reconstruction method is not accurate enough. What is more, the modeling time and cost of this method is moderate, and the model precision is high, and it can be applied to the digital core modeling of all kinds of reservoirs.

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