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Research Article

Numerical Simulation of Seepage-Heat-Solid Coupling of Gas Seepage in Prepumped Boreholes under Electrothermal High Temperature Field

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In order to verify the law of coal bed gas desorption and permeability under electrothermal high-temperature field, by establishing the mathematical model of gas seepage-heat-solid coupling, and taking gas drainage working face in Guizhou as an engineering example, the characteristics of the high-temperature field of coal under different heating hole temperatures are simulated. The COMSOL software is used to simulate the high-temperature field characteristics, thermal damage, and permeability of coal under different heating hole temperatures. The numerical simulation results show the following:(1) the influence trend of a high-temperature field on coal thermal damage and permeability is consistent, when the heating temperature is higher than 600°C, the thermal damage and permeability of coal seam change suddenly and increase with the increase of temperature. (2) When the temperature of a heating hole is 200-800°C, the gas permeability in the damaged area increases with the increase of temperature. When the heating temperature is greater than 600°C, the radial and axial permeability around the heating hole will increase. (3) Compared with the experimental data obtained by the existing researchers, the simulation results of coal permeability under the electric heating high-temperature field have a high consistency with the experimental results of Junrong and others.

1. Introduction

Most of Chinese coal resources are mined by underground mining. With the extension of the mine to the deep, the number of outburst mines increases, and the disaster of the original outburst mines increases [1, 2]. In order to increase coal seam gas permeability and improve gas drainage effect [3, 4], according to the influence of coal seam temperature, domestic scholars such as Yang [5], Wang et al. [6], Zhiqiang et al. [7], and Zhiwei [8] [9, 10] have studied the relationship between coal seam gas adsorption and desorption and high temperature. In 2009, Yang [11] and others [12, 13] measured the permeability and desorption flow rate of coalbed methane under the influence of temperature by using a triaxial adsorption desorption apparatus, and the experiment proved that the increase of coal temperature can enhance the permeability and desorption flow rate of coalbed methane. In 2012, Liu [14] et al., Wang et al. [15], and Dandan [16] studied the relationship between permeability and temperature of coal rock within 200°C through heating experiment and showed that permeability of coal rock with initial permeability within 0.5 mD could be significantly increased to more than 15 mD after heating treatment, and uneven deformation in coal rock caused microcracks under thermal stress. In 2015, Zhiwei et al. and others [17] established the thermian-fluid-solid coupling mathematical model and three-dimensional numerical simulation of dual porous media and showed that the change of temperature field had a great impact on the change of permeability. After the completion of high-temperature fracturing steam, the permeability of coal seam increased by about 13 times than the original gas.

At present, mineral insulated heating cable (referred to as "heating cable") has been used in petrochemical industry, heating and thermal insulation, ice melting and snow melting, agricultural soil heating, combustion preheating device, and other fields. It is composed of a temperature controller and a heating cable. After the heating cable is powered on, it is heated slowly, and the temperature of the heated body is controlled at the set temperature by using a professional temperature controller. When the heated body absorbs heat, the temperature rises to reach the required working temperature. The temperature sensor and supporting temperature controller can accurately control the heating temperature. When the temperature reaches the set value, the temperature controller will automatically disconnect the power supply of the heating cable and stop heating the heating cable. When the temperature is lower than the set value, the thermostat turns on the power supply of the heating cable, and the heating cable starts heating. In 2005, Yanfeng et al. [18], Wu et al. [19], and others carried out the snow melting and ice melting experiment of heating cable road by using the concrete specimen of heating cable asphalt layer, studied the snow melting and ice melting mechanism of heating cable pavement, and studied the pavement high temperature field by using the finite element analysis method. In 2007, Shuyuan [20] established the cable heating snow melting model by using the heating cable snow melting experiment on the airport runway. In 2013, Hou and Xu [21], respectively, used asphalt concrete road and cement concrete road to test the relationship between heating speed and heating power and carried out experiments for arranging reinforcement mesh heating experiments. In 2015, Dengchun et al. [22] conducted the deicing experiment of heating cable with highway bridge specimens and studied the freezing and melting process of heating cable under two different spacing. In 2016, Xiaogang et al. [23] designed the isothermal Mi electric heat tracing method experiment for the whole line of the old hot spring electric heat tracing pipeline in Tanggula Mountain, Qinghai, controlled the operation and stop of the heat tracing system, and successfully limited the oil temperature to 40-43°C. In 2016, Nan et al. [24] carried out the research on soil thermal conductivity, described the mode and type of heat transmission in soil, and analyzed various influencing factors of soil thermal conductivity.

To sum up, the factors affecting the medium heat transfer effect mainly include heat conductivity, heat diffusion coefficient, specific heat capacity, and other parameters [25, 26]. The thermal conductivity of the medium determines the distribution of the temperature field in the steady-state heat transfer process, and the specific heat capacity of the medium can only affect the time of the temperature field established by the medium heat conduction. The heating cable conducts heat through the medium in the melting of ice and snow and soil insulation, and the heat is transmitted to the soil particle solid in the asphalt concrete layer and soil through heat conduction, so as to establish a temperature field on its surface and to achieve the effect of snow melting, ice melting, and soil heating. Therefore, the thermal conductivity of coal is the most important parameter affecting and determining the temperature field distribution of coal. Soil and coal belong to low thermal conductivity media. The temperature field has been successfully established in the above soil engineering examples. By increasing the temperature of heating cable, increasing coal moisture [27], and reducing the control range of heating cable, the required electrothermal high temperature field can be established in the outburst coal seam of mine gas drainage face.

2. Characteristics of Gas Bearing Coal under High Temperature Field

2.1. Adsorption Characteristics of High Temperature Coal to Gas. Coal is a porous medium with developed pore system, and more than 90% of gas exists in the micropores of coal matrix. Due to the changes of temperature and pressure, the gas molecules adsorbed in the micropores of coal overcome gravity, leave the inner surface of coal and enter the free state. The adsorption capacity of coal is closely related to temperature. Under the influence of the heating source, a temperature field with a spherical temperature from high to low is formed in the coal body, and a temperature difference is formed between adjacent coals. The gas molecules in the coal body absorb heat and expand, and the kinetic energy increases. The higher the temperature, the greater the gas pressure. Due to the existence of temperature difference, the gas adsorbed by adjacent media will form a pressure difference, which will increase the gas flow and release the adsorbed gas of coal seam. It is generally believed that the adsorption capacity of coal decreases with the increase of temperature, which changes in a negative exponential law.

2.2. Damage Characteristics of Coal under High Temperature Field. Based on the research results of Zhu et al. [28] and others, this paper establishes a thermal damage model based on the elastic mechanic method. It is assumed that each point in the coal and rock body satisfies the generalized Hooke's law. If the coal deformation caused by gas absorption and desorption, temperature and gas pressure change, the constitutive relationship does not change, and the damage effect of coal and rock mass can be described by weakening the corresponding parameters.

3. Thermal-Fluid-Solid Coupling Mathematical Model

3.1. Equation of Stress Field. Based on the assumption of linear elasticity, the constitutive equation of stress and strain of coal containing gas is established, which can describe the function relationship between the strain and effective stress of coal. Under isotropic and linear assumptions, the total strain of coal containing gas includes the sum of linear adsorption expansion strain caused by gas adsorption, linear thermal expansion strain caused by coal temperature rise, coal compression strain caused by gas pressure increase, in situ stress strain, and other factors. According to the total strain of coal, the constitutive equation of THM coupling is

$$\begin{gathered}\sigma' = 2G\varepsilon + \frac{\nu}{1+\nu}\Theta' - 2G, \\ \left[\frac{\beta}{3}\Delta T - \frac{K_Y}{3}\Delta p + \frac{\varepsilon_L p}{P_L + p}\exp\left(-\frac{c_2 \Delta T}{1 + c_1 p}\right)\right],\end{gathered} \tag{1}$$

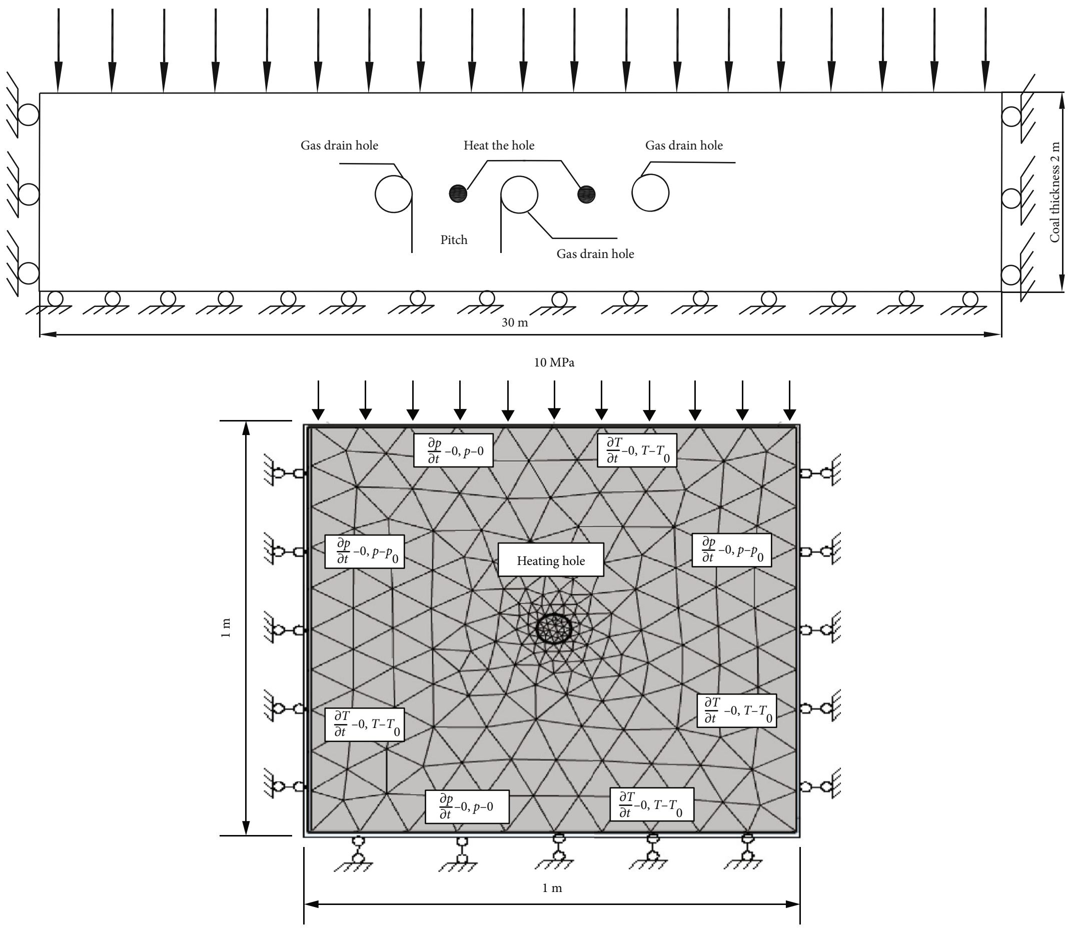


Figure 1: Calculation model of coal seam damage under thermal-fluid-solid coupling.

Table 1: Basic parameters of numerical simulation.

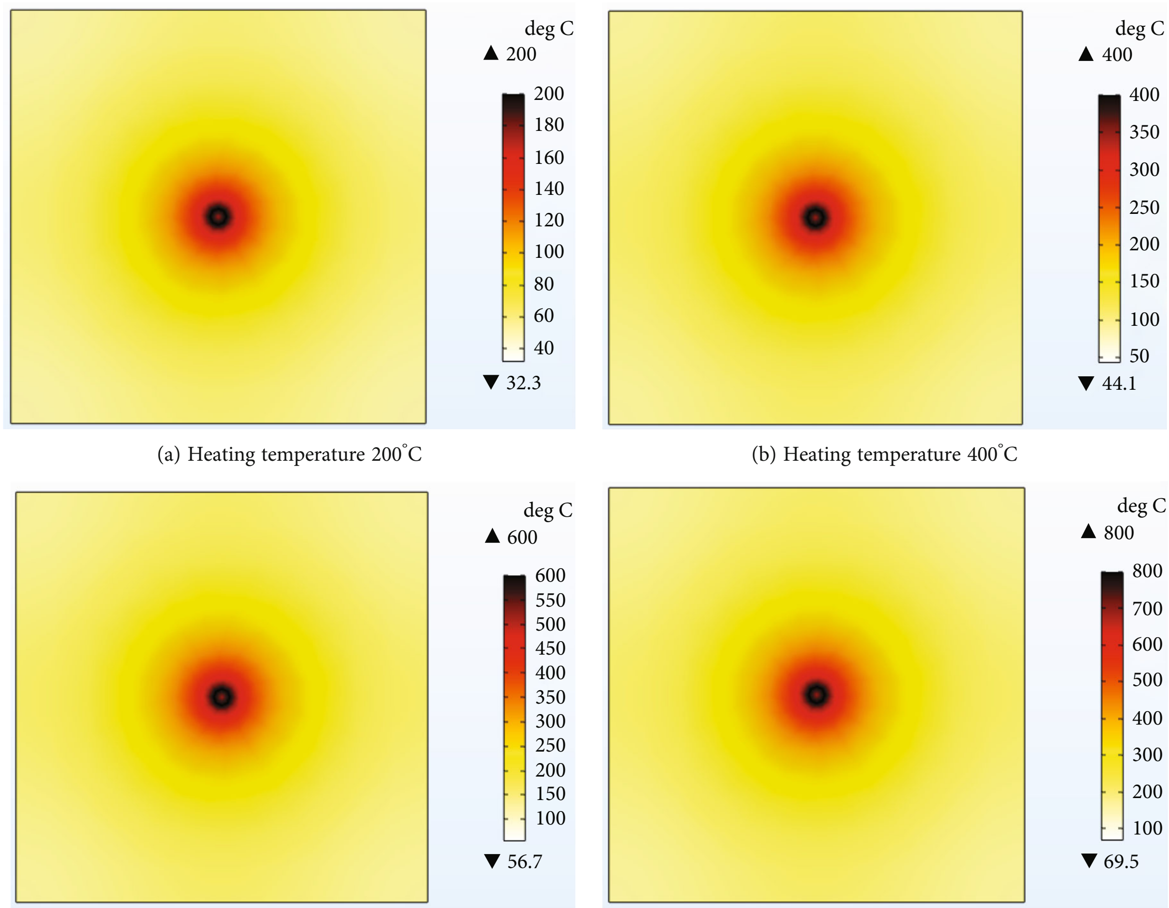
Gas dynamic viscosity coefficient/μ_0	1.087×10^{-5} Pa•s	Density of coal/ρ_c	1.35×10^3 kg/m^3
Initial porosity of coal seam/φ_0	0.045	Gas volume strain constant/ε_L	0.02295
Elastic modulus of coal/E	4×10^9 Pa	Ordinary gas constant/R	8.3143 J/(Mol°C)
Poisson's ratio of coal/υ	0.32	Initial permeability/k_0	1×10^{-15} m^2
Initial gas pressure/p_0	1 MPa	Volumetric thermal expansion coefficient of coal/β	0.116×10^{-3}°C^{-1}
Initial temperature/T_0	20°C	Specific heat capacity of coal skeleton/C_s	1350 J/(kg°C)
Langmuir pressure correction factor/c_1	710 Pa^{-1}	Specific heat capacity of gas/C_g	2160 J/(kg°C)
Langmuir volume correction factor/c_2	0.021°C^{-1}	Thermal conductivity of coal/η	0.443 W/(m°C)
Langmuir pressure constant/P_L	4.109×10^6 Pa	Gas density under standard state/ρga	0.716 kg/m^3
Langmuir volume constant/V_L	0.0477 m^3/kg	Coefficient of thermal expansion of coal	1×10^{-5}/°C

where G is the Ramet coefficient, ε is the total strain, ν is Poisson's ratio, $\Theta' = \sigma_1 + \sigma_2 + \sigma_3 + 3\alpha p$, β is the volumetric thermal expansion coefficient, °C^{-1}, Δp is coal seam gas pressure, Mpa, ΔT is temperature change, °C^{-1}, K_Y is volume compressibility, MPa^{-1}, c_1 is the Langmuir pressure correction coefficient, p^{-1}, c_2 is the Langmuir volume correction coefficient, °C^{-1}, ε_L is Langmuir adsorption strain constant, and P_L is the Langmuir pressure adsorption constant, MP^{-1}.

The tensor form of the constitutive equation can be further deduced from the above equation:

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

3.2. Seepage Field Equation. The flow process of gas in coal conforms to Darcy's law. Assuming that gravity effect is ignored, the seepage velocity is



(a) Heating temperature 200°C

(b) Heating temperature 400°C

(c) Heating temperature 600°C

(d) Heating temperature 800°C

Figure 2: Temperature field distribution under different heating temperatures.

$$q = -\frac{k}{\mu}\nabla p, \tag{3}$$

where k is the seepage rate of coal body, m^2, and μ is kinematic viscosity, Pa·s, P is the pressure gradient, Pa/M.

Assuming that the gas is an ideal gas, and the gas content equation conforms to the modified Langmuir equation and the real gas state equation, the gas content per unit volume is

$$Q = \frac{M_g p}{RT}\varphi + (1-\varphi)\rho_{ga}\rho_c \frac{V_L p}{P_L + p}\exp\left(-\frac{c_2 \Delta T}{1 + c_1 p}\right), \tag{4}$$

where Mg value is 16, R value is 8314 m^2/(s^2 K), ρ GA is the gas density in standard state, kg/m^3, ρ_C is the coal density, kg/m^3, and VL is the Langmuir volume constant, m^3/kg.

The gas flow equation in coal is

$$\frac{\partial Q}{\partial t} + \nabla\left(\rho_g q\right) = 0. \tag{5}$$

Substitute Equation (3) and (4) into Equation (5) to obtain the equation of coal seam gas seepage field:

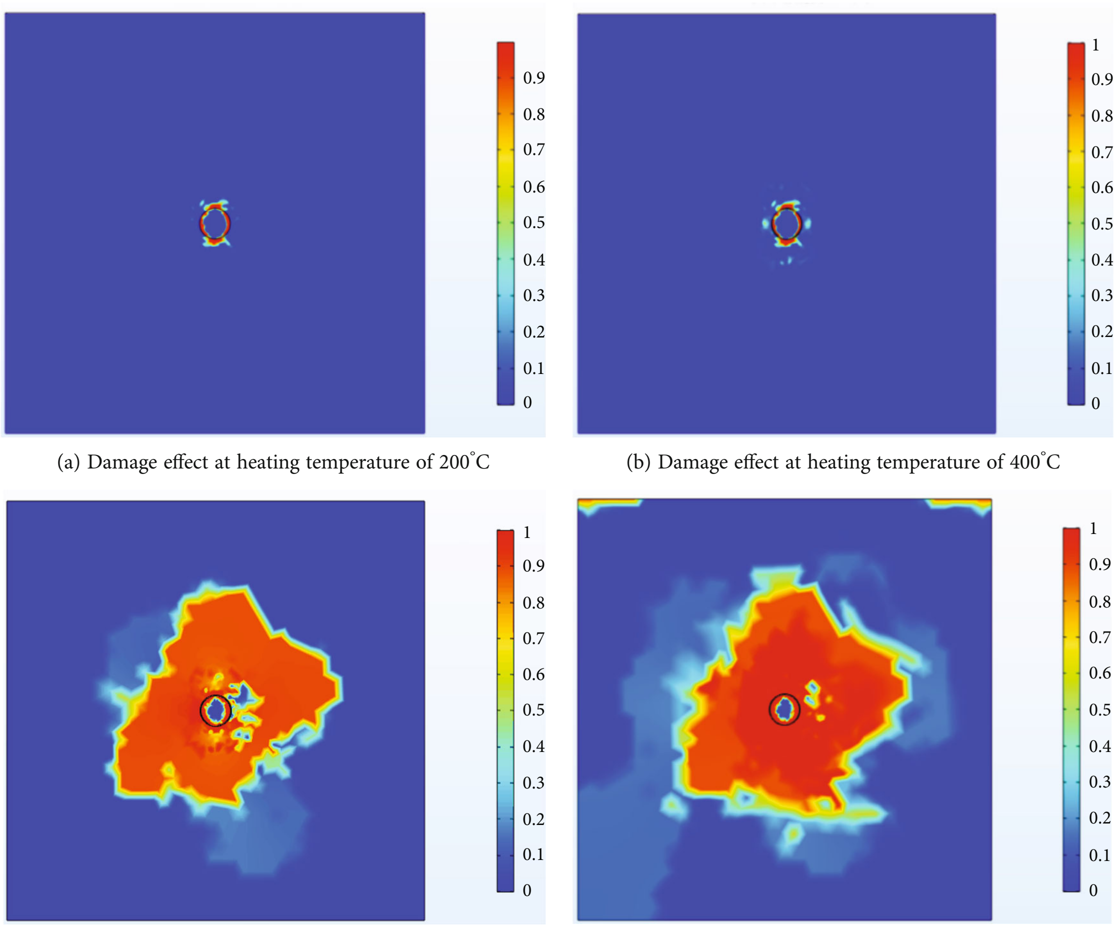
$$\frac{\partial}{\partial t}\left\{\frac{M_g p}{RT}\varphi + (1-\varphi)\rho_{ga}\rho_c \frac{\varepsilon_L p}{P_L + p}\exp\left(-\frac{c_2 (T - T_0)}{1 + c_1 p}\right)\right\} - \nabla\left(\frac{M_g p}{RT}\frac{k}{\mu}\nabla p\right) = 0. \tag{6}$$

3.3. Temperature Field Equation. According to field observation and experiments, it is a complex nonisothermal process that temperature affects gas flow in coal seam.

If the thermal filtration effect is ignored, the influence of temperature on coal includes thermal diffusion and thermal convection. According to the law of energy conservation, the control equation of coupled temperature field of coal containing gas [29] can be deduced as follows:

$$\left[\varphi\rho_g C_p + (1-\varphi)\rho_c C_{p,p}\right]\frac{\partial T}{\partial t} - \rho_g C_p\left(\frac{k}{\mu}\nabla p\right)\nabla T + \nabla\left\{\left[\varphi\eta + (1-\varphi)\eta_p\right]\nabla T\right\} = Q, \tag{7}$$

where (ρC_p), eff, ηeff, p, and η_p are effective specific heat capacity, thermal conductivity coefficient, skeleton constant pressure heat capacity, and skeleton thermal conductivity coefficient of coal body, respectively. C_p and η are the constant pressure heat capacity and thermal conductivity



(a) Damage effect at heating temperature of 200°C

(b) Damage effect at heating temperature of 400°C

(c) Damage effect at heating temperature of 600°C

(d) Damage effect at heating temperature of 800°C

FIGURE 3: Damage effect of coal body under different heating temperatures.

coefficient of gas, respectively. H is the unit heat transfer, and Q is the heat source term.

4. Porosity and Permeability Model

4.1. Porosity Coupling Model. Porosity is an important parameter representing the porosity development degree of coal, and its value is affected by three parameters (temperature, gas pressure, and strain in the stress field). Meanwhile, porosity also affects the changes of the three parameters. Thus, the equation of coal porosity [30] can be analyzed as follows:

$$\varphi = 1 - \frac{1-\varphi_0}{1+e}, \left\{1 + \beta \Delta T - K_Y \Delta p + \frac{\varepsilon_L}{1-\varphi_0}\left[\frac{p}{P_L+p}\exp\left(-\frac{c_2 \Delta T}{1+c_1 p}\right) - \frac{p_0}{P_L+p}\right]\right\}. \tag{8}$$

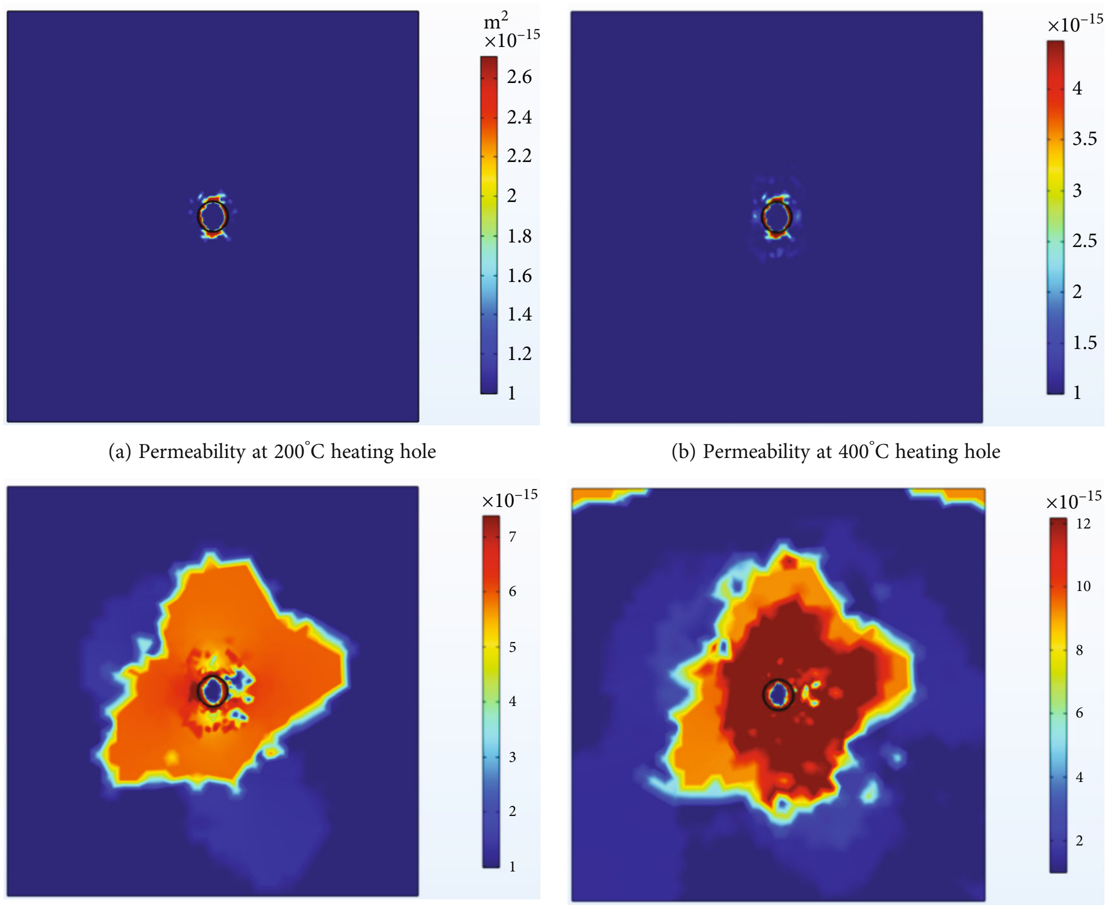
Since $e \ll \varphi 0$, it can be taken as $e = 0$, and the above equation can be simplified as

$$\varphi = \varphi_0 - (1-\varphi_0), \left\{\beta \Delta T - K_Y \Delta p + \frac{\varepsilon_L}{1-\varphi_0}\left[\frac{p}{P_L+p}\exp\left(-\frac{c_2 \Delta T}{1+c_1 p}\right) - \frac{p_0}{P_L+p}\right]\right\}. \tag{9}$$

4.2. Permeability Coupling Model. Permeability is a physical parameter to measure the permeability effect of gas in coal seam. According to literature, permeability is affected by the porosity of coal seam. If porosity is large, permeability is high; otherwise, permeability is small. In the actual mining process, the pores near the wall are not evenly distributed, and the gas flow rate is greater than zero; so, Darcy's law is no longer applicable. Therefore, the Klinkenberg gas permeability calculation model considering slippage effect is adopted in the coal seam permeability model in this paper:

$$k = k_0 \left(\frac{\varphi}{\varphi_0}\right)^3 \left(1 + \frac{b}{p}\right). \tag{10}$$

Substituting Equation (9) into Equation (10), the equation



(a) Permeability at 200°C heating hole

(b) Permeability at 400°C heating hole

(c) Permeability at 600°C heating hole

(d) Permeability at 800°C heating hole

Figure 4: Coal body permeability under different heating temperatures.

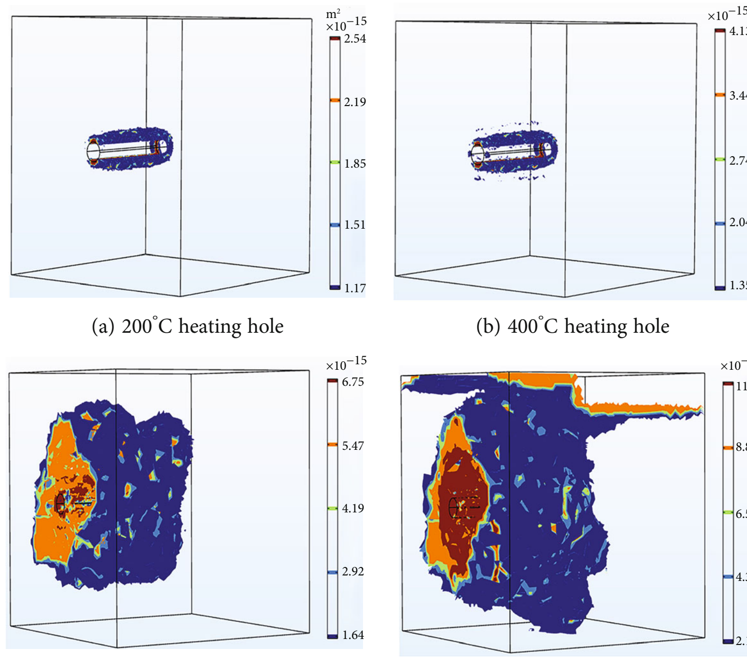
can be obtained:

$$k = k_0\left\{1-\frac{1-\varphi_0}{\varphi_0}\left\{\beta\Delta T - K_Y\Delta p + \frac{\varepsilon_L}{1-\varphi_0}\left[\frac{p}{P_L+p}\exp\left(-\frac{c_2\Delta T}{1+c_1 p}\right) - \frac{p_0}{P_L+p}\right]\right\}\right\}^3\left(1+\frac{b}{p}\right). \quad (11)$$

5. Simulation of Coal Seam Damage Zone under Thermal Fluid Solid Coupling Condition

The control equation of stress field is obtained by combining geometric equation, equilibrium differential equation, and coal constitutive equation; The gas content equation and Darcy's law are introduced into the gas flow equation to obtain the gas seepage field equation. According to the law of gas heat transfer in porous media and coal skeleton heat convection, heat diffusion, and heat radiation, the heat transfer equation of coal temperature field obtained by energy conservation is used. A thermal-fluid-solid coupling mathematical model and a dynamic change model of porosity and permeability of coal seam were established considering the damage effect and the influence of temperature on coal physical parameters. The COMSOL multiphysic multi physical field coupling simulation software is selected to establish the model. In this paper, the transportation roadway and return air roadway of M6 coal face of a mine in Guizhou Province are simulated as the research object. After the experimental steps are completed, the air inlet ends of the two roadways are sealed to isolate the experimental site from other sites, avoid relevant hidden dangers caused by coal heating, and ensure the safety of personnel and facilities. The model layout is shown in Figure 1. Set the thermal fluid solid coupling model as a two-dimensional model, take the heating hole as the center, heat the coal in a certain range through heat conduction, numerically simulate the characteristics of coal electrothermal high temperature field under the thermal fluid solid coupling condition (as shown in Figure 1), and establish a 1 m × 1 m × 1 m cube model with a radius of 0.02 m that is arranged in the middle of the model to represent the heating hole.

5.1. Model Parameter Setting. In order to ensure the accuracy of the model calculation, the gas drainage working face of a mine in Guizhou Province is selected as the numerical model. The K15 coal seam of the mine is 1.8-2.2 m thick, the spacing



(a) 200°C heating hole

(b) 400°C heating hole

(c) 600°C heating hole

(d) 800°C heating hole

Figure 5: Isosurface map of coal permeability at different heating temperatures.

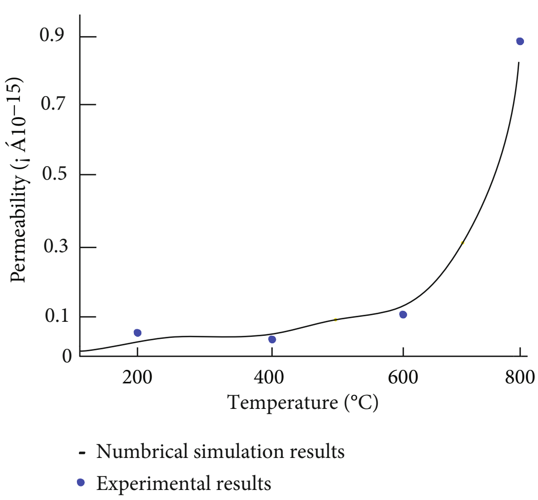


Figure 6: Coal penetration value at different temperatures.

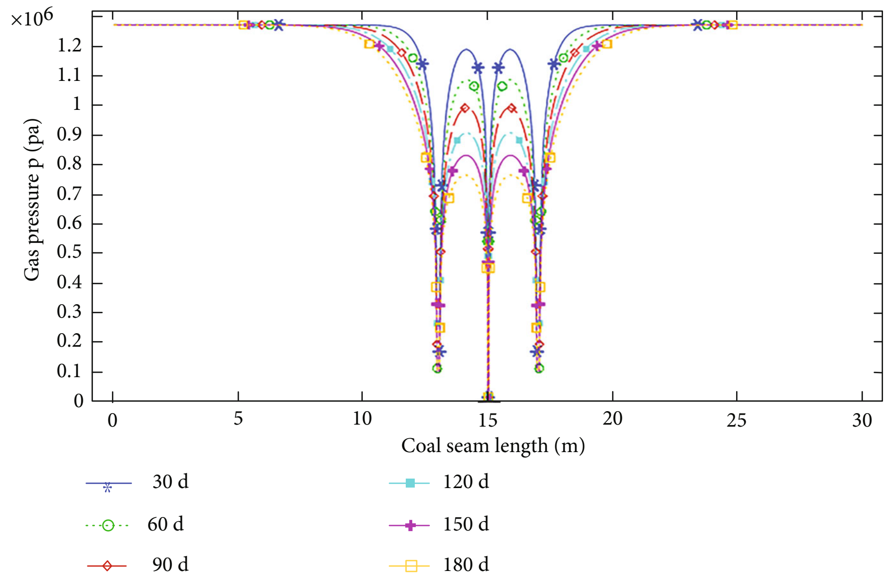
of gas drainage holes is 3 M, and the inclination of the coal seam is 15~20°. A heating hole is arranged between each two drainage holes. Through relevant experiments and calculations, the basic parameters of numerical simulation of K15 coal seam are shown in Table 1.

5.2. Boundary Condition. In order to accurately reflect the coupling relationship of temperature field, stress field, and seepage field, except the upper boundary, other boundaries are set as fixed constraints. Boundary conditions of stress field: the pressure in the vertical direction is set to 10 MPa, as shown in Figure 1. The displacement of the left and right boundaries in the horizontal direction and the upper and lower boundaries in the vertical direction is 0. Boundary conditions of seepage field: set the gas pressure at the left boundary of coal seam as the initial pressure, the right boundary as the atmospheric pressure, and other boundary pressures as 0. Boundary conditions of temperature field: set the heating hole temperature as $T = \text{Tb}$. In this paper, the heating temperatures TB in the numerical simulation process are 200°C, 400°C, 600°C, and 800°C, respectively, and it is assumed that there is no heat transfer at the coal seam boundary.

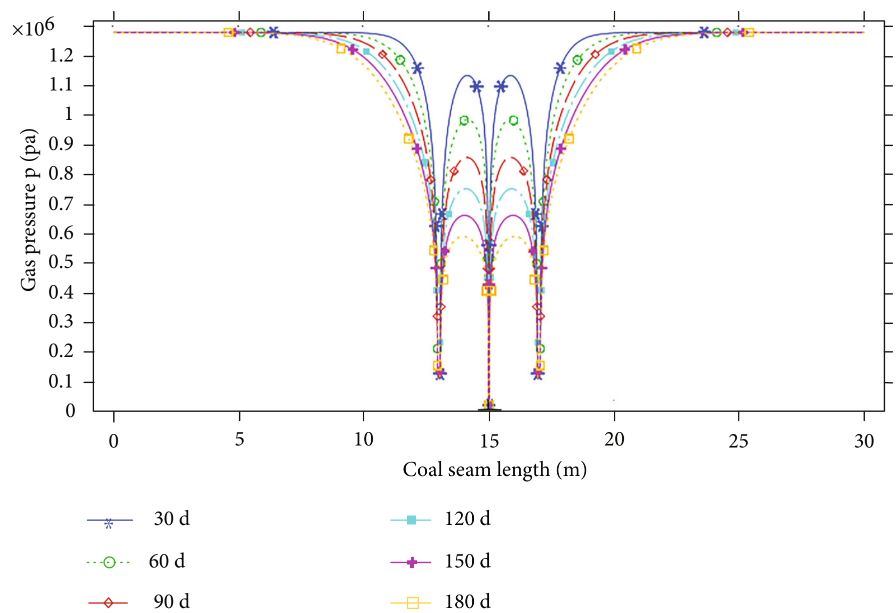
5.3. Analysis of Numerical Simulation Results

5.3.1. Distribution Law of High Temperature Field. The effect of coal heat conduction was observed by setting different temperatures (200°C, 400°C, 600°C, and 800°C). The heating cable heats the gas bearing coal in the heating hole. The numerical simulation results of the temperature field after heating for a period of time are shown in Figure 2.

It can be seen from Figure 2 that with the heating hole as the center, the heat diffuses around with a circle with radius r, gradually forming a stable temperature field, which affects a certain amount of gas bearing coal. When the heating temperature is 200°C, it can be seen from Figure 2(a) that the minimum temperature of coal is 32.3°C. When the heating hole temperature is increased to 600°C, it can be seen from Figure 2(d) that the minimum temperature of coal is 69.5°C, and the minimum temperature of the latter is more than twice that of the former, indicating that with the increase of heating temperature, the overall temperature of coal increases, and the heat conduction effect is better.

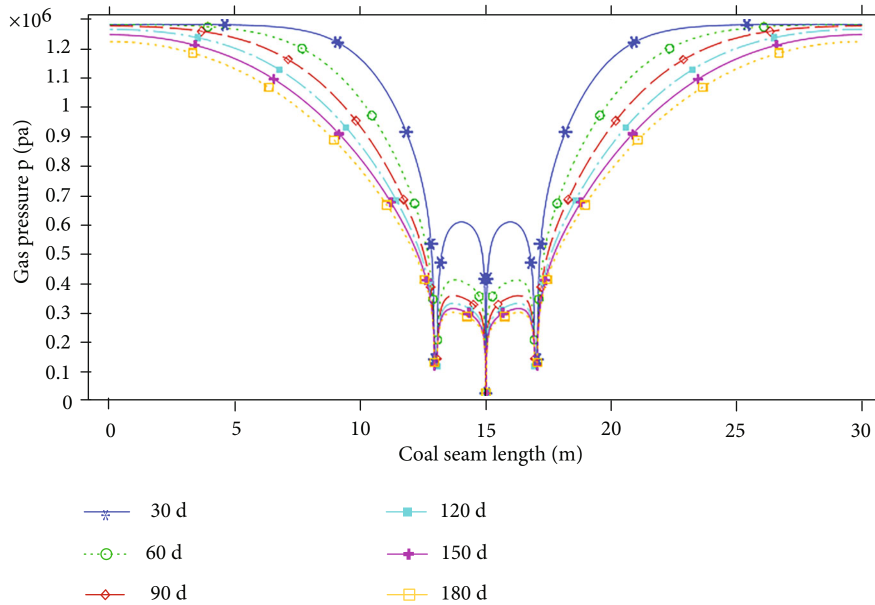


(a) 200°C heating temperature

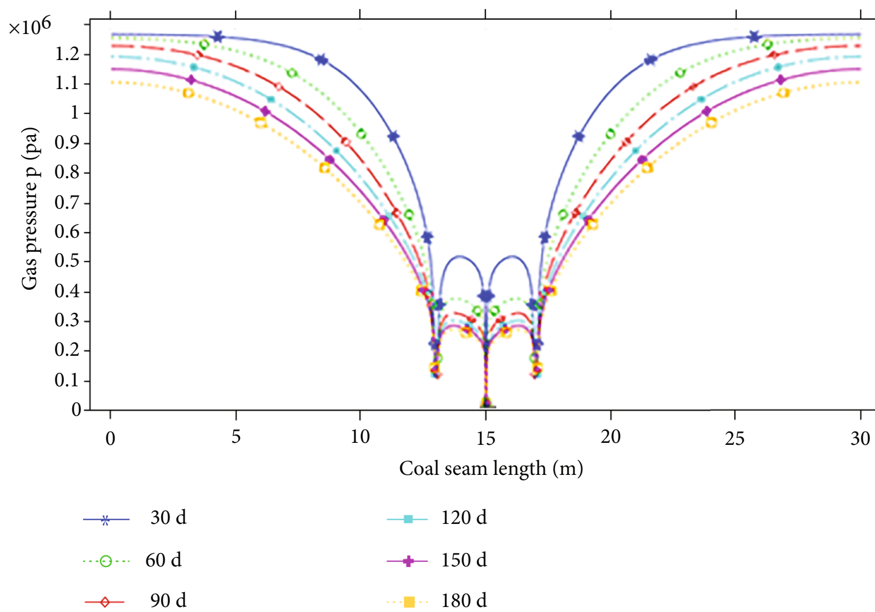


(b) 400°C heating temperature

Figure 7: Continued.



(c) 600°C heating temperature



(d) 800°C heating temperature

Figure 7: Pressure distribution of 180 d gas drainage under different heating temperatures.

5.3.2. Temperature Field and Thermal Damage Effect of Coal. In the process of heating coal by heating cable, too high temperature will lead to thermal expansion deformation of coal and then thermal damage. In order to study the influence of temperature on thermal damage of coal, the following numerical simulation research is carried out in this paper. The thermal damage results are shown in Figure 3.

It can be seen from Figures 3(a) and 3(b) that the temperature of the heating hole is 200°C, and only a small part of the coal is damaged, mainly in the up and down directions. When the temperature rises to 400°C, the damage of the coal is slightly greater than that of the heating hole, which is 200°C, but the action range is also small. It can be seen from Figures 3(c) and 3(d) that when the temperature of the heating hole rises to 600°C, a large area of red appears around the hole; that is, the damage area of the coal body suddenly changes, the shape of the damage area is approximately circular, and the influence range of the damage area is 0.2 ~ 0.3 m. As the temperature rises to 800°C, the damage range expands. The scope of influence is extended to the upper left and right corners of the model.

The analysis shows that when the temperature of the heating hole is high, the temperature causes the thermal expansion stress of the gas bearing coal body to be greater than the overburden pressure in the limited space.

Combined with the influence of fixed boundary constraints, tensile failure and shear failure occur around the heating hole, showing the damage effects of Figures 3(c) and 3(d).

5.3.3. Temperature Field and Coal Permeability. Based on the above research, the permeability is affected by temperature parameters. In order to observe the change of permeability under different temperature conditions, this paper simulates the change law of coal seam permeability when the heating temperature is 200°C, 400°C, 600°C, and 800°C, respectively. The simulation results are shown in Figure 4.

The simulation effect of temperature field on coal seam permeability is shown in Figure 4. It can be seen from Figures 4(a) and 4(b) that the temperature of the heating hole is 200°C, and the coal permeability increases in a very small range around the hole, which is not obvious. When the temperature of the heating hole increases to 400°C, the permeability value also increases, and the increased area is slightly larger than the area at 200°C, which is the same as the distribution law of thermal damage. It can be seen from Figures 4(c) and 4(d) that as the temperature of the heating hole rises above 600°C, the permeability area and permeability value of the coal seam increase sharply compared with 400°C. When the temperature of the heating hole reaches 800°C, the permeability value increases by 11 times. It can be seen from the four diagrams that the influence of temperature field on permeability is similar to the damage trend of coal body.

In order to further illustrate the promoting effect of electrothermal high temperature field on permeability of coal body, this paper analyzed the model stereograph and obtained permeability isosurface Figure 5 of numerical simulation model under different heating temperatures.

It can be seen from Figure 5 that when the temperature of the heating hole is 200°C, 400°C, 600°C, and 800°C, the permeability of coal seam increases by 2.5 times, 4.1 times, 6.7 times, and 11 times, respectively. The permeability improvement area is very small at 200°C and 400°C, but it increases significantly at 600°C and 800°C. In Figures 5(a) and 5(b), when the temperature of the heating hole is below 400°C, the permeability increase around the heating hole mainly occurs in the upper and lower directions around the heating hole, and the influence range is small. In Figures 5(a) and 5(b), when the temperature of the heating hole is 600°C and 800°C, the permeability increases not only along the direction of the heating hole but also along the direction of the heating hole. However, the permeability increases along the direction of the heating hole that is significantly higher than that along the direction of the heating hole.

In order to verify the accuracy of the above numerical simulation, the simulation results are compared with the experimental data of Junrong et al. [31]. The results are shown in Figure 6:

According to Figure 6, the numerical simulation results are consistent with the experimental results of Junrong and others. When the coal temperature is 200°C, 400°C, 600°C, and 800°C, the gas permeability of the experimental coal of Junrong and others increases by 0.8 times, 0.9 times, 4.5 times, and 15 times, respectively, while the gas permeability of the numerical simulation coal in this paper increases by 0.5 times,2.1 times,6.7 times, and 11 times, respectively, and there is a small difference between the two groups of data, which may be due to slight errors in the process of numerical simulation. Therefore, the numerical simulation results are in good agreement with the experimental results of Junrong et al.

6. Temperature Field and Gas Extraction Effect in Working Face

The beneficial effect of temperature field on coal face drainage was revealed by analyzing the variation law of gas pressure under different heating temperatures (200°C, 400°C, 600°C, and 800°C). The gas pressure distribution on the horizontal midline of the coal seam for 180 days under different heating temperatures was numerically simulated (as shown in Figure 7).

It can be seen from Figure 7 that when the influence range of 180 d extraction under the action of heating hole is expressed by gas pressure, the effective radius of extraction hole at 200°C, 400°C, 600°C, and 800°C is 2.2 m, 2.6 m, 4.9 m, and 6.1 m, respectively, increasing by 18.2%, 88.5%, and 24.5%, respectively. When the temperature of the heating hole is 600°C, the influence range of extraction increases dramatically.

7. Conclusion

(1) In the heating process of electrothermal high-temperature field, the heating hole is the center, and the heat diffuses around the circle with radius r, gradually forming a stable temperature field. When the heating temperature increases, the overall temperature of coal increases

(2) With the increase of temperature, the damage area of coal body increases, and the gas permeability of coal seam increases. When the temperature of the heating hole is 200°C, 400°C, 600°C, and 800°C, the permeability of coal seam in the damaged area increases 2.5 times, 4.1 times, 6.7 times, and 11 times, respectively. When the temperature of the heating hole is below 400°C, the permeability increase around the heating hole mainly occurs in the upper and lower directions around the heating hole, and the influence range is small. When the temperature of the heating hole is 600°C and 800°C, the permeability increases not only along the heating aperture but also along the heating aperture

(3) Based on the experimental data of Junrong [20] and others, the simulation results of coal permeability under electrothermal high temperature field are compared, which proves that the numerical simulation results are reliable

(4) The influence range of heating hole depends on the heat conduction coefficient of coal skeleton and gas. The higher the heat conduction coefficient is, the larger the influence range of heating hole is, and the gas extraction has little influence on the temperature field. According to the thermal expansion

characteristics of low stress outburst coal seam in mine, an effective way to increase gas permeability by heating the coal seam is determined

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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