Research on a mechanical model of coal and rock around well based on variable temperature

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Abstract. To analyze the mechanical properties of coal and rock under variable temperature, the mechanical model of coal and rock around the well under variable temperature is studied based on elastic-plastic mechanics and thermodynamic theory. The control equations of coal and rock deformation, seepage field, and temperature field around the well considering temperature and clay mineral content are derived. On this basis, the finite element numerical simulation is carried out by using the relevant parameters obtained from coal and rock mechanics experiments. The numerical simulation results show that the coal rock strength, peak stress, and peak strain show a decreasing trend when the temperature increases and the simulation results of the coal samples are consistent with the experimental results, which verifies the reasonableness of the mechanical model.

1. Introduction

During the CBM extraction process, the temperature of the coal seam changes dramatically due to geological disturbances and heat exchange of drilling fluids [1]. The change in temperature field will cause changes in the seepage and stress fields of the coal seam, resulting in changes in the rock mechanics of the coal seam rock, which will cause the collapse of the coal bed methane well wall [2].

Changes in temperature can cause changes in the mechanical parameters of the rock, including compressive strength, Poisson's ratio, modulus of elasticity, and so on [3,4]. Some previous models of coal rock mechanics have been developed, mainly considering the effects of ground stress and pore pressure on rock mechanical parameters, while less research has been conducted on the effects of temperature. Lu et al.[5]unified the characterization of the intrinsic and structural stresses of coal rocks through the equivalent pore pressure coefficient, modified the KarlTerzaghi equation, and revealed the variation of mechanical properties of gas-bearing coal with effective stress; Wu Shiyue et al.[6]derived the relationship between adsorption properties, swelling stress and surface pressure of coal rocks and the relationship between effective stress and swelling stress, and analyzed the mechanical properties of coal rocks under the action of adsorption and swelling stress. The results of the model solution were compared with the experimental results, and the model's accuracy was verified. At present, the research on the mechanical properties of coal rocks under different temperature conditions is mainly carried out through mechanical experiments, and the research on the dynamic changes of the temperature, seepage and stress fields is not deep enough, while the research on the mechanical model of coal rocks considering the temperature effect is less or imperfect. Therefore, this paper establishes a mechanical model of coal rocks around the well considering temperature and clay mineral content, analyses the influence law of variable temperature effect on the mechanical properties of coal rocks, and compares the experimental results of coal rock mechanics with the numerical simulation results to verify the accuracy of the mechanical model.

2. Control equation of coal and rock around the well under variable temperature

2.1 Control equations for coal rock deformation around wells

The deformation of the coal rock around the well is influenced by three main factors, namely temperature, coal seam pressure, and ground stress. These three factors act together to cause complex deformation of the coal seam rock.

Assuming that the coal seam rock mass is an isotropic elastic medium, the strain equation caused by coal seam temperature, pressure, and in-situ stress follows.

$$\varepsilon_T = \frac{\beta_T}{3}\Delta T; \varepsilon_{PY} = -\frac{K_Y}{3}\Delta P; \varepsilon_{PX} = \frac{2\rho RTaK_Y}{9V_m} In\left(1+bP\right); \varepsilon_\sigma = \varepsilon_n^E + \varepsilon_{\mathrm{m}}^E \quad (1)$$

where β_T is the coefficient of thermal expansion of the coal bed rock, 1/K; ΔT is the coal bed temperature change,

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K; K_Y is the volume compression factor, MPa^{-1}; ΔP is the coal bed pressure change, MPa; ρ is the apparent density of the coal bed rock, t/m^3; R is the Pratt's gas constant, where $R=8.3143J/(mol\cdot K)$; a is the ratio of limiting coal rock adsorption to mass, m^3 /t; V_Q is the molar volume of the gas, where $V_Q=22.4\times 22^{-3}m^3/mol$; b is the adsorption equilibrium constant, MPa^{-1}; P is the coalbed methane pressure; Where ε_n^E and $\varepsilon_{\mathrm{m}}^E$ are the strain due to elastic deformation of the clay mineral and the strain due to elastic deformation of the rock skeleton respectively, %.

The occurrence of elastic strain in coal seam rocks should follow Hooke's Law.

$$\begin{cases}\varepsilon_\sigma=\dfrac{1}{2}\left(\dfrac{1}{G_{\mathrm{n}}}+\dfrac{1}{G_{\mathrm{m}}}\right)\left(\sigma^g-\dfrac{\upsilon}{1+\upsilon}\sigma^g\right)\\ \sigma^g=\sigma_1+\sigma_2+\sigma_3\end{cases} \tag{2}$$

Where G_n, Gm are the coefficients of lamé of clay minerals and rock masses, MPa; υ is the Poisson's ratio; σ^G is the effective stress, MPa; σ_1 , σ_2 , σ_3 are the maximum principal stress, intermediate stress and minimum principal stress, MPa.

The deformation of the coal seam rock is affected by all three of these factors, so by superimposing equations (1) and (2), we can obtain the equation for controlling the deformation of the coal rock around the well.

$$\begin{aligned}\varepsilon&=\varepsilon_T+\varepsilon_{PX}+\varepsilon_{PY}+\varepsilon_\sigma\\&=\frac{\beta_T}{3}\Delta T+\frac{2\rho RTaK_Y}{9V_m}In(1+bP)-\frac{K_Y}{3}\Delta P+\frac{1}{2}\left(\frac{1}{G_{\mathrm{n}}}+\frac{1}{G_{\mathrm{m}}}\right)\left(\sigma^g-\frac{\upsilon}{1+\upsilon}\sigma^g\right)\end{aligned} \tag{3}$$

2.2 Governing equation of coal and rock seepage field around the well

Assuming that the flow of CBM molecules in the pores of the rock is a one-dimensional Darcy seepage, the molecular flow equation, the adsorption equation and the equation of state are as follows.

$$v=\frac{\kappa}{\mu}\nabla P;Q=\left(\frac{abcP}{1+bP}+\varphi_T\frac{P}{P_{\mathrm{m}}}\right)\rho_{\mathrm{m}};\rho_g=\frac{\rho_{\mathrm{m}}p}{\xi P_{\mathrm{m}}} \tag{4}$$

where v is the percolation velocity of CBM molecules, m/s; k is the permeability of the coal bed rock, mD; ∇P is the molecular pressure of CBM per unit burial depth, Pa/m; μ is the dynamic viscosity of CBM molecules, Pa·s; c is the correction factor; φ_T is the coal rock porosity, %; ξ is the CBM compression factor, related to the temperature T; ρ is the density of CBM at standard conditions, kg /m^3; P_n is the pressure of CBM at standard conditions, the value is taken as 1 atm.

The process of molecular flow of coal bed methane satisfies the law of conservation of mass with the following equation.

$$\frac{\partial Q}{\partial t}+\nabla\cdot\left(\rho_g v\right)=I \tag{5}$$

Taking equations (4) into equation (5) gives the following equation.

$$\left[2\varphi_T+\frac{2abcP_m}{(1+bp)^2}+\frac{2abcP_m}{1+bP}\right]\frac{\partial P}{\partial t}+2P\frac{\partial\varphi_T}{\partial t}-\nabla\cdot\left(\frac{\kappa}{\mu}\nabla p^2\right)=I \tag{6}$$

Of which:

$$\frac{\partial\varphi_T}{\partial t}=\left(1-\frac{K'}{K_g}\right)\frac{\partial\varepsilon_V}{\partial t}+\frac{1-\varphi_T}{K_g}\frac{\partial P}{\partial t};\alpha=1-\frac{K'}{K_g};K'=\frac{2\left(\omega G_n+(1-\omega)G_m\right)(1+\upsilon)}{3(1-2\upsilon)} \tag{7}$$

Where K' is the bulk modulus of the coal rock mass, MPa; K_g is the skeletal bulk modulus, MPa; and ω is the clay mineral content, %.

Putting formulas (7) into formula (6), the governing equation of the seepage field of coal and rock around the well can be obtained.

$$I=\left[2\varphi_T+\frac{2abcP_m}{(1+bP)^2}+\frac{2abcP_m}{1+bP}\right]\frac{\partial P}{\partial t}+2P\left[\left(1-\frac{K'}{K_g}\right)\frac{\partial\varepsilon_V}{\partial t}+\frac{1-\varphi_T}{K_g}\frac{\partial P}{\partial t}\right]-\nabla\cdot\left(\frac{\kappa}{\mu}\nabla P^2\right) \tag{8}$$

2.3 Controlling equations for the temperature field of the coal rock around the well

The variation of the coal seam rock's temperature field follows the first and second laws of thermodynamics so that the following equation can be obtained.

$$dK+dU=\delta Q_d+\delta W;\delta W=\sigma_{ij}d\varepsilon_{ij};ds=\frac{\delta Q_d}{T} \tag{9}$$

Where dK and dU are the increment of kinetic energy and internal energy per unit volume of rock per unit time, respectively, J; δ_W and δ_{Qd} are the work done and the heat obtained per unit volume of rock per unit time, J.

According to the references[7,8], it follows that

$$\begin{aligned}dU&=\rho C_V dT+\sigma_{ij}^d\varepsilon_{ij}+\theta T_0 d\varepsilon_V\\&+\theta_{PX}T_0\left[T_0 In\left(1+bP\right)\frac{\partial a}{\partial T}+T_0\frac{aP}{1+bP}\frac{\partial b}{\partial T}+aIn\left(1+bP\right)\right]d\varepsilon_V\end{aligned} \tag{10}$$

Of which:

$$\begin{cases}\chi=\dfrac{E\upsilon}{(1+\upsilon)(1-2\upsilon)}=\dfrac{2G\upsilon}{1-2\upsilon};G=\dfrac{E}{2(1+\upsilon)};\theta_T=\dfrac{(3\chi+2G)\beta}{3}\\ \theta_{PY}=\dfrac{(3\chi-2G)K_Y}{3};\theta_{PX}=\dfrac{(2\rho\mathrm{RK_Y})(3\chi+2G)}{9V_m};G=\left(\omega G_n+(1-\omega)G_m\right)\end{cases} \tag{11}$$

Combining equations (9-11), the control equation of the temperature field of coal and rock around the well can be obtained:

$$\begin{aligned}\delta Q_d&=dK+dU-\delta W=\rho C_V dT+\sigma_{ij}d\varepsilon_{ij}+\theta_T T_0 d\varepsilon_V\\&+\theta_{PX}T_0\left[T_0 In\left(1+bP\right)\frac{\partial a}{\partial T}+T_0\frac{aP}{1+bP}\frac{\partial b}{\partial T}+aIn\left(1+bP\right)\right]d\varepsilon_V+dK\end{aligned} \tag{12}$$

where C_V is the constant volume-specific heat of coal seam rock mass, J/(kg·K).

3. Verification of mechanical model of coal and rock around the well under variable temperature

To verify the mechanical model established in the previous paper, triaxial compression experiments were carried out on coal rock specimens using the RTR-1000 high-temperature and high-pressure triaxial rock mechanics testing system. Three temperature conditions (40.0°C, 70.0°C, and 100.0°C) were set to obtain the specimens' rock mechanics parameters and stress-strain curves under different temperature conditions to provide the basic parameters required for the numerical model. Finally, the experimentally obtained coal rock mechanical parameters and the derived control equations were input into the numerical model for numerical simulation studies, and the reasonableness of the mechanical model was verified by comparing and analyzing the numerical simulation results with the experimental results. The experimental results of coal rock mechanics can be seen in Table 2 and Figure 2.

3.1 Establishment of geometric model and parameter setting of coal and rock around the well

In this paper, a three-dimensional geometric model of the coal seam rock was established, the model size was consistent with the mechanical test, and the size of Φ25mm×50mm was set. The geometric model and the meshing results are shown in Fig 1.

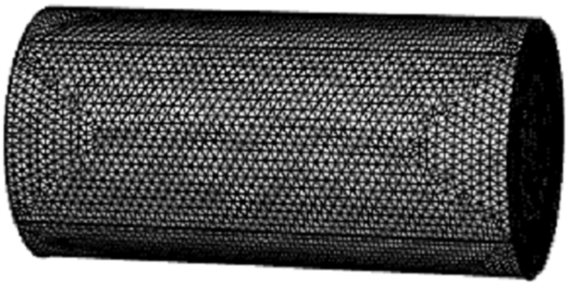


Figure 1. Geometric model and meshing of the coal sample.

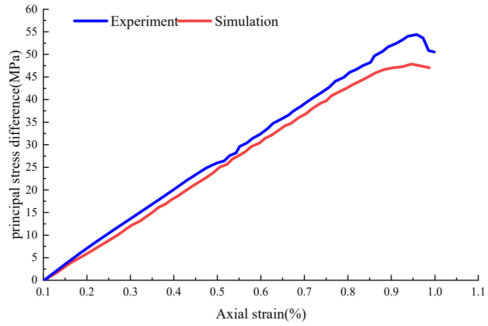
Based on the rock mechanics parameters obtained from the previous coal rock mechanics experiments and the results of the related literature[11], the various model parameters required for the numerical simulations were input into the COMSOL software for the simulations, and some of the model parameter settings are shown in Table 2.

Table 1. Table of parameters for the numerical coal rock model.

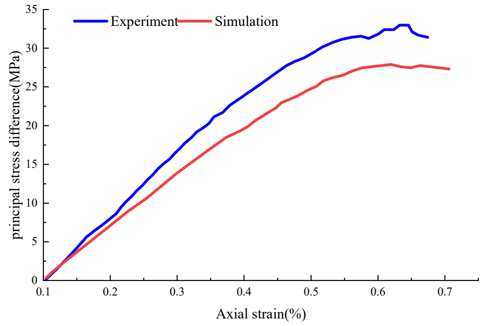
Name of coal sample parameters	Unit	Parameter values
Modulus of elasticity (E_m)	GPa	6.36
Poisson's ratio (υ)	/	0.33
Cohesion (c)	MPa	16.31
Internal friction angle (Φ)	°	29.8
Test temperature (T)	℃	40.0～100.0
The density of the coal sample (ρ_S)	Kg/m^3	1590
The density of coal bed methane (ρ_g)	Kg/m^3	0.714
Coal bed methane compression factor (K_Y)	$Kg/m^3/Pa$	0.9982e-5
Initial penetration rate	m^2	0.6e-13
Initial porosity	/	0.09
Coal bed methane viscosity	Pa*S	1.34e-5
Reference pressure adsorption constant (a)	m^3/Kg	14.5
Adsorption equilibrium constant (b)	m^3/Kg	0.73
Lamé constant (G)	GPa	1.387
Coefficient of expansion of coal rock mass (β)	1/K	1.16×10^{-4}
Clay content (ω)	/	0.5%
Modulus of elasticity of clay (E_n)	GPa	1.27

3.2 Numerical simulation results and analysis of coal and rock around the well

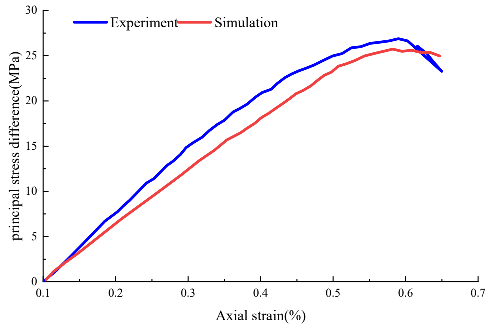
Figures 2, 3, and 4 show the relationship curves between the main stress difference and axial strain in the coal seam rock at temperatures of 40°C, 70°C, and 100°C. The two curves in the figure represent the experimental and simulated values.



(a)Temperature is 40℃



(b)Temperature is 70℃



(c)Temperature is 100℃

Figure 2. Principal stress difference-axial strain curves for coal rocks at different temperatures.

From Figures 2, 3, and 4, it can be seen that the peak principal stress difference of the coal rock specimens gradually decreases as the temperature increases from 40°C to 100°C, and the axial strain when the peak stress is reached shows a decreasing trend. It can also be seen that the stress-strain curves of the experimental and simulated specimens are in better agreement, and the trend of change is consistent.

Table 2. Comparison of experimental and numerical simulation results for coal rock specimens.

Temperature/°C	Compressive strength/MPa		Relative error /%	Peak strain/%		Relative error /%
	Experimental	Simulation		Experimental	Simulation	
40	84.5	78.9	6.63	0.9584	0.9460	1.29
70	65.5	57.8	11.8	0.6324	0.6194	2.06
100	58.0	55.8	3.8	0.5900	0.5822	1.32

As can be seen from Table 2, The relative errors between the experimental and simulated values for the compressive strength of the coal rock specimens were 3.8-11.8%, while the relative errors between the experimental and simulated values for the peak axial strain were 1.29-2.06%, both of which were within a reasonable margin of error. Therefore, the results obtained from the mechanical experiments of the coal rock specimens are in good agreement with the numerical simulation results, which indicates that the established mechanical model of the perimeter coal rock is reasonable and can provide a theoretical basis for the study of the mechanical properties of the perimeter coal rock under different temperature conditions.

4. Conclusion

(1) By deriving the deformation control equation of coal and rock around the well, the seepage field control equation of coal and rock around the well and the temperature field control equation of coal and rock around the well, the mechanical model of coal and rock around the well under the action of variable temperature is established.

(2) As the temperature rises from 40°C to 100°C, the coal rock strength weakens, the peak principal stress difference decreases, and the peak strain decreases.

(3) The results of the numerical simulation of the perimeter coal rock specimens agree with the mechanical test results, the relative error is within a reasonable range, and the mechanical model established is reasonable and can be used for the study of the mechanical properties of the perimeter coal rock under different temperature conditions.

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