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Research Article

Thermos-Solid-Gas Coupling Dynamic Model and Numerical Simulation of Coal Containing Gas

Xiao Fukun,[1,2,3] **Meng Xin**,[1,2,3,4] **Li Lianchong**,[5] **Liu Jianfeng**,[6,7] **Liu Gang**,[2] **Liu Zhijun**,[3] **and Xu Lei**[3]

[1]*School of Safety Engineering, Heilongjiang University of Science & Technology, Harbin Heilongjiang 150022, China*
[2]*Heilongjiang Ground Pressure & Gas Control in Deep Mining Key Laboratory, Heilongjiang University of Science and Technology, Harbin, Heilongjiang 150022, China*
[3]*College of Mining Engineering of Hust, Heilongjiang University of Science and Technology, Harbin Heilongjiang 150022, China*
[4]*Shandong Energy Zibo Mining Group CO., LTD., Planning and Development Department, Zibo, Shandong 255000, China*
[5]*School of Resources & Civil Engineering, Northeastern University, Shenyang Liaoning 110819, China*
[6]*State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, Sichuan 610065, China*
[7]*College of Water Resource & Hydropower, Sichuan University, Chengdu, Sichuan 610065, China*

Correspondence should be addressed to Xiao Fukun; xiaofukun@hotmail.com

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Based on gas seepage characteristics and the basic thermo-solid-gas coupling theory, the porosity model and the dynamic permeability model of coal body containing gas were derived. Based on the relationship between gas pressure, principal stress and temperature, and gas seepage, the thermo-solid-gas coupling dynamic model was established. Initial values and boundary conditions for the model were determined. Numerical simulations using this model were done to predict the gas flow behavior of a gassy coal sample. By using the thermo-solid-gas coupling model, the gas pressure, temperature, and principal stress influence, the change law of the pressure field, displacement field, stress field, temperature field, and permeability were numerically simulated. Research results show the following: (1) Gas pressure and displacement from the top to the end of the model gradually reduce, and stress from the top to the end gradually increases. The average permeability of the *YZ* section of the model tends to decrease with the rise of the gas pressure, and the decrease amplitude slows down from the top of the model to the bottom. (2) When the principal stress and temperature are constant, the permeability decreases first and then flattens with the gas pressure. The permeability increases with the decrease of temperature while the gas pressure and principal stress remain unchanged.

1. Introduction

Gas flow in coal seams is an extremely complex thermo-solid-gas coupling dynamic problems, which involve multiple factor and multiple coupled fields. In the process of coal mining, various gas dynamic disasters occurred, such as coal and gas outburst and abnormal methane discharge, which are closely related to the interaction of coal and gas under the thermo-solid-gas coupling effect. The permeability of coal is a physical parameter that reflects the characters of methane seepage and significant parameters in studying thermo-solid-gas coupling. When the gas flows in the coal seam, the permeability change is very complex, affected by the gas pressure, temperature, and principal stress. Therefore, establishing the thermo-solid-gas coupling model of gassy coal, studying the permeability under the thermo-solid-gas coupling effect has an important significance to the prevention and control of gas dynamic disasters and improving gas drainage efficiency [1]. The thermo-solid-gas coupling model of gassy coal and the change of permeability have been studied before [2–11]. Xiao [2] made a study of gas release through floors from lower adjacent seam; the influence of coal mining process on the working face floor and gas release is explored, which provides a basis for the study of underground permeability. According to the characteristic of gas flow in low-permeability coal, Guozhong et al. [3] found the dynamically coupled deformation and gas flow model by the dynamically varied porosity, gas seepage equation, and controlling equations of deformation of the coal. The results show that gas flow predictions correspond to the test results from the sample. Lower permeability gives closer agreement to the test results: The minimum error is 0.9%. As Guangzhi et al. [4] consider the variation of the porosity and permeability of coal containing gas at differential deformation stages, a dynamic model for porosity and permeability is developed based on the previous research results. Furthermore, taking coal containing gas as a kind of isotropic elastoplastic material and taking into account the effect of gas adsorption, the solid-gas coupling model for coal containing gas is constructed. In addition, the numerical simulation model is built by using the finite element method, and the research results may have a meaning for further enriching and improving solid-gas coupling theories for coal containing gas. As Ping et al. [5] consider the Klinkenberg effect and gas adsorption swelling effect on gas transportation in coal, the porosity model, the dynamic permeability model, and gas-solid coupling model were established finally, and the numerical simulation results in natural discharging conditions is obtained. Qixiang [6] studied the effect of gas pressure on permeability in the whole stress-strain process of coal or rock. The result shows that the permeability increases with the increase of gas pressure within a certain range of gas pressure. Xin-le and Yong-li [7] considered the effect of temperature on permeability and made relevant studies. The experimental results show that the permeability changes with the decrease of effective stress, and the permeability increases with the decrease of effective stress. At the beginning, the permeability degradation gradient at low temperature decreases faster than that at high temperature, and at the end, the permeability gradient at high temperature rises faster than that at low temperature. Jia-wei et al. [8] studied the mechanics and permeability characteristics of raw coal and briquette. The results show that the increase of gas pressure leads to the decrease of coal-rock strength; therefore, it leads to the decrease of the permeability. Yongjiang et al. [9] carried out the permeability test that was performed in ZYS-1 equipment for the measurement of permeability to study the effects of confining stress, axial stress, and temperature on permeability of coal briquette specimens. Ruiduan et al. [10] found that the temperature has a close relationship with permeability. When the confining pressure, pore pressure, etc. are fixed values, in the high temperature area, the permeability increases with the increase of temperature. Shu-gang et al. [11] conducted experiments on gas seepage characteristics of coal outburst under variable gas pressure under different coaxial pressure and confining pressure. With the increase of gas pressure, it is proved that the seepage velocity of gas increases as a quadratic polynomial function. The air permeability of the outburst coal is in the form of "V," which first decreases and then increases. Zhao et al. [12–15] studied the mechanical properties, crack evolution, and fracture precursors of rocks. Mu et al. [16] used the numerical simulation method to study the shear deformation characteristics of grouting rock.

The aforementioned was mainly through experiments to research the effect of gas pressure, temperature, and principal stress on the permeability, and then processing and analyzing experiment data, getting the change law; there is no systematic theoretical analysis, through the analysis of theoretical model which is rarely reported. Under uniaxial and pseudo-triaxial conditions, the monotonic factors are considered. The combined effects of stress, temperature, and pressure are not taken into account. Therefore, based on the theory of gas flow and coal deformation, the thermoelastic expansion, absorption gas expansion, pore pressure, and compression deformation of coal are fully considered, together with the dynamic equations of porosity and permeability which are comprehensively considered by gas pressure, temperature, and principal stress that are established, and the thermo-solid-gas coupling model were established finally. In addition, the numerical simulation model is built by using the finite element method, and the numerical solution of the model for a special loading case is given in terms of the constraint conditions and corresponding parameters. The research results may have a meaning for further enriching and improving thermo-solid-gas coupling theories for coal containing gas.

2. The Basic Assumption

At a macro level, coal is a porous medium. The factors affecting the flow of gas in coal are extremely complex; therefore, in the establishment of the thermo-solid-gas coupling model of gassy coal to grasp the main factors, secondary factors were abnegated, and the relationship between the main influencing factors was found. Therefore, the following assumptions are made: (1) gassy coal is homogeneous isotropic, and the gas flow in the coal is laminar flow, obeying Darcy's law. (2) Coal is the single-phase gas saturation, the gas adsorption and desorption were completed, and the gas follows the Langmuir equation in an instant. (3) The coal gas content is free gas and adsorbed gas. (4) The deformation of coal belongs to the small deformation.

3. Theoretical Model of Porosity and Permeability of Coal

In the process of coal mining, the condition of coal is very complex, which is affected by gas pressure, stress, temperature, etc., causing the changes of internal structure of coal, which will lead to the change of porosity and permeability of coal.

3.1. Theoretical Model of Gassy Coal Porosity. According to the definition of porosity of porous medium [17, 18], the expression of the gassy coal porosity is

$$\phi == 1 - \frac{1-\phi_0}{1+\varepsilon_V}\left(1 + \frac{\Delta V_S}{V_S}\right). \tag{1}$$

In the formula, φ_0 is the initial porosity of gassy coal, ε_v is the volumetric strain of gassy coal, V_S is the initial frame volume of gassy coal, and ΔV_S is the change of frame volume of gassy coal.

Allowing for the effect of gas pressure, principal stress, and temperature on coal deformation, the increment of volumetric strain is mainly composed of the increment of thermal strains $\Delta V_{ST}/V_S$, the increment of gas pressure strain $\Delta V_{SP}/V_S$, and the increment of adsorption gas expansion strain $\Delta V_{SF}/V_S$, namely

$$\frac{\Delta V_S}{V_S} = \frac{\Delta V_{ST}}{V_S} + \frac{\Delta V_{SP}}{V_S} + \frac{\Delta V_{SF}}{V_S} = \beta \Delta T - K_Y \Delta p + \frac{\varepsilon_p}{1-\varphi_0}. \quad (2)$$

In the formula, the increment of adsorption gas expansion strain of unit volume of coal [19] is

$$\varepsilon_p = \frac{2\rho RT\alpha K_Y}{3V_m} \mathrm{In}(1+bp). \quad (3)$$

Plug formula (2) and (3) into formula (1), we get a theoretical model of gassy coal porosity:

$$\begin{aligned} \phi &= 1 - \frac{(1-\phi_0)}{1+e}\left\{1+\beta\Delta T - K_\gamma \Delta p + \frac{\varepsilon_p}{1-\phi_0}\right\} \\ &= 1 - \frac{(1-\phi_0)}{1+e}\left\{1+\beta\Delta T - K_\gamma \Delta p + \frac{2\alpha\rho RTK_\gamma \ln(1+bp)}{3V_m(1-\phi_0)}\right\}. \end{aligned} \quad (4)$$

3.2. Theoretical Model of Gassy Coal Permeability. Permeability, an important index of coal seam permeability, can reflect the gas migration in coal. Therefore, study on dynamic change law of gassy coal permeability has a guiding significance to the prevention and control of gas dynamic disasters.

According to the Kozeny-Carman [19] equation, the expression between permeability and porosity is

$$k = \frac{\phi}{k_Z {S^2}_P}. \quad (5)$$

In the formula, k is the permeability, S_P is the pore surface area of the coal volume per unit volume, and k_z is the dimensionless constant.

In the process of coal stress and strain, it can be considered that the per-unit volume of coal particle surface area keeps invariant, and combining with the dynamic equation of porosity (4), there is

$$\frac{k}{k_0} = \frac{1}{1+e}\left[1+\frac{e}{\phi_0} - \frac{(\beta\Delta T - K_Y\Delta p)(1-\phi_0)}{\phi_0} - \frac{\varepsilon_p}{\phi_0}\right]^3. \quad (6)$$

The theoretical model of the gassy coal permeability is

$$k = \frac{k_0}{1+e}\left[1+\frac{e}{\phi_0} - \frac{(\beta\Delta T - K_\gamma\Delta p)(1-\phi_0)}{\phi_0} - \frac{\varepsilon_p}{\phi_0}\right]^3. \quad (7)$$

The formula (4)–(7) define the porosity and permeability equation of gassy coal under the thermo-solid-gas coupling condition, which reflects the effects of gas pressure and temperature on permeability. The influence of gas pressure and temperature on permeability is very difficult by using the finite element software COMSOL.

4. The Thermo-Solid-Gas Coupling Model of Gassy Coal

4.1. The Stress Equation. Under the small deformation and elastic isotropic assumption of gassy coal, the stress field should obey the equilibrium equation, thermosetting gas constitutive equations, and geometric equations.

(1) Equilibrium of equation

$$\sigma_{ij,i} + X_i = 0. \quad (8)$$

In the formula, X_i is a volume force.

According to the principle of effective stress of gassy coal (not considering damage)

$$\sigma_{ij,j}{}' + \left(\alpha p \delta_{ij}\right)_{,j} + \sigma_{sw}\delta_{ij,j} + F_i = 0. \quad (9)$$

(2) Thermosetting gas constitutive equations

$$\sigma_{ij}{}' = \lambda e \delta_{ij} + 2G\varepsilon_{ij} - \theta_T \Delta T \delta_{ij} - \theta_{pY}\Delta p \delta_{ij} - \theta_{pY}\alpha T \ln^{(1+bp)}\delta_{ij}. \quad (10)$$

In the formula, λ is Lame coefficient; G is shear modulus; e is volume deformation; θ_T is thermal stress coefficient; θ_{PY} is gas pressure coefficient; and θ_{PX} is gas adsorption coefficient.

(3) Geometric equation

$$\varepsilon_{ij} = \frac{1}{2}\left(U_{i,j} + U_{j,i}\right). \quad (11)$$

Joint type (9), (10), and (11) obtained stress equation of gassy coal is as follows:

$$\begin{aligned} &Gu_{i,jj} + \frac{G}{1\text{-}2\upsilon} u_{j,ji} \text{-} \theta_T (\Delta T)_{,i} \text{-} \theta_{PY} (\Delta p)_{,i} \text{-} \theta_{PX} aT \left[\ln^{(1+bp)}\right]_i \\ &\quad + \alpha p_i + F_i = 0. \end{aligned} \quad (12)$$

4.2. Seepage Equation. The paper only considers the gas flow in the coal body in one way, and to meet the Darcy's law [19]

$$v = -\frac{k}{u}\nabla p. \quad (13)$$

(1) Gas flow equation

$$V = -\frac{k_g}{u}\left(1 + \frac{m}{p}\right) gradp \tag{14}$$

(2) The state equation of gas flow

$$\rho = \frac{\rho_n p}{\rho_m z} \tag{15}$$

(3) Continuous flow equation

$$\frac{\partial Q}{\partial t} + \nabla.(\rho V) = 0. \tag{16}$$

Joint type (14), (15), and (16) obtained gas seepage equation of gassy coal:

$$2\alpha p \frac{\partial e}{\partial t} + 2\varphi + \frac{2(1\text{-}\varphi)}{k_s} p + \frac{2abcp_n}{(1+bp)^2} + \frac{2abcp_n}{1+bp} \text{-} \nabla \cdot \left(\frac{k}{u} \nabla p^2\right) = I. \tag{17}$$

4.3. Temperature Field Equation. Coal gas adsorption, desorption, and seepage are thermal effect and are a nonisothermal process; containing gas coal body under external force deformation also produces thermal effects, so with coal and gas coupling temperature field equation of coupled stress field and seepage field effect. The temperature change of coal containing gas is mainly caused by gas adsorption and desorption, adsorption and desorption of gas equivalent to a heat source. Therefore, to solve the problem of coal containing gas temperature field is the three-dimensional unsteady heat conduction with internal heat source. The temperature field equations of coal containing gas seepage are

$$(pC)_M \frac{\partial T}{\partial t} - (T_{ar} + T) K_g a_g \nabla \cdot \left(\frac{k}{u} \nabla p\right) + (T_{ar} + T) \cdot K \alpha_T \frac{\partial \varepsilon_v}{\partial_t} = \lambda_M \nabla^2 T + \frac{\rho_{ga} p T_a C_g}{p_a (T_{ar} + T) u} \frac{k}{u} \nabla p \nabla T. \tag{18}$$

4.4. Thermo-Solid-Gas Coupling Model. Combining the type (4), (7), (12), (17), and (18), we get the control equations of thermo-solid-gas coupling model of gassy coal. This equation reflects the interaction of porosity and permeability of gassy coal, gas flow characteristics, and dynamic changes of coal and gas. For the control equations of thermo-solid-gas coupling model of gassy coal, to the specific problems, giving the initial conditions and boundary conditions constitutes the thermo-solid-gas coupling model of gassy coal.

Table 1: The material parameters of model.

Parameter name	Numerical value
Modulus of elasticity	$6.78 * 10^8$ MPa
Poisson ratio	0.35
Original porosity	0.0828
Initial permeability	$8.0 * 10^{-15}$ m^2
Gas density	0.714 kg/m^3
Gas dynamic viscosity coefficient	$1.08 * 10^{-5}$ Pa · s
Thermal conductivity	0.443 J/(m•s · K)
Specific heat	4.35 J/(kg · K)
Coefficient of thermal expansion	$1.2 * 10^{-4}$ 1/K
Gas compression ratio	$4 * 10^{-10}$ 1/Pa
Gas specific heat	1.4

According to the process of gas migration in coal body, consider the following boundary conditions.

(1) Initial Conditions. The initial condition refers to the time of $t = 0$, the original distribution of gas pressure in gassy coal

$$p|_{t=0} = p_{\text{int}}. \tag{19}$$

(2) Boundary Conditions. Displacement boundary conditions are as follows:

$$u|_L = u_{\text{b}}. \tag{20}$$

Stress boundary condition:

$$\sigma_{ij} n_j = f_i. \tag{21}$$

Pressure boundary condition:

$$p|_L = p_{\text{b.}} \tag{22}$$

Flow boundary:

$$q|_L = q_m. \tag{23}$$

5. Numerical Simulation Analysis

According to the above analysis, the mathematical model of thermo-solid-gas coupling mathematical model is a very complicated nonlinear equation group, which needs to be solved by numerical method. In this paper, using the finite element software COMSOL [12] by partial differential equations calculation tool PDE in the system platform for secondary development, we fill in the need of porosity, permeability, stress field, seepage field, and temperature field equation and establish the containing coal gas heat-solid-gas coupling mathematical model, suitable to determine the actual

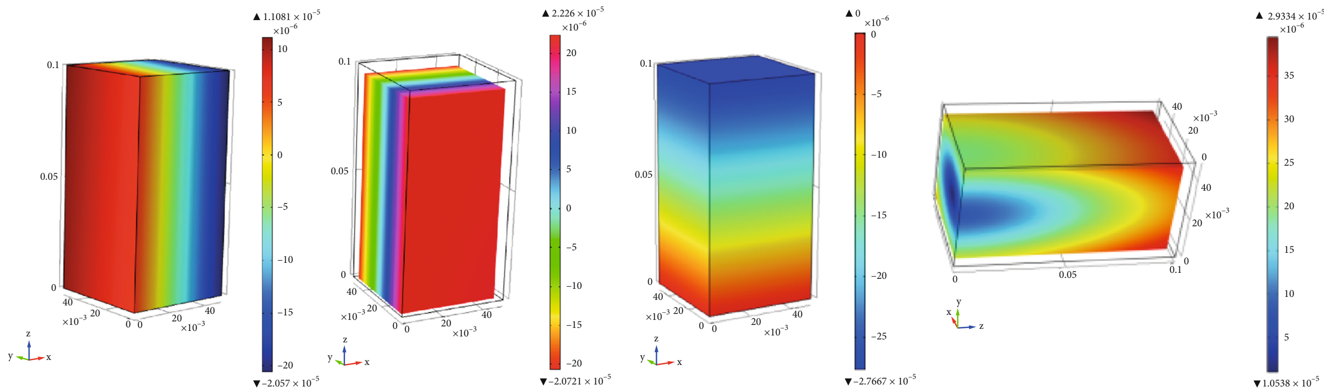

FIGURE 1: The change of displacement field of coal body. (1) X displacement field. (2) Y displacement field. (3) Z displacement field. (4) Change of total displacement field.

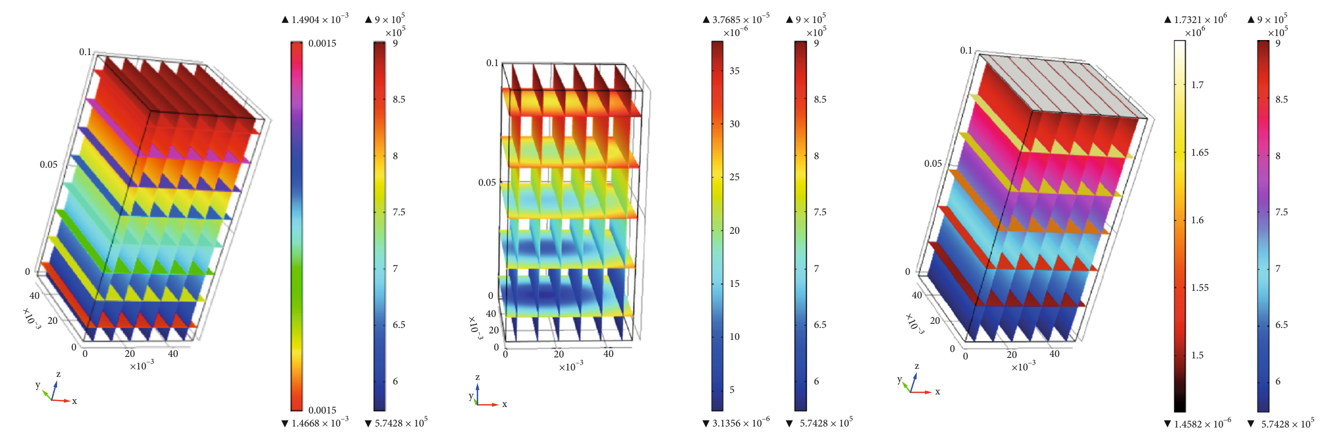

FIGURE 2: Coupling of pressure field and velocity, displacement, and stress field of gas bearing coal. (1) Pressure field-velocity field. (2) Pressure field-displacement field. (3) Pressure field-stress field.

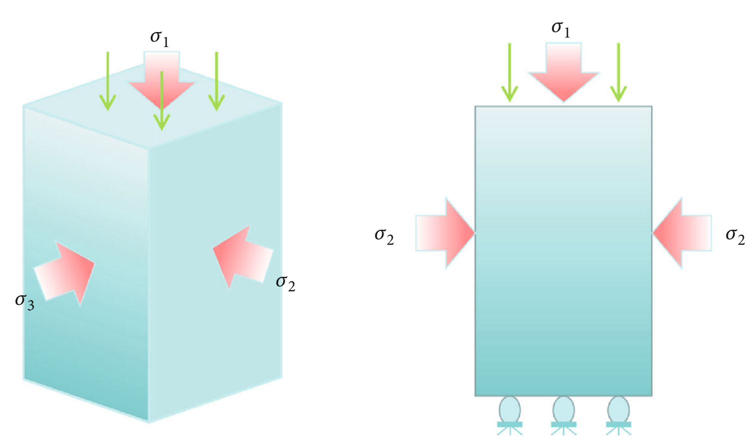

FIGURE 3: Geometrical model and boundary conditions of gas.

boundary conditions and initial conditions. The distribution of seepage field and deformation field of gas bearing coal body and the permeability change of gas bearing coal body under the action of different gas pressure, effective stress, and temperature is obtained by using the calculation tool, and the relationship between seepage field and deformation field and gas pressure, effective stress, and temperature is also obtained.

5.1. Geometric Model and Boundary Conditions. The built model is the actual size of gassy coal in this paper, and the model is 50 mm long, 50 mm wide, and 100 mm high. The

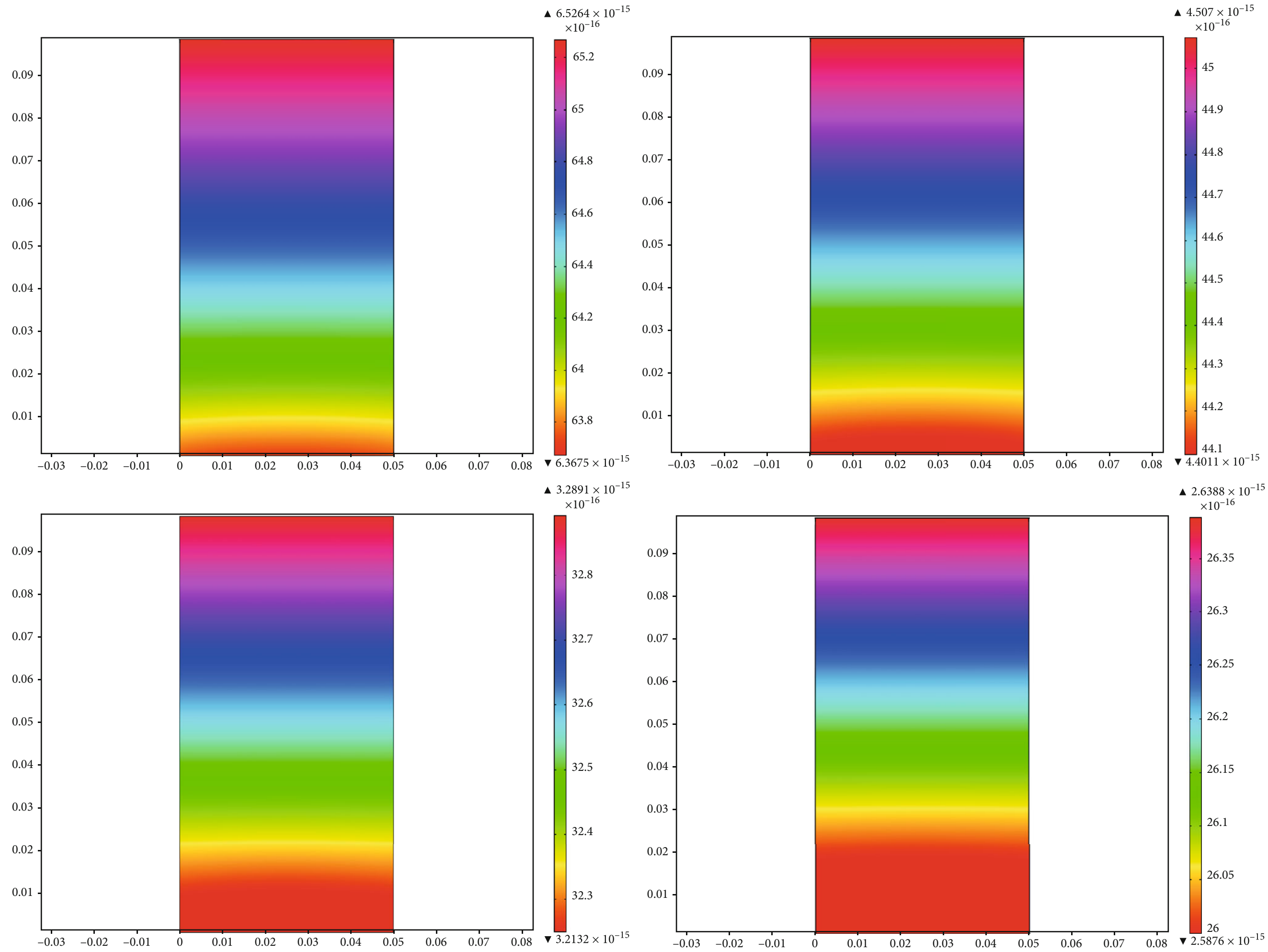

Figure 4: The change of coal body permeability under different gas pressure. (a) $p = 0.3$ MPa. (b) $p = 0.4$ MPa. (c) $p = 0.5$ MPa. (d) $p = 0.6$ MPa.

material parameters of model are shown in Table 1. According to the test of raw coal seepage, the finite element model was set up. The upper end of the model is subjected to vertical principal stress of σ_1, the left and right end under vertical principal stress of $\sigma_2 = 3$ MPa, the front end under vertical principal stress of $\sigma_3 = 4$ MPa, and the bottom under the displacement constraints; at the same time, the model has the gravity load. The gas pressure at the upper boundary of coal has initial gas pressure of $p_0 = 0.1$ MPa. Initial temperature of coal body is T, and gas flow in coal.

5.2. Numerical Results. Figure 1 shows the displacement field of gassy coal under the gas pressure of 0.6 (MPa) and the temperature of 30 (°C). As can be seen from the figure, with the principal stress and gas pressure being applied, coal is gradually compressed along the X axis, Y axis, and Z axis, and strain increment of thermoelastic expansion, absorption gas expansion, and pore-pressure compression increased cause the change of porosity and permeability.

Figure 2 shows the pressure field and velocity field, displacement field, principal stress field coupling of gassy coal under the gas pressure of 0.6 (MPa) and the temperature of 30 (°C). In Figures 2 and 3, longitudinal section shows that the change of gas pressure field and cross section represent the change of the velocity field, displacement field, and stress field, respectively. In Figure 2, red indicates that the gas pressure is relatively large, and blue shows a smaller value. As can be seen from the analysis of Figure 2, the pressure of gas is 0.6 MPa on the top ends of model. With the gas migration in coal, the gas pressure decreases gradually from top to bottom. Figure 3 shows that the gas seepage speed gradually decreases from the top to bottom of coal; the reason is that when a large amount of gas enter into the coal, the internal cracks and pores in the coal will begin to absorb, adsorbing gas will increase, and the inner wall of the coal will become thicker. The Klinkenberg effect is more obvious, namely, the gas in the coal is easier to slide, resulting in the decrease of gas seepage speed. In Figure 1, with the principal stress and pressure of gas being applied, the top of coal will become the first and the maximum to withstand stress; therefore, the maximum deformation of compressed top coal, maximum relative compressive deformation of top coal, and the displacement are maximal. With the transfer of the stress, the top to bottom of coal gradually affected by stress; thus, the

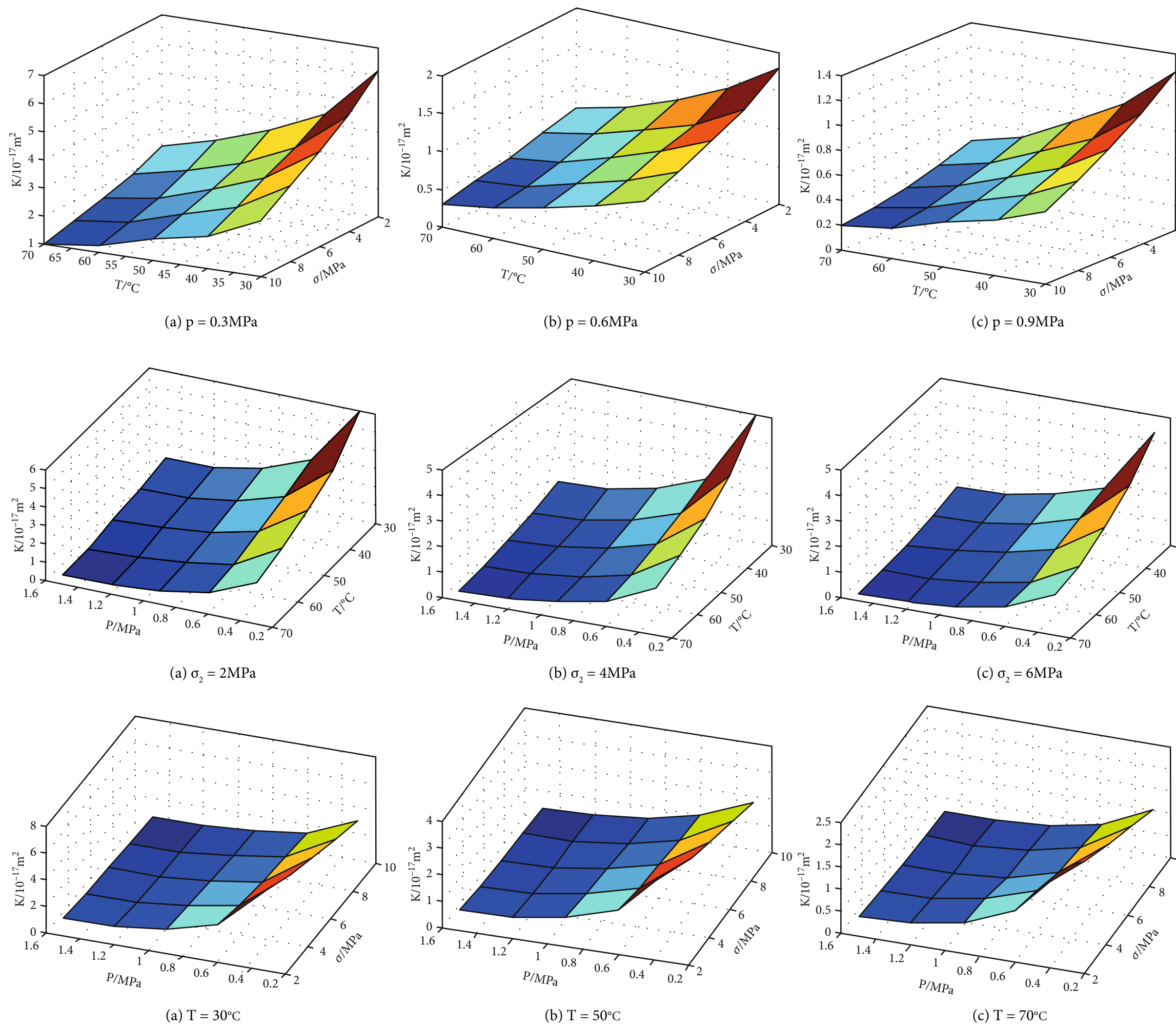

FIGURE 5: The permeability surface of coal body. (a) k-T-surface graphs of coal samples. (b) k-p-surface graphs of coal samples. (c) k-p-surface graphs of coal samples.

displacement decreases gradually from top to bottom. Figure 2 shows the change of stress of gassy coal, the color represents the stress value, the blue color represents the area of small stress value, and red represents the area of large stress value. The deeper the blue, the smaller the stress value; the deeper the red, the larger the stress value. As seen in the figure, the stress increases gradually from top to bottom under the action of gas pressure and principal stress.

Figure 4 shows the average permeability of the YZ section of the thermo-solid-gas coupling model of the gassy coal with the change of gas pressure. As can be seen from the figure, the average permeability of he YZ section of the model tends to decrease with the rise of the gas pressure, and the decrease amplitude slows down from the top of the model to the bottom. As far as the reason is concerned, with the increase of gas pressure, the adsorption capacity of coal to gas is enhanced, thus reducing the porosity of coal. Porosity affects the adsorption, analysis, and permeability of coal and thus reduces the permeability of coal. With the increase of gas content, coal gas has adsorption expansion deformation, which will not produce new fine holes, but expands inward, narrowing the internal cracks, thus reducing the permeability. With the increase of gas pressure, the suction capacity of coal gradually tends to balance, so the permeability decline rate gradually decreases and tends to be flat.

To study the variation of permeability in the thermo-solid-gas coupling, the dynamic model of gassy coal, the numerical value of different gas pressure, different principal stress, and different temperatures was calculated at the outlet end of the model, the numerical solution is introduced into MATLAB, the permeability curve of gassy coal is obtained by programming calculation, and the variation law of permeability is obtained. In Figure 5, when the temperature and the main stress are kept constant, the permeability of the gas pressure increases with the increase of the gas pressure at 0.3-0.9 MPa; and when the gas pressure is increased to 0.9 MPa, the trend of the decline of permeability is gentle. This is an increase of gas pressure, inevitably accompanied by an increase in gas flow, when a large number of gas penetration into the inside of the coal body, the existing cracks and pores in the coal body, will begin adsorption. When a large amount of gas is adsorbed, under the restraint of the three principal stresses, the coal body will not expand outward but will develop internally. Due to internal expansion effect, the original fractures and pores in the coal are compressed, or the gas molecules occupy; originally, supplied gas flow channel was diverted, resulting in gas more difficult from the coal permeability, and hence, the permeability decreases. The original offer of gas seepage channel was diverted, causing gas harder to penetrate from the coal body, so the permeability decreased. On the other hand, as the gas pressure and flow rate increase, the inner wall of the coal becomes thicker. The Klinkenberg effect is more obvious, namely, the gas in the coal is easier to slide; this leads to a decrease in permeability. With the increase of gas pressure, the suction capacity of coal gradually tends to be balanced. Swelling deformation of coal framework is also becoming smaller and smaller; therefore, the rate of permeability decline gradually decreases and tends to be flat. When the gas pressure and principal stress remain constant, the permeability decreases with the increase of temperature. This is because the viscosity coefficient of the gas increases with the increase of temperature, making it more difficult for the gas to flow in the coke. Expansion occurs inside the coal, and the pores inside the coal are compressed, which narrows the gas passage and thus reduces the permeability of the coal. When the gas temperature and pressure are fixed, the coal permeability reduces rapidly firstly and slowly where after with the principal stress increasing. With the increase of the principal stress, the deformation of coal body is gradually increasing, the fracture pore is compacted, the seepage channel becomes smaller, and so the permeability decreases. When the principal stress is higher, the coal body is gradually compressed, the compression effect is reduced, and the seepage channel is stable, so the permeability change tends to be gentle.

6. Conclusion

(1) Based on gas seepage characteristics, effects of gas pressure, principal stress, and temperature on gas coal are considered; the porosity model and the dynamic permeability model of coal body containing gas were derived. Furthermore, taking into account the basic theory of thermo-solid-gas coupling, the thermo-solid-gas coupling dynamic model was established

(2) By using the thermo-solid-gas coupling model, the gas pressure, temperature, and the principal stress influence, the change law of the pressure field, displacement field, and other physical field and permeability were numerically simulated. Research results show that gas pressure and displacement from the top to the end of the model gradually reduce, and stress from the top to the end gradually increases. Average permeability of YZ section of the model tend to decrease with the rise of the gas pressure, and the decrease amplitude slows down from the top of the model to the bottom

(3) Applying the COMSOL Multiphysics finite element software to numerically solve the thermo-solid-gas coupling mode of gassy coal permeability, the effects of gas pressure, temperature, and the principal stress on relative permeability of gassy coal are analyzed. The results show that when temperature and principal stress are fixed, the permeability reduces rapidly firstly and slowly whereafter with gas pressure increasing. When gas pressure and principal stress are kept constant, the permeability decreases with the increase of temperature. If gas temperature and pressure are fixed, the relative permeability of coal reduces rapidly firstly and slowly whereafter with the principal stress increasing; the results have an important significance of the prevention and control of gas dynamic disasters and improving gas drainage efficiency

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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