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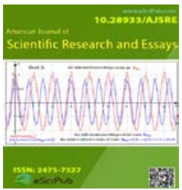

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Numerical simulation and analysis of coupled Thermal-Hydrological-Mechanical in coalbed methane heating mining

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ABSTRACT

In order to verify the effect of heating on the effect of coal seam extraction,based on the theory of elasticity, seepage mechanics and heat transfer,a Thermal-Hydrological-Mechanical coupling model for gas extraction in high temperature field is established. The numerical simulation was carried out in the engineering background of Qinghe coal mine in China.The changes situation of gas pressure and permeability under the conditions of different heating temperature were calculated respectively.The following conclusions are drawn:(1) The coupled thermo-hydro-mechanical model of gas drainage under temperature field is established, and the gas drainage effect under different working conditions is verified by numerical simulation.(2)When the heating temperature is below 453K, the high temperature can increase the permeability of coal seam,but it can not greatly increase the permeability of coal seam, and it has little effect on the reduction of coal seam gas pressure. It shows that the method of increasing coal seam permeability by heating coal can not reach the expected effect.

Keywords:
coalbed methane; high temperature field; thermal fluid solid coupling; heating mining; permeability; numerical simulation.

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Coalbed methane is an unconventional clean energy source and has important strategic significance for energy reserves. China is a large country of coalbed methane storage and production. The shallow coalbed methane resources with a depth of 2000m are 22.5×10^4 billion cubic meters. In 2015, China's coalbed methane production is 30 billion cubic meters. The deeper the 14 billion cubic meters coal seam is buried, the more complicated the geological conditions are. The greater the influence of ground stress on coal seam porosity and permeability[1,2]. There are many low-permeability gas seams in coal mines in China, which increases the difficulty of coalbed methane mining. Therefore, it is particularly important to study the law of coalbed methane seepage under low geostress conditions in low permeability gas seams.

In the study of the migration law of coalbed methane in reservoirs, some scholars have researched on the coalbed methane permeability model. It is inferred that the effective stress of the coal seam and the change of reservoir pressure will cause the coal body to deform, resulting in changes in coal seam porosity and permeability(). Various permeability models have been proposed to adapt to different geological conditions.Palmer and Mansoori[4,5] established a P&M permeability model by uniaxial stress-strain relationship while maintaining vertical reservoir stress; Clarkson et al.[6,7] further improved the P&M model after comparing the changes in permeability in P&M and actual production wells.; Shi and Durucan[8,9]pointed out the exponential relationship between permeability and porosity according to the effective vertical stress, and proposed the S&D permeability model; based on the S&D model, Cui and Bustin[11] built a C&B permeability model that can control horizontal effective stress is proposed.

Coal is also a kind of porous medium and natural absorbent that is sensitive to temperature. It is necessary to research on the influence of temperature on the mechanical properties of coal and gas. In view of this, domestic and foreign scholars have carried out a lot of research, CHAROENSUPPANIMIT P et al found that temperature changes the gas adsorption capacity, thus affecting the permeability of coal rock[12]; ZHU Wancheng[13]and TENG Teng et al[14] have different The coal seepage experiment under temperature conditions shows the damage of coal and rock and micro-cracks caused by high temperature; J Xie[15] studied the meso-structural evolution of coal at 25-80 °C, and obtained most of the lean coal samples. The permeability increases with increasing temperature. A large number of studies have shown that temperature has a certain impact on coalbed methane infiltration. By changing the coal seam temperature, the coal seam permeability can be increased and the coalbed methane mining efficiency can be enhanced.

In this paper, the theory of elastic mechanics, seepage mechanics and heat transfer is used to establish a fluid-solid coupling seepage model for coalbed methane extraction. The solution is solved by COMSOL Multiphysics software, which provides a theoretical basis for the prediction of coalbed methane drainage under heating conditions.

Influence of temperature on coal seam basic parameters

The elastic modulus and gas kinematic viscosity of coal body are greatly affected by temperature. With the increase of temperature, the elastic modulus decreases gradually, and the viscosity of gas movement increases[16], The former people are carrying out the thermal fluid-solid coupling of high temperature coal seam gas. In the numerical simulation study, the influence of temperature on the basic parameters of gas-containing coal is neglected, resulting in some error in the simulation results. In view of this, the effects of temperature on the elastic modulus and the gas kinematic viscosity are introduced into the model.

According to the measured data of 15# coal seam in Songhe Coal Mine in China, the relationship between elastic modulus and temperature is calculated. As shown in Fig.1, the elastic modulus of the coal body is reduced during the elastic phase, and the coal body resists elastic deformation. The ability to weaken, the function of the modulus of elasticity obtained as a function of temperature is: $E=-10.84T+5995$.

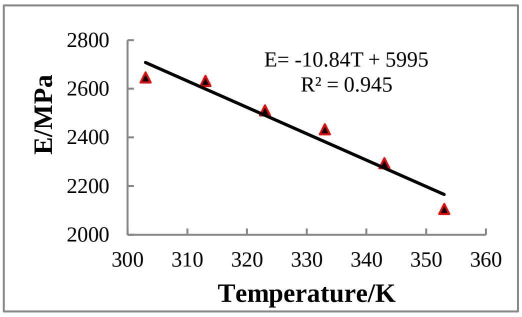

Fig.1 the law of elastic modulus with temperature

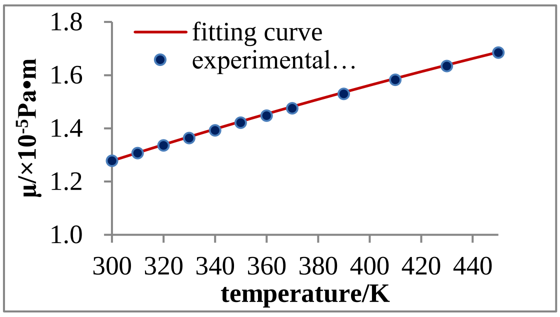

Fig.2 the variation of viscosity with temperature

Viscosity is a measure of the internal friction of a fluid. The stronger the force between fluid molecules, the greater the viscosity[17]. When the gas pressure is constant, the greater the viscosity, the greater the permeability. It can be seen from Fig.2 that the temperature has a linear relationship with the viscosity of the gas, and the relationship between the viscosity of the gas and the temperature changes is:

$$\mu=\mu_0\left(\frac{T_0+800}{T+800}\right)\left(\frac{T}{T_0}\right) \tag{1}$$

Coalbed methane extraction Thermal-Hydrological-Mechanical coupling control equation

Basic assumptions

Gas-containing coal is a porous medium containing complex fractures and pores. The fractures and pores are both a place to store coalbed methane and a seepage channel for coalbed methane migration. During the process of coalbed methane extraction, a series of coupling effects such as coal deformation, coalbed methane desorption and temperature change will occur. In order to reveal the multi-physics coupling mechanism in the coalbed methane extraction process under heating conditions, the thermal fluid-solid coupling coalbed methane pumping is established. According to the characteristics of coal body and the characteristics of coalbed methane, the following assumptions are made[18]: (1) The coal body is saturated by single gas; (2) The seepage law of coalbed methane in coal seam is in accordance with Darcy's law; (3) The free gas obeys the modified Langmuir equation and the real gas state equation respectively; (4) the coal body deformation is in the linear elastic deformation stage, obeying Hooke's law; (5) the stress and strain symbols are the same as the elastic mechanics, the compressive stress is negative, the tensile stress is positive, and the displacement along the positive direction of the axis is positive and the reverse direction is negative.

Stress field equation

The coal body strain is mainly composed of four parts, including the strain caused by the effective stress change, the strain caused by the gas pressure change, the coal matrix adsorption (desorption) gas strain and the thermal strain caused by the temperature change. Each factor interacts with each other to affect the deformation of the coal body. The total strain equation of coal is[19]:

$$\varepsilon_{ij}=\frac{1}{2G}\delta_{ij}-\left(\frac{1}{6G}-\frac{1}{9K}\right)\sigma_{kk}\delta_{ij}+\frac{\beta\left(T-T_0\right)}{3}\delta_{ij}-\frac{\alpha p}{3K}\delta_{ij}+\frac{\varepsilon_s}{3}\delta_{ij} \qquad （2）$$

Where: $G=E/2\left(1+\nu\right)$， $\alpha=1-K/K_s$, $\varepsilon_s=\frac{\varepsilon_L p}{P_L+p}\exp\left(-\frac{c_2\left(T-T_0\right)}{1+c_1 p}\right)$; G is the shear modulus, MPa; E is the elastic modulus of coal, MPa; υ is the Poisson's ratio of coal; δ_{ij} is the symbol of Kronecker operator; K is the bulk modulus of coal; σ_{kk} is the effective volume stress (k=1,2,3 represents the x,y,z direction of force); β is the volumetric thermal expansion coefficient of coal, K^{-1}; T is the temperature of the coal seam, K; T_0 is the initial temperature of the coal seam, K; α is the effective stress Coefficient; K_s is the coal seam skeleton bulk modulus; p is the coal seam gas pressure, MPa; ε_s is the adsorption gas strain; ε_L is the Langmuir adsorption strain constant, m^3/kg; P_L is the Langmuir pressure adsorption constant, MP^{-1}; c_1, c_2 are Langmuir pressure correction factor and volume correction factor, P^{-1}, K^{-1}.

Combining equation (1) with the equilibrium equation and geometric equation of elastic mechanics, the stress field equation is:

$$G\mu_{i,jj}+\frac{G}{1-2\nu}\mu_{j,ji}+\alpha p_{,i}-K\beta\Delta T_{,i}-K\varepsilon_s\delta_{ij}+F_i=0 \qquad （3）$$

Where μ is the displacement component in the x, y, and z directions; $\mu_{i,jj}$ can be expressed as $\nabla^2\mu$, $\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$ is the Laplace operator symbol (i, j=1, 2, 3 respectively represent the x, y, z direction of the displacement change); $\mu_{j,ji}$ is the volume strain to x, respectively. The first-order partial derivatives of the y, z directions (i, j = 1, 2, 3 represent the x, y, z directions of the volumetric strain, respectively).

Seepage field equation

Gas flows in coal in accordance with Darcy's law, using Darcy's law to calculate coal seam permeability, namely:

$$q=-\frac{k}{\mu}\nabla p \qquad （4）$$

Where q is the gas percolation velocity, m/s; ▽p is the coalbed methane pressure gradient, Pa/m; μ is the gas kinematic viscosity, Pa•S.

The gas in the coal seam is regarded as the ideal gas. Considering the adsorption and desorption of gas and the influence of temperature, the modified gas state equation and the langmuir equation calculate the gas content per unit volume of coal seam[20]:

$$Q=\frac{M_g p}{RT}\varphi+\left(1-\varphi\right)\rho_{ga}\rho_c\frac{\varepsilon_L p}{P_L+p}\exp\left(-\frac{c_2\left(T-T_0\right)}{1+c_1 p}\right) \tag{5}$$

Where Q is the coal seam gas content, m^3/t; Mg is the relative molecular mass of methane, 16; R is the gas universal constant, 8314m^2/(s^2•K); φ is the coal seam porosity; ρ_{ga} is the gas under the standard state density, kg/m^3; ρ_c is the density of coal, kg/m3.

The flow equation of gas in coal is:

$$\frac{\partial Q}{\partial t}+\nabla\left(\rho_g q\right)=0 \tag{6}$$

Substituting equations (3) and (4) into equation (5) can obtain the control equation of gas seepage field in coal seam:

$$\frac{\partial}{\partial t}\left\{\frac{M_g p}{RT}\varphi+\left(1-\varphi\right)\rho_{ga}\rho_c\frac{\varepsilon_L p}{P_L+p}\exp\left(-\frac{c_2\left(T-T_0\right)}{1+c_1 p}\right)\right\}-\nabla\left(\frac{M_g p}{RT}\frac{k}{\mu}\nabla p\right)=0 \tag{7}$$

Temperature field equation

The effects of temperature on the coal include convection and diffusion. The heating process of the heating cable on the coal body causes the heat to gradually diffuse from the heating hole to the periphery, eventually forming a stable temperature field. During gas flow, there is heat exchange between the gas and the coal matrix. Convection and diffusion jointly affect the adsorption, desorption and seepage of gas in the coal seam. The heat transfer equation of coalbed methane and coal skeleton in coal seam is:

$$\left(\rho C_p\right)_{eff}\frac{\partial T}{\partial t}+\rho_g C_p q\nabla T+\nabla h=Q \tag{8}$$

where $h=-\eta_{eff}\nabla T$ (9)

$$\left(\rho C_p\right)_{eff}=\varphi\rho_g C_p+\left(1-\varphi\right)\rho_c C_{p,p} \tag{10}$$

$$K_{eff}=\varphi\eta+\left(1-\varphi\right)\eta_p \tag{11}$$

Substituting equations (9)-(11) into equation (8) gives the temperature field control equation as:

$$\left[\varphi\rho_g C_p+\left(1-\varphi\right)\rho_c C_{p,p}\right]\frac{\partial T}{\partial t}-\rho_g C_p\left(\frac{k}{\mu}\nabla p\right)\nabla T+\nabla\left\{\left[\varphi\eta+\left(1-\varphi\right)\eta_p\right]\nabla T\right\}=Q \tag{12}$$

Where $(\rho C_p)_{eff}$ is the effective specific heat capacity of the coal, J/(kg▪K); C_p is the constant pressure heat capacity of gas, J/(kg▪K); h is the unit heat conduction, W/m; Q is Heat source term; ηeff is the effective thermal conductivity, W/(m ▪ K); Cp, p is the constant pressure heat capacity of the coal body skeleton, J/(kg▪ K); η is the gas thermal conductivity, W/(m ▪ K) ; η_p is the thermal conductivity of the coal body skeleton, W/(m ▪ K).

Coupled equation

The stress field equation, the seepage field equation and the temperature field equation are coupled by coal porosity and permeability. According to the definition of porosity and permeability:

$$\varphi = 1 - \frac{1-\varphi_0}{1+e}\left[1 - \frac{p-p_0}{K_s} + \beta\left(T-T_0\right) + \frac{\varepsilon_s}{1-\varphi_0} + \frac{\varphi_0}{1-\frac{\chi\Delta T}{\left(3-D_0\right)T_0}} - \varphi_0\right] \qquad (13)$$

$$k = k_0\left(\frac{\varphi}{\varphi_0}\right)^3\left(1+\frac{\alpha_k k_0^{-0.36}}{p}\right) \qquad (14)$$

Where φ_0 is the initial porosity of the coal seam; e is the volumetric deformation of the coal body; χ is the thermal cracking factor, and the value is 0.46; D_0 is the thermal cracking constant, and the value is 2.83. k_0 is the initial permeability of the coal seam, m^2; α_k is the Klinkenberg influence factor, and the general value is 0.251.

The equations (3), (7) and (12) are combined to obtain the thermal fluid-solid coupling mathematical model of the gas drainage in the heated coal seam, using the solid mechanics module of COMSOL Multiphysics, the heat transfer of porous media and the Darcy law module. Numerical Simulation.

Model verification

(1) Temperature field verification

The mineral insulated heating cable is an electric energy source that uses an alloy resistance wire to conduct electricity and heat, and uses a thermostat to control the temperature of the heated body to a set temperature[21]. In order to verify the effect of the temperature field on the heating effect of the coal seam, a similar experiment as shown in Fig. 3 was performed. The temperature field is heat exchanged by means of heat conduction and heat radiation. Since no gas is injected, the heat convection phenomenon is small. Fig.4 shows that the heating temperature for 10 days, the experimental temperature values of the pressure taps and the calculated temperature of the model are very good, the error is low, and can meet the numerical simulation requirements.

Fig.3 Heating layout of coal body

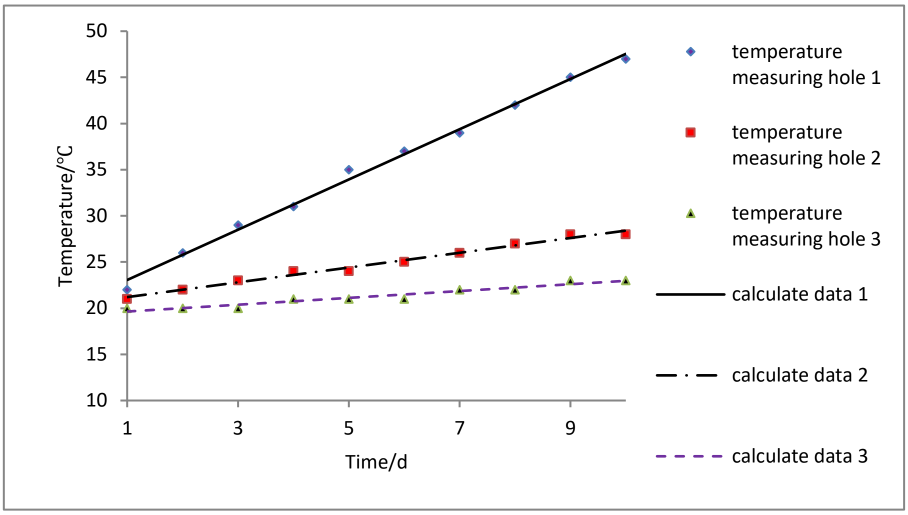

Fig.4 Temperature variation with time

(2) Permeability model verification

In order to verify the accuracy of formulas (13) and (14), the experimental data of Hu Yaoqing [22] were compared and fitted. When the axial pressure is 7 MPa, the confining pressure is 6 MPa, and the gas pressure is 1.5 MPa, the permeability changes with temperature. As shown in Fig. 5, when the temperature is between 330K and 350K, the model fitting value and the experimental numerical error are within 5%, which can meet the numerical simulation requirements.

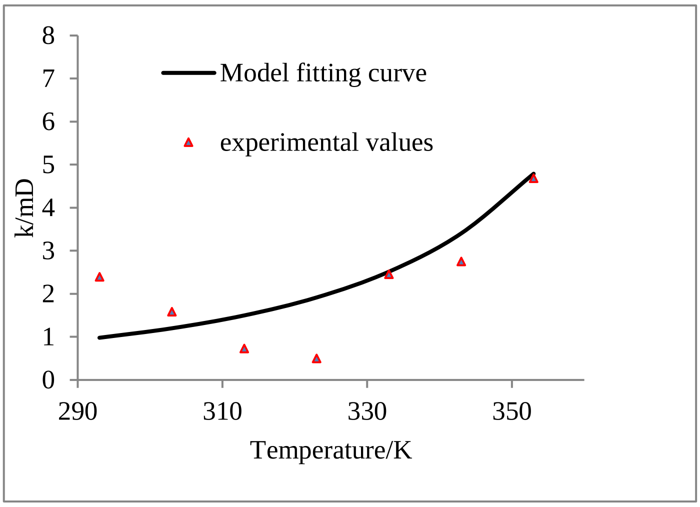

Fig.5 The variation of permeability with temperature

Numerical simulation of coalbed methane heating extraction

Geometric model

Qinghe Coal Mine is located in the western part of China. It is an alpine mountainous landform with strong topographic cuts and high height difference, with a relative height difference of 346.2m. The coal mine has a production capacity of 3×10^5t/a, and the relative gas emission of the mine is 44.18 m^3/t. The mining coal seam is a medium-thick coal seam with low permeability and is representative of Chinese coal mines.

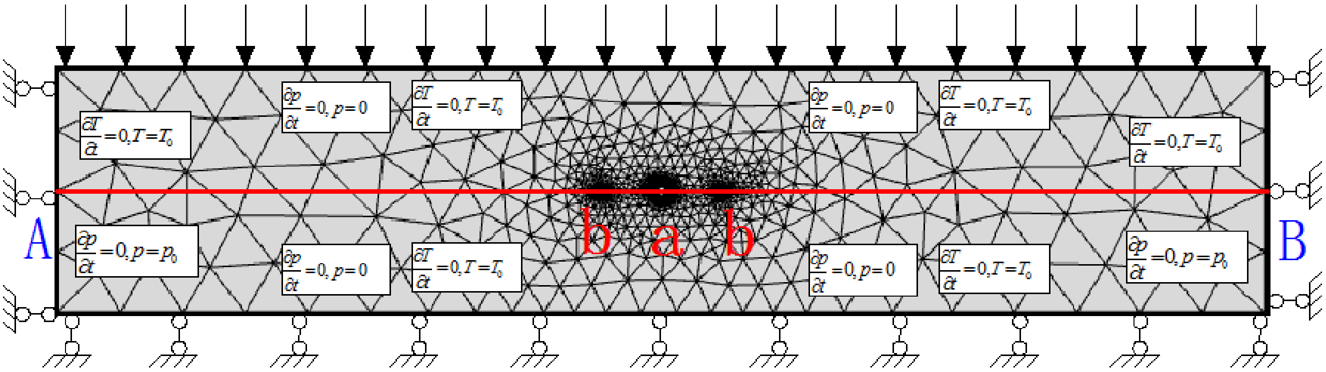

Fig.6 Geometric model diagram

The calculation model is based on the mining face of 10141 coal seam of Qinghe Coal Mine, and the simulation parameters are obtained.The geometric model is shown in Fig.6. The basic parameters in the calculation process are shown in Table 1.

Table 1 Basic parameters of numerical simulation

Gas initial dynamic viscosity coefficient μ_0	1.2279×10^{-5}P•s
Coal seam initial porosity φ_0	0.045
Coal body elastic modulus E_0	2.713×10^{9} Pa
Coal Poisson υ	0.32
Gas volume strain constant ε_L	0.02295
Initial gas pressure p_0	1.47MPa
Initial temperature T_0	303K
Langmuir pressure correction factor c_1	710Pa^{-1}
Langmuir volume correction factor c_2	0.021K^{-1}
Langmuir pressure constant P_L	4.109×10^{6}Pa
Coal skeleton density ρ_s	1470 kg/m^3
Coal density ρ_c	1.2×10^{3} kg/m^3
Ordinary gas constant R	8.3143 /(mol·K)
Initial permeability k_0	7.8×10^{-16} m^2
Klinkenberg impact factor α_k	0.251
Gas pressure in standard state p_a	0.1MPa
Coal volumetric thermal expansion	0.116×10^{-3} K^{-1}

coefficient β	0.716 kg/m^3
Gas density ρga under standard condition	5.22×10^{10} Pa
ρ_{ga}	2260J/(kg·K)
Bulk modulus of solid particles Ks	1350 J/(kg·K)
Gas constant pressure heat capacity C_p	0.026 J/(m·s·K)
Coal skeleton heat capacity $C_{p,p}$	0.12J/(m·s·K)
Gas heat transfer coefficient η	0.013MPa
Coal skeleton heat transfer coefficient η_p	0.46
Pumping negative pressure p_z	2.83
Thermal cracking factor χ	
Thermal cracking constant D_0	

Boundary conditions

In order to accurately reflect the influence of heating on the extraction effect, the model uses numerical simulation of the separation of the extraction holes and the heating holes. The model range is 10m×2m rectangle, and the extraction hole a and the heating hole b are arranged respectively. The heating hole is 0.5m away from the extraction hole, the heating hole diameter is 0.02m, the diameter of the extraction hole is 0.075m, and the model is divided into grids as shown in Fig.6.show.

(1) Temperature field initial value and boundary conditions

Initial condition: At t=0, the internal temperature of the coal seam $T|_{t=0}=T_0$, and T_0 is the initial temperature of the coal seam.

Boundary conditions: at the heating hole b, $T = T_b$, T_b is the heating temperature.

(2) Stress field boundary conditions

Initial condition: At t=0, the coal body skeleton is displaced by u(x, y).

$$u=0,\ \frac{\partial u}{\partial t}=0.$$

Boundary conditions: the overburden pressure F_A=10MPa, the fixed constraint on the four sides of the model, the displacement is zero.

(3) Seepage field boundary conditions

Initial conditions: At t = 0, the original gas pressure in the coal seam region is $p|_{t=0}= p_0$.

Boundary conditions: the negative pressure of the extraction hole is $p=p_z$, the gas pressure at the left and right boundary of the coal seam is $p=p_0$, and the gas pressure at the upper and lower boundaries is p=0.

Analysis of numerical simulation results

Effect of temperature on gas drainage

In order to study the influence of temperature field on coal seam gas under different heating temperatures, the heating hole temperatures were set to 70 °C, 120 °C and 170 °C, respectively. The effect of gas drainage in the coal seam for 180 days of heating extraction was calculated by numerical simulation, and the changes of coal seam porosity, permeability and gas pressure were studied. The distribution law of gas pressure under different extraction time is shown in Fig. 7. The distribution law of gas pressure under heating extraction 180 days is described by Fig. 8.

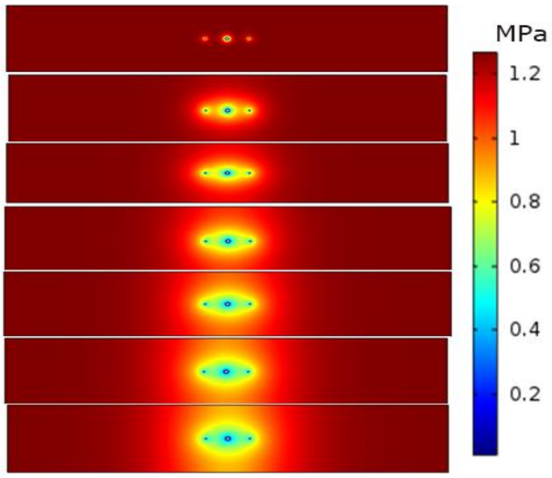

Fig.7 Gas pressure distribution at different times

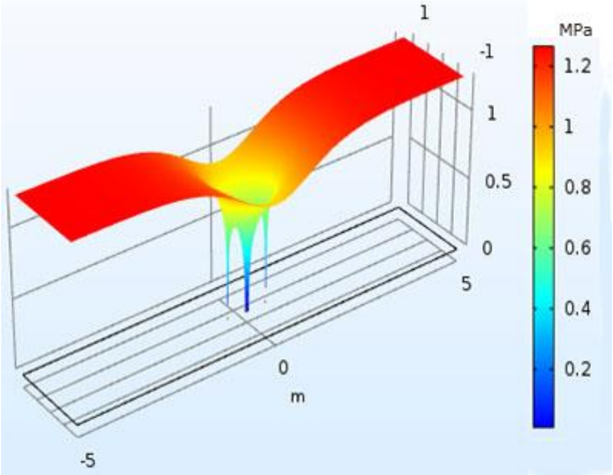

Fig.8 Gas pressure distribution in heating extraction 180 days

We can get conclusion from the Fig.7 and Fig.8 that under the joint action of the extraction hole and the heating hole, a low negative pressure drainage area is formed, and the extraction radius gradually increases with the passage of time. It is easy to see that the heating hole increases the extraction radius .

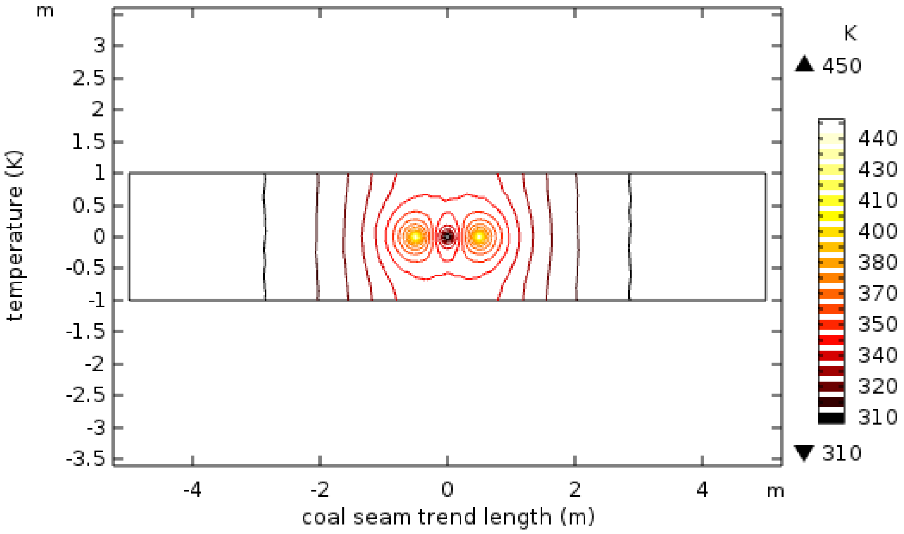

Fig.9 Temperature isotherm under 453K heating hole

Fig 9 shows the isothermal curve at a heating temperature of 453 K. It can be seen the coal body is heated by the heat radiation in the heating hole, and the heating hole is centered, and the temperature is gradually increased to the periphery in a round manner. After the temperature fields of the two heating holes are penetrated, the temperature effects of the two holes are superimposed to heat the holes. The elliptical region formed at the center has a relatively high temperature, and then conducts heat to the periphery to form a temperature field, which in turn has a certain influence on the gas containing coal. The heating effect is shown in Figs.

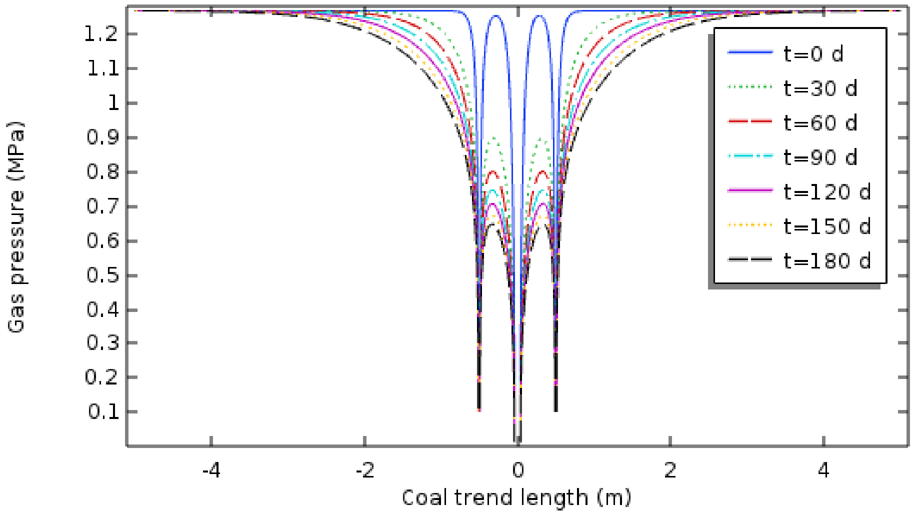

Fig.10 Gas pressure distribution at different extraction times under 453K heating hole

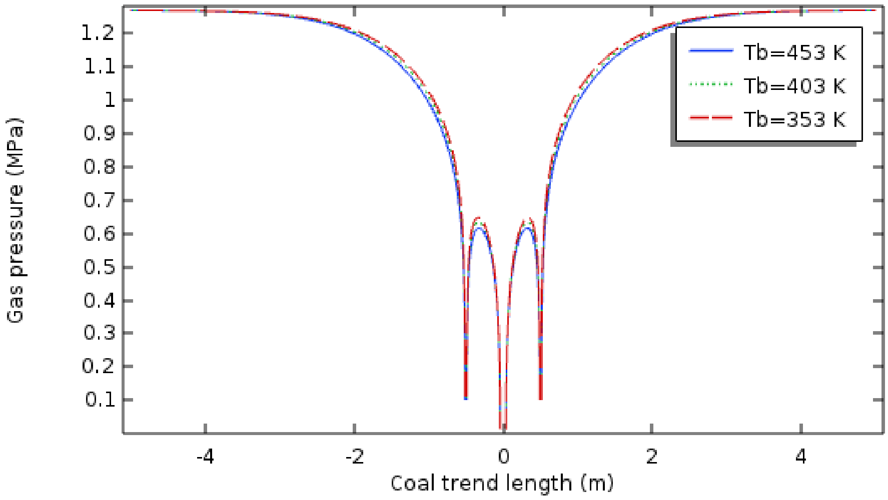

Fig.11 Gas pressure distribution at different heating temperature

It can be seen from Fig.10 that at the same temperature, the coalbed methane is pumped for 180 days, the gas pressure from the left and right boundary to the extraction hole is gradually reduced, and the gas pressure drop is gradually decreased, and the gas drainage and heating holes reduces the gas in the coal seam to some extent pressure.

After 180 days of extraction in Fig.11, the gas pressure drop is small under the conditions of heating pore temperature of 353K, 403K and 453K, indicating that the elevated temperature can not effectively promote the gas pressure drop in the coal seam. The reason is analyzed that the void in the coal seam is certain, driven by high temperature, although a large amount of gas acquires energy and promotes the adsorption gas desorption and free gas heat movement, but due to the small increase in porosity (as shown in Fig.10), the gas storage space is limited, and the desorbed large amount of gas quickly fills up. The gap creates a congestion effect. After some gas in the gap is removed, a large amount of gas is filled to fill the space. The macroscopic expression is that raising the temperature does not effectively promote the gas pressure reduction.

Effect of temperature on permeability

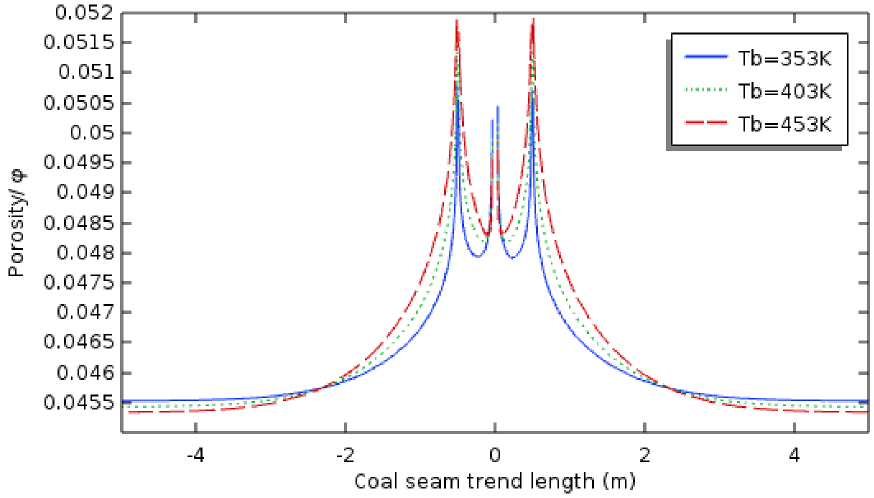

Fig.12 Porosity changes at different heating temperature

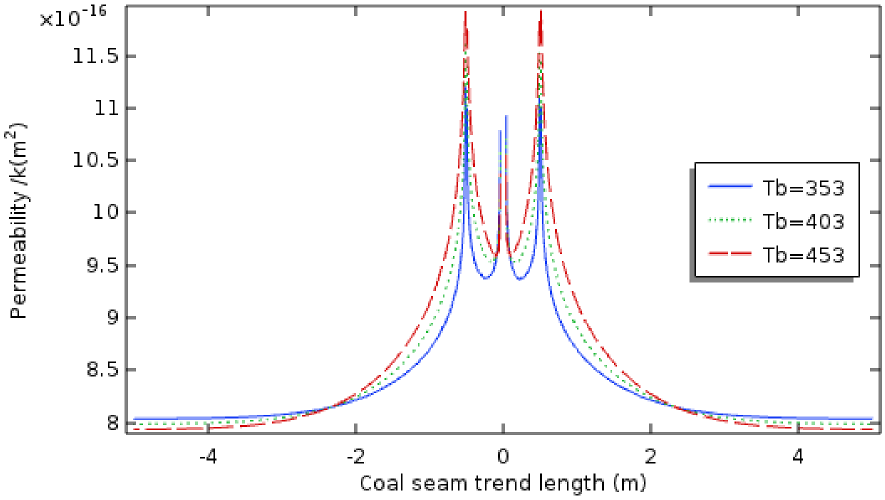

Fig.13 Permeability changes at different heating temperature

We can infer from Fig.12and Fig.13 that after 180 days of extraction, under the conditions of heating pore temperature of 353K, 403K and 453K, both porosity and permeability form small peaks at the heating holes, and the temperature is higher. The higher the peak value, the higher the peak and permeability of the porosity and permeability at the heating hole are 0.051 and $1.15\times10^{-15}m^2$, respectively, which increase by 13.3% and 47.4% relative to the initial porosity and permeability, respectively, indicating that the heating can promote the porosity and permeability.

The reason is that: (1) the high temperature zone formed around the heating hole destroys the coal structure, produces fine cracks, and increases the porosity and seepage rate. (2)From the mechanical point of view, the coal matrix is affected by effective stress, adsorption expansion stress and thermal stress. The higher the temperature, the smaller the gas adsorption expansion stress and the greater the thermal stress. Due to the high temperature conditions, the competition between thermal stress and adsorption expansion stress is manifested as the overall expansion of the coal matrix, resulting in a decrease in the absolute value of the effective stress. The macroscopic performance is that the coal expands outside, and the porosity and permeability increase.

Through analyzing the effects of different heating temperatures on gas drainage, the increase of temperature can slightly increase the permeability of coal seam, and has little effect on the reduction of coal seam gas pressure. In the range of heating 200°C, it can not greatly increase the permeability of coal seam, indicating the method of heating the coal body in order to increase the coal seam permeability does not achieve the desired effect.

Conclusions

In this study, first we created a fully coupled thermo-hydro-mechanical (THM) model using a fully coupled finite element (FE)approach and history data matching to ensure the reliability and validity of this model. Second, with numerical simulations we analyzed the sensitivities of gas extraction with a heating hole. Final, we indicating the method of heating the coal body in order to increase the coal seam permeability does not achieve the desired effect. From this study we can draw the following conclusions:

(1) The coupled thermo-hydro-mechanical model of gas drainage under temperature field is established, and the gas drainage effect under different working conditions is verified by numerical simulation.

(2) The effects of different heating temperatures on gas drainage are analyzed. The increase of temperature can slightly increase the permeability of coal seam, and has little effect on the reduction of coal seam gas pressure. In the range of heating 100 °C, it can not greatly increase the permeability of coal seam. It shows that the method of using heated coal to increase the permeability of coal seam can not achieve the expected effect.

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