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Simulation study on seepage of nitrogen in porous medium of oil-rich coal

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ABSTRACT

The study of coal microstructure based on 3D reconstruction is of great practical significance for CBM extraction, thermal convection in situ pyrolysis, and oil and gas transport in coal seams. In this paper, oil-rich coal is scanned by CT, and then, 3D reconstruction is performed by using 3D visualization software AVIZO to establish a 3D pore structure model of oil-rich coal. Finally, COMSOL Multiphysics software is used to simulate the changes of seepage velocity and seepage path during the seepage of nitrogen in the pore space. The results show that Oil-rich coal has anisotropy; the permeability in X, Y, and Z directions is very low and shows a great difference, with the increase of N_2 temperature, the effective permeability in all three directions increases; with the increase of pressure gradient, methane seepage velocity increases gradually, and the curve shows the obvious non-linear relationship.

Keywords: Oil-rich coal, porous media, nitrogen, seepage

1. INTRODUCTION

China's energy structure is characterized by the resource endowment of "lack of oil, less gas and relatively rich in coal", which directly determines that China's primary energy is dominated by coal, and the external dependence of oil and gas will reach 73.5% and 43.2% respectively in 2020 [1], and the security of energy supply has become an important factor affecting national economic development. Under the constraint of "double carbon" target, how to develop coal industry with high quality and efficiently utilize coal resources has become an urgent issue to be solved. Coal is an important raw material for oil and gas production and high value-added chemicals, among which oil-rich coal, with tar yield between 7% and 12% [2], has advantages in improving oil and gas conversion efficiency and reducing economic costs. Western China is rich in oil-rich coal, with 129.1 Gtonnes of oil-rich coal in Shaanxi province alone [3]. Previous studies have shown that pyrolysis of one ton of oil-rich coal can yield about 10% oil and 500 m³ of combustible gas, as well as semi-coke that can replace anthracite and coke [2]. Large-scale development of oil-rich coal development and high-efficiency conversion industry with oil and gas production as the main products is an urgent need to increase the domestic oil and gas supply pathway and an important way to achieve clean and efficient low-carbon cycle development of coal [4].

Oil-rich coal is completely solid in its natural state and cannot be extracted like natural gas in reservoirs; only through pyrolysis can oil-rich coal be converted into products such as oil and gas[5]. The two main types of oil-rich coal pyrolysis technologies are aboveground pyrolysis and underground pyrolysis. Aboveground pyrolysis technologies face problems such as environmental pollution and low efficiency [6]. In contrast, underground in-situ pyrolysis can largely avoid these problems, thus becoming a promising coal conversion technology. Previous studies have shown that convective heating method is an efficient in situ pyrolysis technology [7]. Coal is a natural and complex porous medium with a large number of pore-fracture structures in different spatial locations [8]. The pore structure of coal not only affects the macroscopic physical properties of coal, but also affects the adsorption, diffusion and percolation of gas in coal [9], therefore, exploring the percolation in the microscopic pore structure of coal is of great practical significance for coalbed methane extraction, thermal convective in situ pyrolysis and transport of oil and gas in coal seams. Wang et al. [10] studied the microstructure, coal deformation and water transport of non-homogeneous coal using micro-CT behavior and quantified the relationship between pore structure parameters and fractal dimension of coal samples with different degrees of metamorphism. shi et al. [11]analyzed the detailed structure of microfractures in coals of different coal grades by micro-CT scanning and determined the effect of coal grade on the physical properties of microfractures. CT-based 3D simulations were widely used to study the flow in coal porous media [12]. In comparison with experimental results, visualization of microscopic seepage in coal macropores was achieved. Many previous works have been done in the simulation of seepage in porous media, but the complex real pore space flow is yet to be studied.

In this paper, oil-rich coal is taken as the research object and scanned by CT. On the basis of 2D image segmentation, the 3D spatial distribution of pores is extracted and reproduced. A 3D pore structure model of oil-rich coal is established, and the 3D visualization of coal macropore seepage is realized by importing the output model of AVIZO into COMSOL, revealing the changes of seepage velocity and flow path of N_2 in the process of macropore space seepage. This study provides a theoretical basis for the study of pore space fluid transport law in coal, and provides some reference for the actual convective heating in situ pyrolysis process.

2. NUMERICAL APPROACH

2.1 Model description

Oil-rich coal is used as the study object, and CT is used to scan it. Based on the 2D image segmentation, the 3D spatial distribution of pores is extracted and reproduced. The 3D pore structure model of oil-rich coal is established, and the 3D visualization of coal macropore seepage is realized by importing the output model of AVIZO into COMSOL, and the specific pore model is shown in the following figure 1.

2.2 Numerical methods

Flow simulations in pore space can be achieved using the single-phase flow module in COMSOL. The simulation is based on the incompressible Navier-Stokes equation, which follows the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy. The incompressible N-S equation can be expressed as follows [13].

$$\rho\left[\frac{\partial v}{\partial t}+(v\cdot\nabla)v\right]=\rho f-\nabla p+\mu\nabla^2 v \qquad (1)$$

where ρ is the gas density (kg/m3); v is the gas flow velocity (m/s); ∇p is the pressure difference (Pa); μ is the dynamic viscosity (Pa·s); the left side of the equation represents the inertia force; ρf represents the mass force; $\mu\nabla^2 v$ represents the viscous force.

In complex pore space flow, the compressibility of the gas has a great influence on the microscopic flow of the gas, such as the density change and heat transfer effect caused by the fluid flow. In order to simplify the calculation of COMSOL and fast convergence, we assume that the fluid in the pore space is incompressible and obeys the Navier Stokes equation. The post-processing module based on COMSOL software characterizes the variation of seepage velocity and flow path during nitrogen seepage.

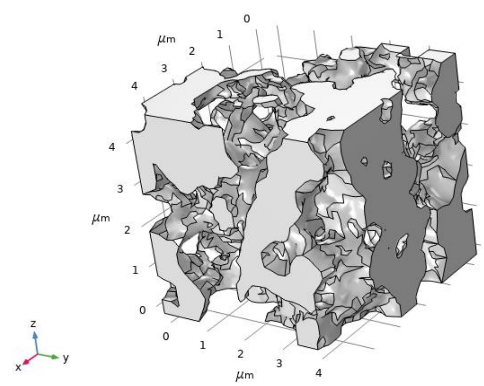


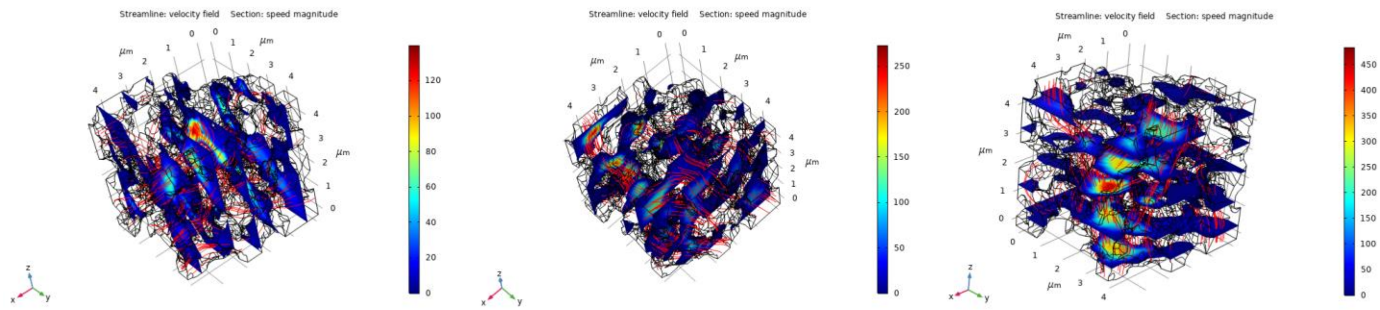
Fig 1 Pore structure of oil-rich coal

3. RESULTS AND DISCUSSION

Among the pore structures, the connecting pore is the main channel for fluid transport and plays a decisive role in the permeability of N_2. Therefore, it is important to study the percolation law of connected pores. However, it is difficult to analyze the seepage of connected pores from a microscopic perspective by experimental methods. By importing the output model of AVIZO into COMSOL, the pore-scale seepage simulation was realized.

3.1 Distribution of velocity field and streamline of N_2 seepage

The inlet pressure is set to 1.1 MPa, the outlet pressure is 0.1 MPa, and the N_2 temperature was 550°C. The post-processing module based on COMSOL characterized the changes in seepage velocity and flow path during N_2 percolation, as shown in Figure 2.



X direction Y direction Z direction

Fig 2 Changes of flow path and seepage velocity in three directions in the process of N_2 seepage

In order to truly reflect the spatial heterogeneity of oil-rich coal, N_2 seepage inlet and outlet interfaces in X, Y and Z directions are defined, as shown in figure 2. Along the N_2 seepage direction, although the pressure gradients in X, Y and Z directions are the same, the velocity field distribution in each direction is different. This is due to the highly irregular pore structure, which is reflected in the differences in size, shape, connectivity and permeability between each pore. From the streamline in figure 2, although all the pores are connected, the pore seepage path only appears in part of the pore space. The reason for this phenomenon is that the real flow of N_2 in the pore structure of oil-rich coal is complex, and there is a non-Darcy flow which does not conform to the N-S equation. It can also be seen from the figure that the seepage velocity in each direction is different, which also reflects the characteristics of anisotropy. The average seepage velocity of 5 sections is extracted from three directions. as shown in figure 3, the seepage velocity of this section fluctuates obviously with the change of cross-section volume flow, and the seepage velocity increases in some areas. Along the direction of nitrogen seepage, the difference of seepage velocity between inlet and outlet in X, Y and Z directions is 0.71m/s, 3.41m/s, 2.20m/s, respectively.

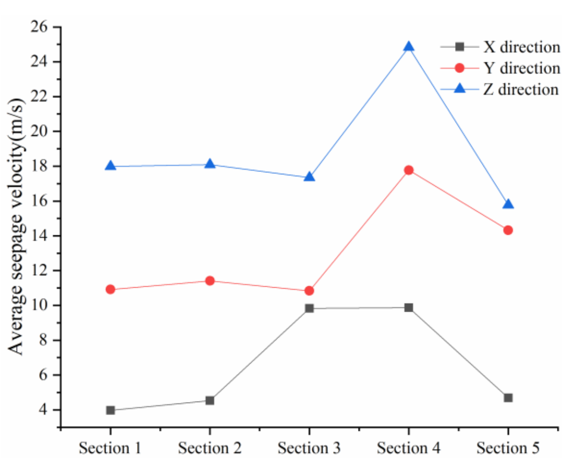


Fig 3 Average seepage velocity in different sections

3.2 Effect of different N_2 temperature on effective permeability

In order to explore the effect of different nitrogen temperature on effective permeability, the pressure difference between inlet and outlet was controlled as 1MPa, and the effective permeability of N_2 at 450, 500, 550, 600 and 650 °C was studied respectively. The results are shown in figure 4 below.

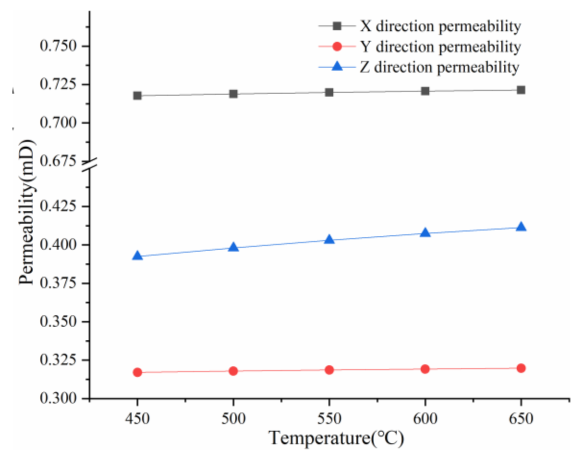


Fig 4 Effect of different nitrogen temperature on effective permeability in three directions

As can be seen from the diagram, the permeability of oil-rich coal in X, Y and Z directions is very low and shows great differences. Among them, the permeability in X direction is the highest, while that in Y and Z direction is relatively low. This shows that the permeability of N_2 shows obvious anisotropy in different directions, which shows that reasonable wellbore layout is the key to in-situ pyrolysis mining of oil-rich coal. At the same time, with the increase of N_2 temperature, the permeability in all three directions increases, because when the temperature of N_2 increases, the viscosity of N_2 will increase. At the same time, according to the area fraction of the outlet velocity of N_2, the volume flow rate of N_2 will decrease. According to Darcy's law, when the viscosity of N_2 increases more than the volume flow rate of N_2 decreases, the effective permeability will increase.

3.3 Effect of different pressure difference on seepage velocity

In order to analyze the variation law of seepage velocity under different pressure gradients. When the outlet pressure is kept constant at 0.1Mpa, when the pressure difference in Y direction is 0.5,1.5,2.5 and 3.5Mpa respectively, the average seepage velocity of section 1 to 5 is shown in figure 5. With the increase of pressure gradient, the seepage velocity of each section in Y direction increases gradually, and the curve shows obvious nonlinear relationship. Under the same pressure gradient, the seepage velocity of N_2 is obviously different along different seepage directions, which is due to the existence of Darcy flow and non-Darcy flow in the actual pore seepage. In the numerical simulation, the N_2 seepage which obeys the Navier-Stokes equation is mainly studied.

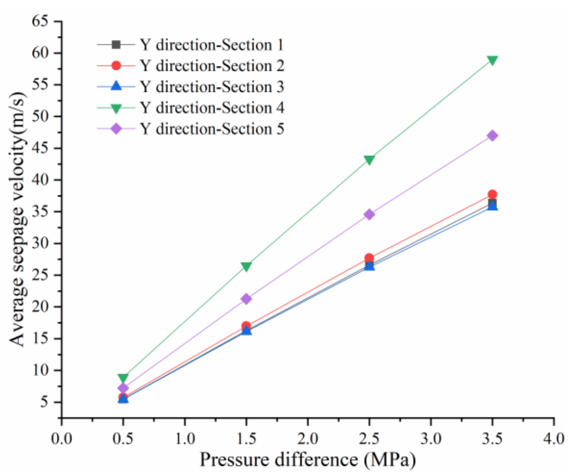


Fig 5 The variation of seepage velocity under different pressure gradients

4. CONCLUSION

In this paper, the changes of seepage velocity and flow path of N_2 in the real pore space of oil-rich coal are simulated. The main conclusions are as follows:

(1) Along the N_2 seepage direction, although the pressure gradients in X, Y and Z directions are the same, the velocity field distribution in each direction is different, which is caused by the height irregularity of pore structure, which also reflects the characteristics of anisotropy.

(2) The permeability of oil-rich coal in X, Y and Z direction is very low and shows great difference, and the effective permeability in all three directions increases with the increase of N_2 temperature.

(3) With the increase of pressure gradient, the methane seepage velocity increases gradually, and the curve shows obvious non-linear relationship.

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