Numerical modelling of fluid transportation based on digital core model

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Abstract. Rock pore is the storage space and migration channel of geo-fluid resource like petroleum, coalbed methane and shale gas etc. In this paper, the rock core microscopic pore structure based on CT image is studied through image processing. Then the parameters are analyzed statistically by numerical modelling. The reconstructed software Mimics is used to reconstruct the core structural model. Finally, the relationship between the pore structure parameters and penetrability is studied by numerical simulation. The equivalent permeability of the reconstructed core is calculated by using FEM software Abaqus. The results shown that fluid percolation is directly related with porosity, pore shape, pore connectivity. The permeability of core can be obtained by substituting flow numerical simulation for seepage laboratory experiment.

1. Introduction
Pore structure of the oil and gas reservoir has significance for geofluid resource development. Pores are not only the reservoir fluid storage space, but also the reservoir fluid flow channel. Study on reservoir micro-pore shape, connectivity, pore size distribution and coordination number can facilitate the reasonable classification and evaluation of reservoirs, and identify reservoir distribution. In the process of oilfield development, well logging is often used to explain pore structure. Pore connectivity, specific surface area and pore structure of particles of water film thickness parameters influence the resistance of reservoir rock rate, petrophysical parameters such as permeability. Rock as a porous medium, permeability is a basic variable that characterizes the flow capacity. Due to the complexity and randomness of rock pore structure, it is often difficult to test rock micropermeability [1]. Permeability of different kinds of rock has a great deal of difference, even for the same type of rock, due to different environmental and geological conditions, permeability changes is up to several orders of magnitude. Through testing the permeability change in the whole stress-strain experiment process of rock, the permeability of rock presents a relatively large change, and the change rule is quite complex. Although fractal and multifractal models were induced into porous media research [2, 3], but as the complexity of rock pore structure, it is still difficult to predict permeability accurately.
In different research fields, there have been many research achievements on pore structure. CT, SEM and NMR methods were used to obtain the digital pore structure. Numerous computational models have been proposed and used to study the relationships between pore internal structure and physical, chemical and mechanical properties [4-8]. In order to reveal the rock physics relationships between the macroscopic properties and the microstructure, many models and methods have been introduced and applied in this study, for example, capillary models, lattice gas model, network model, percolation network model. However, most of these models are ideal simplified models, which can not reflect the real pore complex topologies. With the development of computer technology, rock microstructure reconstruction technology is widely used because it can reflect the real three-dimensional digital cores and the actual pore network topology. Based on pore network model, percolation theory is start to be used to calculate the macroscopic physical properties of Rock [9-11].

In many areas, porosity and permeability of rock have important impacts on engineering project. At present, a lot of scientists and engineering conducted researches on the macroscopic physical and mechanical properties of porous rock, and have achieved certain results. Although pore volume in the rock is not a large proportion, macroscopic mechanical parameters of rock, such as effective elastic modulus, strength and poisson's ratio, are significantly affected by pores and the fluid in them. Numerical simulation of rock physics must be based on a physical model of rock, and rock physics modeling accuracy determines numerical simulation of petrophysical results accuracy [12]. Rock physics models of evolution evolved from the simple to the complex, according to the complexity of the model, the models can be divided into two kinds, simplified ideal pore network model and real pore structure digital model. Simplified pore scale network model is too idealistic, often leads to big differences between simulation results and actual results. Using numerical core model and numerical simulation method to study the physical characteristics of rock is attracting more and more attention. This paper introduces the process of constructing three-dimensional digital core based on CT technology, and carries out numerical simulation of pore fluid flow through Abaqus finite element software, and analyzes the correlation between rock microstructure and macroscopic transmission behavior. The results can provide reference for the study of rock seepage.

2. Numerical simulation of flow in pore structure model

2.1. Reconstruction of rock pore structure model

In order to quantitatively analyze the pore structure of rocks, this paper constructs a digital core model of three real rocks based on CT scan data. Before using CT scan data to construct digital core, CT gray images must be filtered to make the transition between pore space and skeleton more natural and smooth, and to remove partially isolated pores and skeleton elements in core gray images. In Figure 1, pore space is represented by black, rock matrix is represented by white. The original CT image was binarized by image segmentation method, and the processing results are shown in Figures 1(a), 1(c) and 1(e). The images after binarization were imported into Mimics software to identify the boundary line between the black and white areas and vectorize it to obtain Figures 1(b), 1(d) and 1(f). The digital core established by this method is more in line with the actual rock system and has the real core pore space topological structure. The porosity and other parameters of the three cores can be obtained through image processing, and the results are shown in Table 1. Input the 3D CT image files into the Mimics software can get the core of three-dimensional reconstruction models. Mimics is software specially developed by Materialise for medical image processing. Use Mimics for the segmentation of 3D medical images (coming from CT, MRI, microCT, CBCT, Ultrasound, Confocal Microscopy) and the result will be highly accurate 3D models of your patient’s anatomy.

In this study, the boundary condition of the calculation model is set as the boundary of inlet and outlet constant pressure. The upper and lower surfaces of the model were set as pressure inlet and outlet boundary respectively, and the other four surfaces were set as impermeable boundary. It is assumed that the flow state of the fluid flow is laminar flow, and the simulated environment is constant temperature at 270K without considering the change of temperature.
Table 1. Porosity of rock core image.

| Sample No. | Resolution μm | Pixels Number | Matrix volume mm³ | Pore volume mm³ | Porosity % |
|------------|---------------|---------------|-------------------|----------------|-----------|
| S4         | 1479.00       | 300³          | 68985099.35       | 34789381.25    | 33.5      |
| S8         | 1479.00       | 300³          | 74724989.11       | 49124854.28    | 39.7      |
| S9         | 2017.00       | 260³          | 39210978.79       | 15205686.44    | 27.9      |

2.2. Flow simulation of single fluid
The upper boundary pore pressure is 2MPa, and the lower boundary pore pressure is 1MPa, pressure difference is 1MPa. Left and right borders was set impervious boundaries. Model S4 pressure field and
velocity field results are shown in Figure 2 and Figure 3. From which we can see pore fluid pressure field distribution and fluid flow field in rock pores.

Single-phase numerical simulation after convergence can get export flows of data, using Darcy's law to calculate the permeability of the model. By changing the pressure gradient direction, get the model permeability along the x, y, z three directions. Penetration of unstructured mesh data is shown in Table 2, which represents models along to permeability.
Table 2. Permeability of S4, S8 and S9 models.

| Sample No. | Model length | Net number | Porosity % | $k_x D$ | $k_y D$ |
|------------|--------------|------------|------------|---------|---------|
| S4         | 8.97         | $6 \times 10^6$ | 6.98       | 12.16   | 10.67   |
| S8         | 7.69         | $6 \times 10^6$ | 9.49       | 17.71   | 14.83   |
| S9         | 4.32         | $6 \times 10^6$ | 4.67       | 7.37    | 6.49    |

3. Conclusions

(1) Using the core microstructure CT scanning image processing software of the research group, a large number of core CT images in the research group were analyzed statistically to study the core pore structure parameters (such as aperture, throat radius, porosity, etc.) and Pore structure of the statistical analysis of the law, the establishment of core microscopic pore structure statistical model.

(2) Based on the established statistical model, the core model of sandstone core is established by using the maximum ball principle proposed by Dong et al. The network model parameters of the largest spherical pore structure are established.

(3) Based on the established model of pore structure network, three-dimensional micro-pore structure model was reconstructed by three-dimensional microstructure reconstruction software Mimics.

(4) For the reconstructed core model, the finite element mesh is divided, and the equivalent permeability of the reconstructed core is calculated by using Abaqus software. The relationship between core equivalent permeability and its pore characteristic parameters is established, and core permeability and porosity are established. The relationship between the structural parameters is established, and the calculation model of the core equivalent permeability with the microscopic pore structure parameters is established.

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