

Based on Finite Element Analysis, The Main Controlling Factors of Coal Rock Permeability Under True Triaxial Stress Are Analyzed

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Abstract: The COMSOL Multiphysics multi-physical field coupling software is used to explore the seepage of coal rock in the true triaxial stress environment. The simulated working condition is the coal rock with a buried depth of more than 1500 m in ChengZhuang, JinCheng. The basic physical parameters of coal rock, such as elastic modulus, Poisson's ratio, porosity and density, are obtained by uniaxial compression test and mercury injection test. The parameters are input into numerical simulation software to ensure the real reliability of simulation. At the same time, Darcy's law is selected to define the seepage field, and the physical field of solid mechanics is added to ensure the construction of true triaxial stress environment. The temperature environment of coal seam is simulated by porous media heat transfer module. The simulation results are consistent with the experimental results.

Keywords: Coalbed methane ; Finite element ; Numerical simulation ; True triaxial.

1. Introduction

Permeability is a key factor affecting gas production and production efficiency. Permeability reflects the difficulty of fluid flow in coal seam rock, which is directly related to the release capacity of coalbed methane. Coal reservoirs with high permeability can release coalbed methane more efficiently, thereby increasing gas production, while low permeability brings about the difficulty of gas flow in coal matrix, increasing the difficulty and cost of mining.

The permeability of coal is affected by many factors. In addition to the nature of coal itself, such as porosity, pore connectivity and other factors, the most influential factor is its stress state. The stress environment of coal rock in reservoir is often three-dimensional unequal true triaxial stress. Therefore, it is of great guiding significance to study the evolution law of coal permeability under true triaxial stress environment for coalbed methane mining.

In recent years, the study of true triaxial gas-bearing coal seepage has become a hot spot. Through the self-developed triaxial coal-rock gas seepage test system, Liu et al. found that water content has a significant effect on permeability. The experiment shows that at a constant temperature, the permeability of gas-bearing coal decreases exponentially with the increase of water content. In addition, the influence of gas pressure on permeability is greater than that of confining pressure, and in the process of increasing gas pressure, the permeability shows a V-shaped change trend of 'first decrease and then increase', which is consistent with the Klinkenberg effect. Wang Kai et al. developed a true triaxial gas-solid coupling coal seepage test system, which can simulate the mechanical and seepage characteristics under different stress paths. The composite coal-rock specimens with transition interface are made by pressing method, which solves the problem that the interface effect of traditional splicing specimens is not true. Zhang Chenyang et al. [1] found that the permeability of coal under different stress paths was significantly different through the true triaxial loading and

unloading test. When the intermediate principal stress σ_2 was unloaded, the permeability of coal gradually increased with the accumulation of damage, and the peak strength decreased. Li Wenxin et al. [2] The purpose of developing a true triaxial coal seepage test system is to study the damage deformation and gas seepage of coal rock. Wang et al. [3] carried out a coal adsorption seepage test using methane and helium as objects. The results show that under the condition of equal helium, methane adsorption is affected by confining pressure and the intermediate principal stress has a double effect.

In addition to the use of experimental methods, the use of numerical simulation methods for the seepage of true triaxial coal rock is also favored by a large number of scholars. The 'matchstick' model initially received the favor of a large number of scholars. The model is mainly based on the uniaxial stress state, in which it is assumed that the coal matrix blocks are completely separated by cleats and are not connected to each other. However, the pore structure and seepage characteristics of coal rock have obvious heterogeneity and anisotropy, so the model has its limitations. With the rapid development of CT technology, image processing and computer technology, more and more numerical simulation methods have been discovered by experts and scholars. Bird et al. [4] first used Avizo software to construct a digital core of carbonate rock, and then used the finite element software Comsol to simulate the seepage of water flow and current in pore space. Ni et al. [5] carried out the seepage simulation of single-phase water flow in coal rock by solving Navier-Stokes equation and using Avizo and Comsol docking technology. Based on the constructed three-dimensional digital core of shale, Zhang et al. [6] studied the seepage behavior of pores of different scales by using lattice Boltzmann (LBM) method. Ju et al. [7] simulated the seepage behavior of methane gas in sandstone by LBM method, and analyzed the influencing factors of its flow. Sun et al. [8] used the parallel lattice Boltzmann method to effectively realize the three-dimensional flow process of gas in organic-rich mudstone, and obtained the velocity distribution map of gas

flow in X, Y and Z directions. Liu Xiangjun et al. [9] established a three-dimensional digital core model of sandstone that can reflect the real pore structure characteristics by using micron CT scanning technology. By perfectly docking with the finite element software Comsol, the pore-scale seepage simulation was realized and the absolute permeability of sandstone was calculated. Wang Zhen et al. [10] proposed the multiscale extended finite element method (XFEM) to simulate the seepage of large-scale disordered fracture groups through coarse grids. The calculation amount is reduced by 90 %, and the error of single well production is only 5 %, which significantly improves the local seepage prediction accuracy of fracture network under true triaxial conditions. Jiang Yuannan [11] established a true triaxial fluid-solid coupling model based on COMSOL-Multiphysics to simulate the dynamic evolution of coal permeability around the dynamic pressure roadway. [12,13,14]It was found that the permeability of the plastic zone was 2-3 times that of the elastic zone, and the design criterion of borehole spacing was optimized. Tao [15] developed a thermal-solid-gas multi-field coupling finite element model to reveal the mechanism of coal temperature rise inhibiting permeability decline under true triaxial unloading path, and proposed the ' thermal driving effect ' of temperature gradient on gas migration.

Therefore, In this paper, the sampling finite element analysis software COMSOL Multiphysics multi-physical field simulation software is used to couple the multi-physical field of heat flow and solid, and the mechanical characteristics and fluid migration law of deep coal reservoir under true triaxial stress environment are studied.

2. Basic Physical Properties and Modeling Process of Coal Rock

2.1. Basic physical properties of coal rocks

The uniaxial compressive strength of coal rock refers to the maximum axial pressure that the rock can withstand before failure. It is an important parameter to evaluate its mechanical properties. The expression is as follows.

$$\sigma_c = \frac{P}{A} \quad (1)$$

Where σ_c is the uniaxial compressive strength ; P is the maximum axial pressure at failure ; A is the cross-sectional area of the specimen.

The test sample is selected from Jincheng ChengZhuang high-order anthracite, and the buried depth is greater than 1500 m. It is made into a standard sample ($\Phi 50\text{mm} \times 100\text{mm}$ coal pillar). The experimental instrument is the RMT-150 rock mechanics test system, as shown in Figure 1. This system can carry out uniaxial compression test, triaxial compression test, compression-shear test, indirect tensile test, direct tensile test, sine wave, square wave, triangular wave fatigue test. It can be controlled by load and displacement, controlled by computer, displayed in real time, and automatically collected. The stress-strain curve during the whole test of the sample can be obtained. The uniaxial compression stress-strain curve of coal rock is shown in Eq 2. It can be seen from the test results in the figure that the deformation of coal rock specimens under uniaxial compression can be divided into four stages : pore fracture compaction stage, elastic deformation to micro-

elastic fracture stable development stage, unstable fracture development stage and post-fracture stage. The parameters such as Poisson 's ratio, elastic modulus and shear modulus can be calculated by the axial strain and transverse strain obtained by the test. The uniaxial compressive strength of the sample after testing is 41.76 MPa ; the maximum strain is 2.1648 mm ; the elastic modulus is 2.113 GPa ; poisson 's ratio is 0.185. Page Numbers

Mercury intrusion method (MIP) is the main method for the determination of mesopores and macropores, pore size distribution The total pore volume, total pore area, median pore size, average pore size, bulk density, apparent density, porosity, pore size distribution, interstitial porosity, permeability and other data can be obtained. The basic principle of the test is that mercury, as a non-wetting liquid, needs to apply external pressure to enter the pores. According to the Washburn equation, the pressure is inversely proportional to the pore size. By gradually increasing the pressure, the mercury fills the pores of different sizes in turn, and the pore size distribution can be obtained by recording the intrusion volume. This method is suitable for mesopores (2-50 nm) and macropores (> 50 nm), and has the advantages of wide measurement range and high precision. However, due to the high pressure demand and the toxicity of mercury, it needs to be carefully operated. Based on the principle of liquid lifting in capillary, the relationship between pressure P and capillary radius r in the process of mercury injection is obtained by WASHBURN equation , as follows :

$$P = \frac{2\sigma \cos\theta}{r} \quad (2)$$

In the formula : P is the pressure applied in the process of pressing mercury ; θ is the wetting contact angle between coal and mercury ; σ is the surface tension of mercury ; r is the capillary radius.

The mercury intrusion method was used to measure the mercury curve of the raw coal and the histogram of the pore size distribution of the raw coal. It can be seen that the porosity of the raw coal is 17.74 %, and the pore size of 10nm ~ 100nm accounts for 76.13 % of the total specific surface area, indicating that the raw coal is dominated by excessive pores. The density of the tested coal sample is 1.324g / ml, and the porosity is 17.74 %.



Figure 1. Uniaxial compression experimental instrument

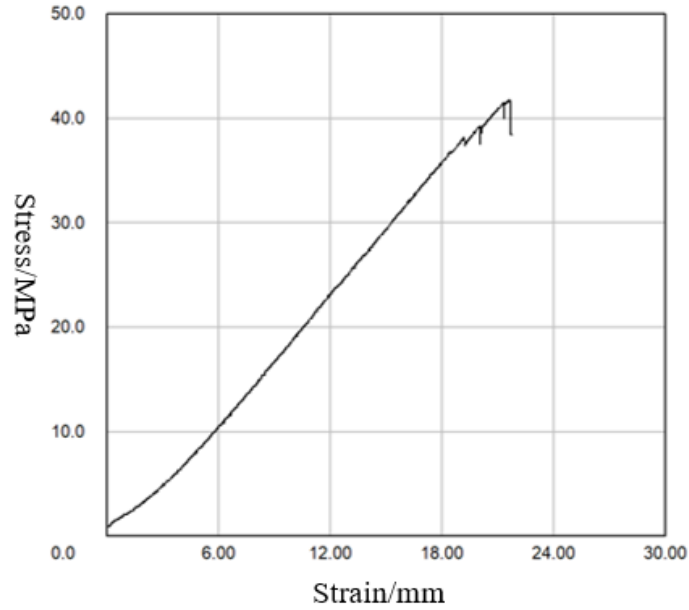


Figure 2. Stress-strain curve

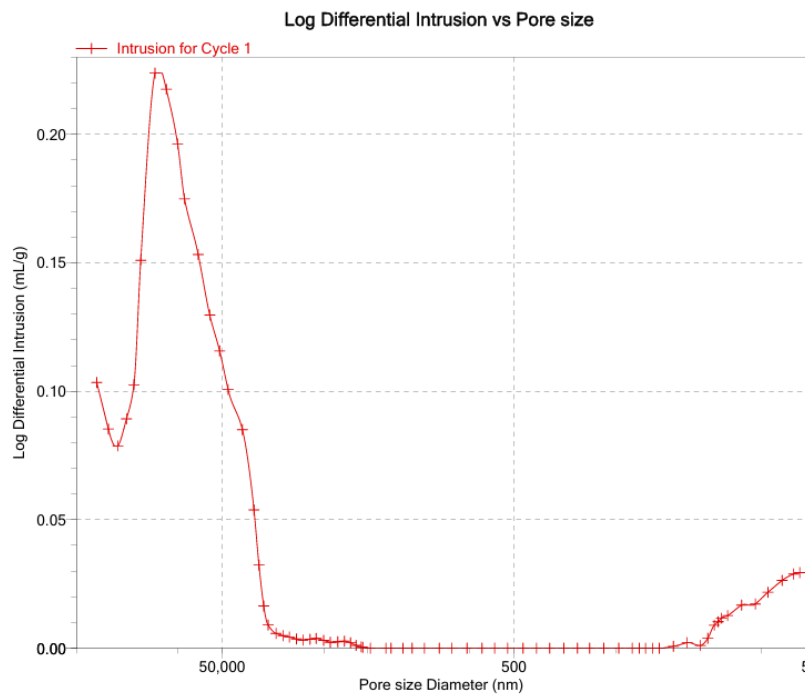


Figure 3. Pore size distribution

2.2. Modeling process

The flow mechanism of fluid in porous media under true triaxial stress is very complex, which is a process of coupling between multiple physical fields. In this paper, the thermal-fluid-solid coupling model under true triaxial stress is established by defining the physical field of Darcy's law, the physical field of solid mechanics and the heat transfer field of porous media. All the equation derivation and result discussion in the model are based on the following basic assumptions :

1) There is only single-phase methane gas in the pores of coal ;

2) Methane gas conforms to the ideal gas equation, its viscosity coefficient is constant and the gas migration is in an isothermal state ;

3) The porosity, elastic modulus, Poisson's ratio, and other physical parameters of the coal-rock model are obtained by the experimental test in the third chapter.

4) The influence of adsorption effect on gas flow is not considered, and the flow of gas in coal seam conforms to Darcy's law.

5) The model is a homogeneous model, which does not consider the difference of the elastic modulus in the bedding and different directions ;

In porous media, the seepage phenomenon is usually described by Darcy's law, especially when gas or liquid fluid flows in porous media such as coal rock. The flow law of fluid in porous media can be reflected by the seepage equation, including the relationship between pore pressure and flow velocity. Darcy's law is the basic equation describing fluid flow.

$$q = -\nabla \cdot k \cdot p \quad (3)$$

where q is the flow rate of the fluid, m^3 / m^2s ; k is the permeability of the medium; p is the fluid pressure gradient, Pa / m .

Through Darcy's law, it can be found that the flow of fluid is controlled by permeability and pore pressure gradient. Permeability k can be expressed as a constant or a function related to porosity and other physical parameters. Permeability may vary for different fluids and media.

In addition to Darcy's law, it is also necessary to consider the conservation of mass in porous media. The fluid flow in the pores is constrained by the law of conservation of mass, forming a continuity equation. The continuity equation is usually expressed as:

$$\frac{\partial p}{\partial t} + \nabla \cdot q = 0 \quad (4)$$

where p is the pore pressure, pa ; $\partial p / \partial t$ is the change of pore pressure with time.; $\nabla \cdot q$ is the divergence of the flow velocity describes the entry or exit of the fluid.

By defining the equation, it can be ensured that the mass will not increase or disappear without reason when the fluid flows in porous media. In porous media such as coal rock, the seepage behavior not only depends on the flow of fluid, but also is affected by the deformation of coal rock. In the fluid-solid coupling model, the permeability will change with the deformation of coal rock.

In solid mechanics, equilibrium equations (such as linear momentum balance), constitutive equations (such as Hooke's law) and geometric equations (strain-displacement relationship) are usually used as shown in Figure 2. These equations have been built in COMSOL, so there is no need to manually define partial differential equations (PDEs), but rather by selecting the appropriate physical interface and parameter settings. However, since the research model is based on the test results to customize the material model or nonlinear stress-strain relationship, it is necessary to use the PDE interface to manually input the equation. Different stresses are applied in three orthogonal directions respectively to ensure that the model constraints are correct and avoid rigid body displacement. As in COMSOL, translation or rotation can be prevented by applying a force or pressure load while fixing the appropriate boundary.

In solid mechanics, the basic equation of deformation is the relationship between stress and strain. By introducing the Biot model, the deformation and stress response of coal rock under fluid pressure can be described. The stress-strain relationship of Biot model is:

$$\sigma_{ij} = 2G\epsilon_{ij} + \lambda\delta_{ij}\epsilon_{kk} - \alpha p\delta_{ij} \quad (5)$$

Where σ_{ij} is the stress of coal rock, Mpa ; λ is Lamé constant; α is Biot constant; ϵ_{ij} is strain component; δ_{ij} is Kronecker sign; p is pore pressure, Pa .

According to these relationships, the deformation process of coal rock can be described by stress equilibrium equation. The relationship between stress and strain can be expressed as

$$\sigma_{i,j,j} + f_i = 0 \quad (6)$$

Where: f_i is body force, It usually includes external forces such as gravity. An equation is found to ensure the mass conservation of the fluid, that is, the amount of fluid flowing in and out is equal.

It is a complex process to realize thermal-fluid-solid coupling in coal rock. Thermal-fluid-solid coupling refers to the interaction between fluid, solid and thermal energy systems. In the process of gas flow, the thermal convection effect will also affect the temperature field distribution in the rock. The deformation of the rock skeleton can lead to changes in physical parameters such as porosity and permeability, which in turn affect the seepage process of the pore fluid. In addition, the deformation energy generated by coal deformation will also affect the temperature field distribution. The temperature field changes the seepage field by affecting the permeability and gas pressure. In short, the migration of gas in coal reservoirs is a dynamic multi-physical field coupling process.

The heat conduction of porous media, the energy equation of fluid phase, and the heat exchange between solid and fluid phases need to be considered in the true triaxial thermo-fluid-solid coupling field. Therefore, the following physical equations need to be added to the model : Heat conduction equation of porous media :

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + q \quad (7)$$

Where T is temperature, α is thermal expansion coefficient, q is heat source term

Fluid phase energy equation:

$$\rho c_f \frac{\partial T}{\partial t} + \nabla \cdot (\rho c_f v T) = \nabla \cdot (k_f \nabla T) \quad (8)$$

Where ρ is the density of the fluid, c_f is specific heat capacity of fluid, v is Velocity field of fluid, k_f is Thermal conductivity of fluid

Heat exchange between solid phase and fluid phase.:

$$Q = h(T_s - T_f) \quad (9)$$

Where h is heat transfer coefficient, T_s is Solid phase temperature, T_f is fluid phase temperature

$$\sigma_e = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3} - \alpha P_p \quad (10)$$

Where σ_e is effective stress; σ_1 , σ_2 , σ_3 they are maximum principal stress, intermediate principal stress and minimum principal stress respectively.; P_p is pore pressure

$$k = k_0 \exp(-\alpha \sigma_e) \quad (11)$$

Where k is the permeability under the effective stress σ_e ; k_0 is the permeability at atmospheric pressure; α is the stress sensitivity coefficient.

In order to simulate the fluid-solid coupling experiment of

shale under true triaxial stress conditions, a $100 \times 100 \times 100$ mm three-dimensional cube geometry model is established as shown in Fig.3. The Z direction is the gas pressure gradient direction, and the upper surface (boundary A) is the inlet boundary. The model meshing diagram established by the free tetrahedral meshing method is shown in Fig.4. The whole mesh system is composed of 100551 tetrahedral elements, 4692 triangular elements and 216 edge elements, and the unit volume ratio is 0.0056. The total volume of the mesh is $1 \times 10^6 \text{mm}^3$.

Table 1. Physical parameter

sign	parameter name	value	unit
ρ	Coal density	1.324	Kg/m ³
k	Initial permeability of coal rock	1×10^{16}	m ²
φ	Coal rock porosity	17.7	%
E	elastic modulus	2.113	Gpa
ν	poisson ratio	0.185	/
μ	CH ₄ viscosity	1.08×10^5	Pa·s
M	Molecular mass of methane	16	g/mol
R	Gas state constant	8.414	J/mol/K
T	geothermal temperature	293.15	K

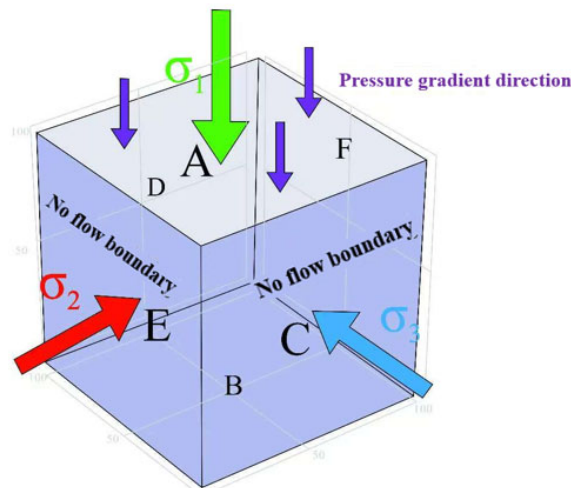


Figure 3. Geometric model

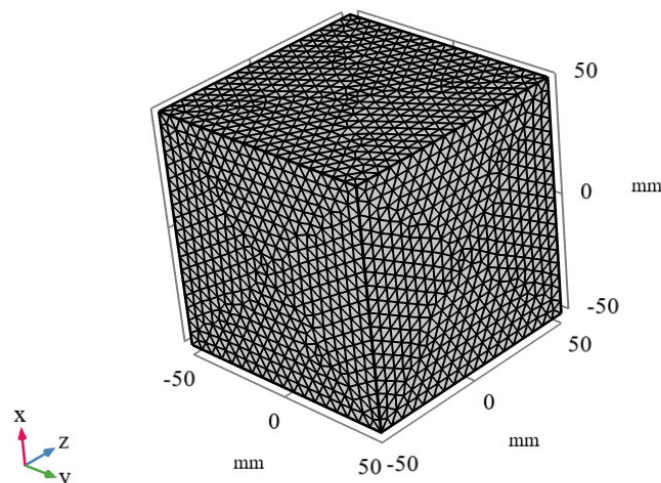


Figure 4. Mesh subdivision

3. Analysis of Effect

3.1. Model Validation

The fixed constraints in the X and Y directions are added to the model, and the stress in the Z direction (1-5MPa) is

applied step by step to simulate the axial pressure loading to obtain the model stress-strain and uniaxial compression test. It can be seen that by defining the measured elastic modulus and Poisson 's ratio in the model, the deformation trend of the model is consistent with the experimental results, which ensures the reliability of the model.

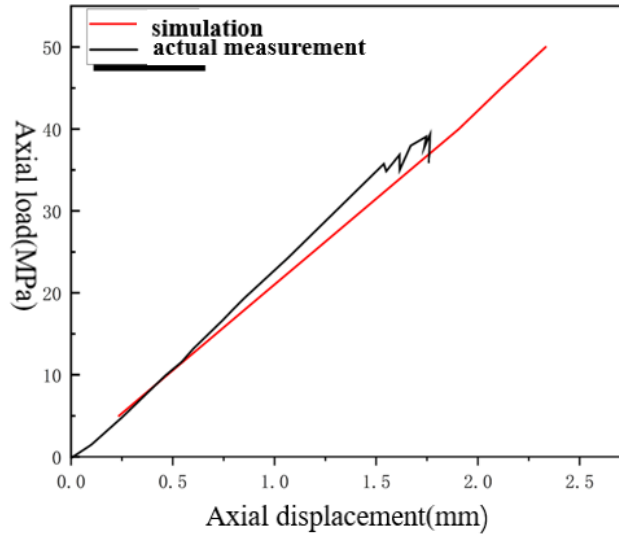


Figure 5. Stress-strain curve (experiment and simulation)

3.2. Permeability evolution law under axial pressure and confining pressure

The gas pressure was kept at 1MPa, and the axial pressure in the Z direction was simulated step by step (1-5MPa). The same pressure was applied in the X and Y directions to simulate the confining pressure (1-5MPa), and the relationship between permeability and axial pressure was studied. It can be seen from the test results that the permeability decreases significantly under the action of axial pressure and confining pressure, but the permeability

decreases significantly under the action of axial pressure and confining pressure. The effect of axial pressure on permeability is obviously less than that of confining pressure, and the results are consistent with the experimental results. Sun et al. [80] studied the response characteristics of the permeability of two different coal samples to the change of axial pressure and confining pressure. The results also showed that the influence of confining pressure change on the permeability of coal samples was much greater than that of axial pressure when the same stress was applied, which was also consistent with the test results in the previous chapters.

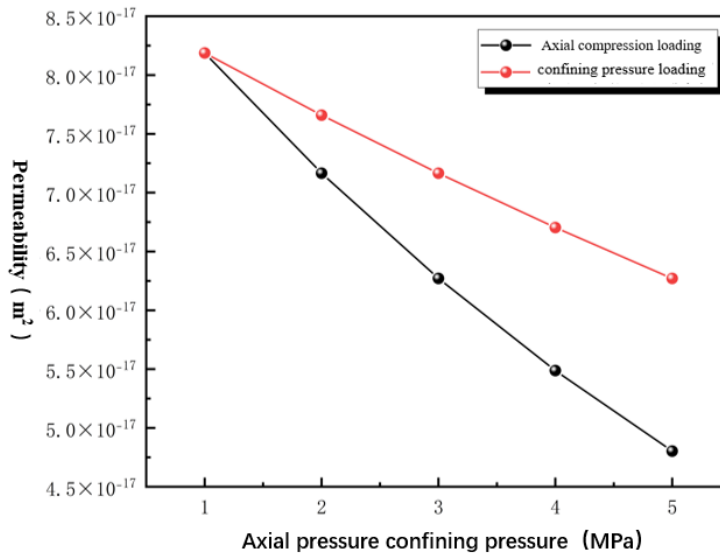


Figure 6. Axial pressure confining pressure and permeability

3.3. Effect of intermediate principal stress coefficient on permeability

The deep stress environment of coal and rock mass is a true triaxial stress state ($\sigma_1 > \sigma_2 > \sigma_3$) with three-dimensional unequal stress. Uniaxial or conventional triaxial stress conditions cannot truly reflect the field stress environment. The research results ignore the influence of intermediate principal stress σ_2 on the mechanical properties and seepage law of coal and rock. The influence of intermediate principal stress on permeability can be explored by using the coefficient of intermediate principal stress.

$$b = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} \quad (12)$$

Where b is the intermediate principal stress coefficient and σ_1 is the maximum principal stress ; σ_2 is the intermediate principal stress ; σ_3 is the maximum principal stress.

The intermediate principal stress σ_2 is loaded step by step according to (15,20,25,30,35,40), so that the intermediate principal stress coefficient b gradually increases from 0 to 1 with a step of 0.1.

- (1) Fixed stress difference $\sigma_1 - \sigma_3 = 25\text{MPa}$ ($\sigma_1 = 40\text{MPa}$, $\sigma_3 = 15\text{MPa}$)
- (2) Fixed stress difference $\sigma_1 - \sigma_3 = 20\text{MPa}$ ($\sigma_1 = 40\text{MPa}$, $\sigma_3 = 20\text{MPa}$)
- (3) Fixed stress difference $\sigma_1 - \sigma_3 = 15\text{MPa}$ ($\sigma_1 = 40\text{MPa}$, $\sigma_3 = 25\text{MPa}$)
- (4) Fixed stress difference $\sigma_1 - \sigma_3 = 10\text{MPa}$ ($\sigma_1 = 40\text{MPa}$, $\sigma_3 = 30\text{MPa}$)
- (5) Fixed stress difference $\sigma_1 - \sigma_3 = 5\text{MPa}$ ($\sigma_1 = 40\text{MPa}$, $\sigma_3 = 35\text{MPa}$)

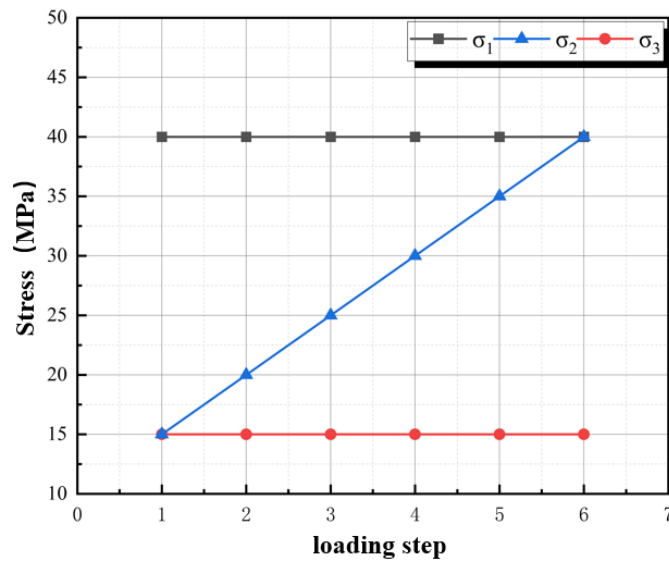


Figure 7. Path of loading

After the coal rock is subjected to stress, deformation and displacement will occur, thus affecting the permeability, as shown in the figure. It can be seen that with the continuous loading of stress, the deformation of coal rock becomes larger,

the stress is concentrated on the edge and vertex position, and the deformation is large (the model is the mean value model, and the elastic modulus in each direction is equal).

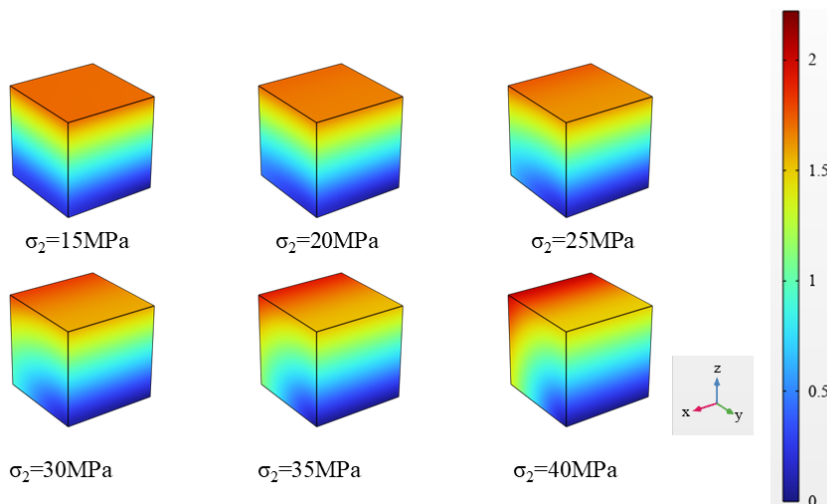


Figure 8. Displacement under stress

It can be seen that the flow velocity gradually decreases with the increase of σ_2 and the flow velocity is not evenly distributed. The flow velocity near the boundary is greater than that in the middle position. This is because with the increase of intermediate principal stress, the starting point of rock expansion shows a decreasing trend, the peak strength decreases gradually, and the dip angle of shear failure surface increases linearly. These changes may lead to the closure or reduction of pores and fissures in the rock, thereby reducing the permeability and resulting in a decrease in flow velocity.

The relationship between the coefficient of intermediate principal stress and shale permeability under different stress differences is shown in Fig.9. It can be seen from the figure

that in the process of the intermediate principal stress coefficient b changing from 0 to 1, the coal rock permeability k decreases with the increase of the intermediate principal stress coefficient b . Under the same principal stress coefficient, as the stress difference increases step by step, the permeability is There is a downward trend, which is due to the compression of the pore structure inside the coal seam with the increase of stress difference. When the stress difference is low, the pores of the coal body are relatively open, and the gas or fluid can pass through more easily. However, with the increase of stress difference, the pores of coal are further compressed, which leads to the increase of the difficulty of fluid passage and the decrease of permeability.

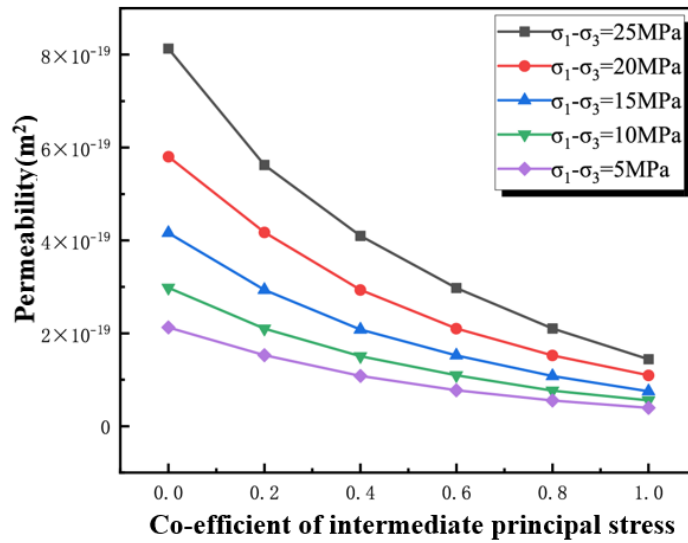


Figure 9. Intermediate principal stress coefficient and permeability

Under the same stress difference, the permeability decreases with the increase of the intermediate principal stress coefficient, which indicates that the high intermediate principal stress coefficient means that the material undergoes stronger compression during the compression process, and the pore structure may be more dense. In this way, the channel of fluid flow becomes narrow, and the permeability will decrease. With the increase of stress difference ($\sigma_1 - \sigma_3$), the influence of intermediate principal stress coefficient on coal rock permeability is increasing (the larger the slope of the curve). When the stress difference is large, the variation range of the intermediate principal stress increases, and the variation range of the effective stress increases, which leads to the increase of the compression effect of the coal rock pores, so the influence of the intermediate principal stress coefficient on the shale permeability increases. When the stress difference is small, the variation range of the intermediate principal stress decreases, and the effect of the pore compression of the coal rock decreases, so the influence of the intermediate principal stress coefficient on the shale permeability decreases. At the same time, under the same gas pressure gradient, the permeability of coal rock decreases with the decrease of stress difference. This is because when the stress difference decreases, the effective stress increases,

and the constraint effect of stress on shale bedding and pores becomes larger, so the permeability decreases.

Through the downward trend of the curve, it can also be seen that the intermediate principal stress coefficient has a negative exponential relationship with the permeability. The simulation results are consistent with the results obtained by Fan Xiangyu [16] using the true triaxial fluid-solid coupling test system. Therefore, the model shows high accuracy for the evolution of permeability under stress. The later simulation is based on the model.

3.4. Permeability evolution law under pressure gradient

Gas pressure in coal seam is one of the important factors affecting coal and gas outburst. Based on COMSOL Multiphysics numerical simulation software, a numerical model was constructed, and five sets of numerical simulation experiments with different gas pressures were carried out. The effect of gas pressure on permeability was investigated by changing the inlet pressure of methane in the model. Five gas pressure gradients of 1, 3, 5, 7 and 9 Mpa were set as shown in the figure. The pressure distribution inside the model can be seen under different gas pressures.

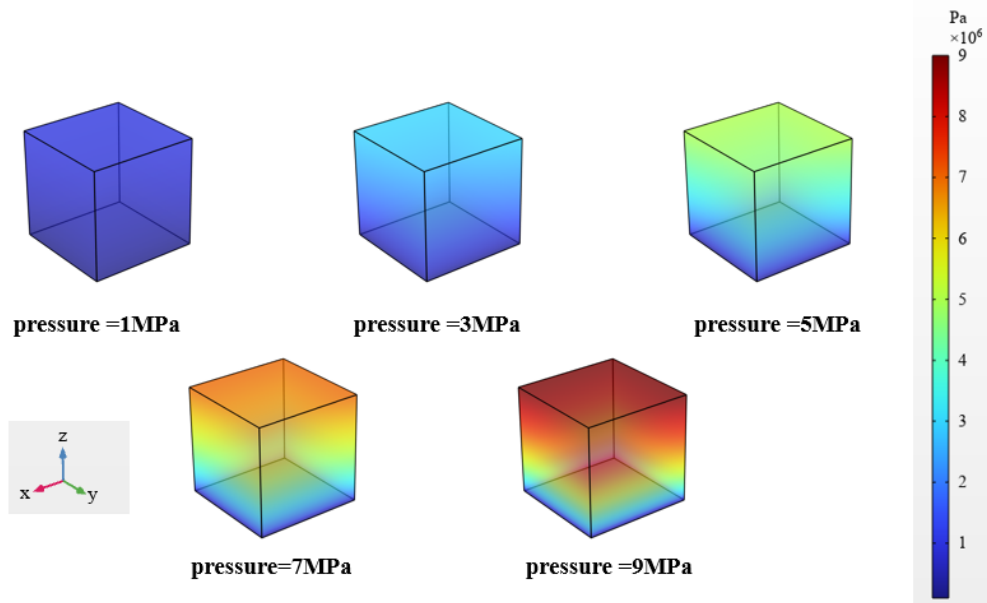


Figure 10. Air pressure distribution

Under different gas pressures, the permeability variation law is shown in the figure. It can be seen that with the increase of gas pressure, under the stress difference of 25 MPa, the permeability increases with the increase of gas pressure, and the increase of permeability decreases with the increase of gas pressure. This is due to the increase of gas pressure. The internal pressure of the model will also deform with the increase, thus squeezing the pores, so that the increase of

permeability will not increase linearly with the increase of gas pressure. At the same time, the simulation results are consistent with the conclusions obtained from the experiment in chapter 2.5 : the permeability of coal seam increases with the increase of inlet pressure (gas pressure), and the stress sensitivity coefficient also increases. The permeability of coal seam is more vulnerable to stress damage, which can verify the accuracy of the model.

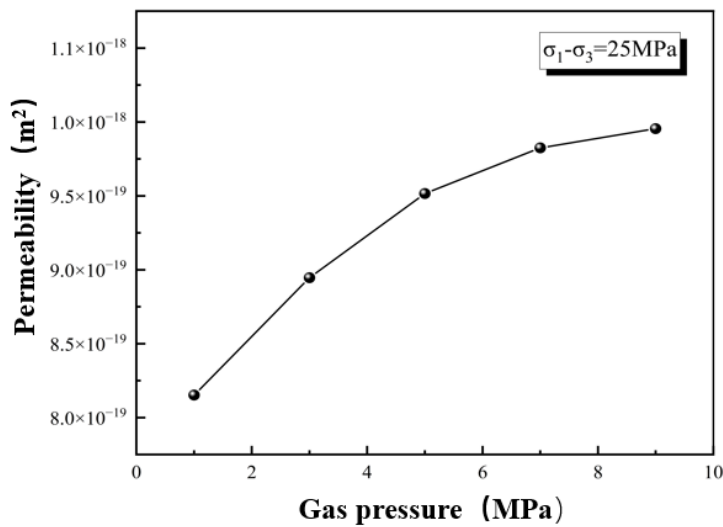


Figure 11. Gas pressure and permeability

3.5. The relationship between temperature and permeability

In the process of deep coal seam gas extraction, the ground temperature is high and the pore pressure is gradually reduced [83]. Therefore, this section will simulate the influence of temperature, pore pressure and stress difference on permeability, and explore its regular changes.

Since the influence of temperature on gas viscosity is not

considered, the gas pressure is set to 1Mpa, the maximum principal stress σ_1 (Z direction) 40Mpa is unchanged, and the σ_2 and σ_3 in X and Y directions are set to 15Mpa, and the temperature is gradually increased to explore the influence of temperature on permeability under triaxial stress. The outlet temperature was set at 25 °C (298.15K).

In the modeling process, the porous medium heat transfer interface is used to consider the influence of temperature on the gas flow in the coal seam. As a porous medium, the

permeability of coal seam is closely related to the temperature change. According to the heat transfer model of porous media, coal and rock show different thermal physical properties under different temperature conditions. Especially at high temperature, the expansion effect of coal and rock will significantly change its pore structure, thus affecting the flow of fluid in it. As shown in Fig.5-10, with the increase of temperature, the permeability of coal seam shows a gradual upward trend. This phenomenon is due to the increase of temperature, which leads to the expansion of coal rock and the increase of pore volume, thus improving the flow channel of gas. Specifically, when the temperature rises, the pressure change inside the coal rock leads to the adjustment of the microstructure of the coal seam, and the originally tight pores

gradually expand, increasing the path of gas flow. In this process, the thermal expansion effect in the coal seam plays an important role, which makes the influence of temperature rise on permeability show a linear growth trend.

The thermal expansion coefficient defined in the model reflects the influence of temperature change on the volume of coal rock. In practice, the thermal expansion coefficient of coal rock is often small, so although the increase of temperature causes volume expansion, the magnitude of this change is limited. However, in the process of gas extraction, the temperature of the coal seam can reach hundreds of degrees Celsius to a certain extent, so even if the thermal expansion coefficient is small, the temperature change is enough to have a significant impact on the permeability.

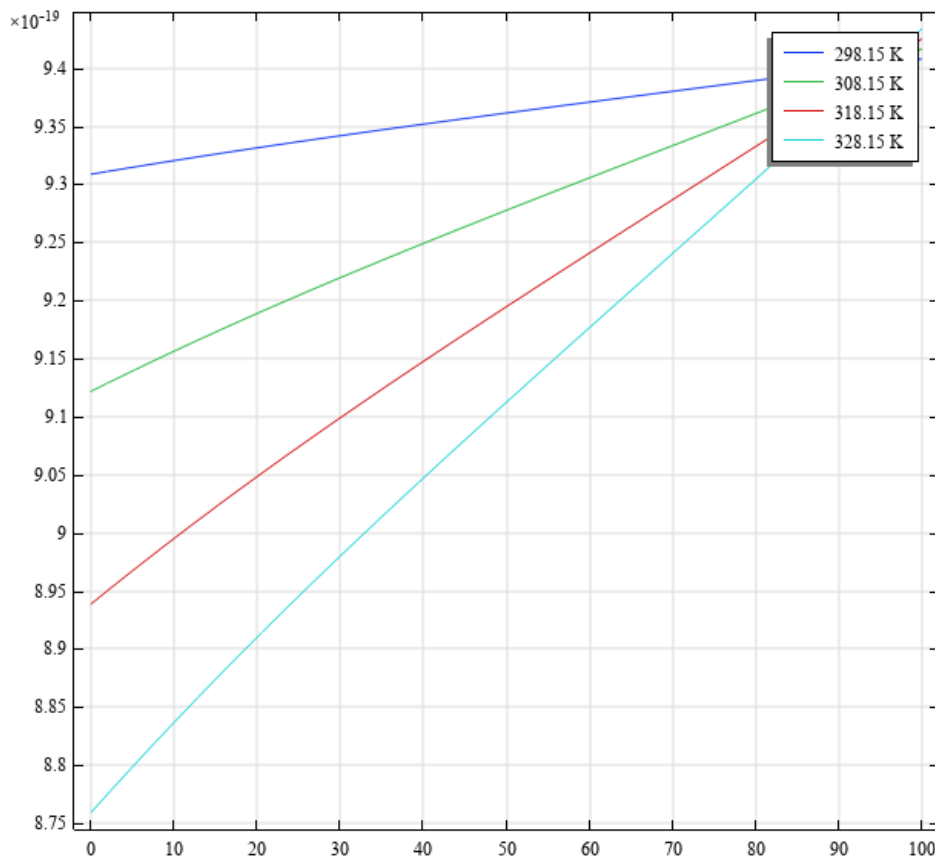


Figure 12. The relationship between temperature and permeability

4. Summary

(1) The permeability decreases exponentially with the increase of stress difference. This is due to the increase of stress difference, and the closure effect of effective stress on pores is enhanced. In particular, small-scale pores and fractures are closed first due to weak compressive capacity, resulting in a rapid decline in permeability. This compression process has nonlinear characteristics : in the initial stage, the pore closure rate is high, and the permeability decreases sharply ; as the stress further increases, the remaining pores gradually stabilize, the closure rate slows down, and a negative exponential relationship is formed.

(2) With the increase of gas pressure, under the same stress difference, the permeability increases with the increase of gas pressure, and the increase of permeability decreases with the increase of gas pressure. This is due to the increase of gas

pressure, the internal pressure of the model will also deform with the increase, thus squeezing the pores, so the increase gradient of permeability decreases gradually.

(3) Permeability decreases with the increase of buried depth. When the buried depth is greater than 2100 m, the downward trend of permeability becomes slower. This is because the maximum principal stress is converted from vertical overburden pressure to horizontal extrusion pressure. The influence of confining pressure on the permeability of parallel bedding samples is weaker than that of axial pressure, so the downward trend of permeability gradually slows down.

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