ON DISTRIBUTION CHARACTERISTICS OF THE TEMPERATURE FIELD AND GAS SEEPAGE LAW OF COAL IN DEEP MINING

by

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Original scientific paper
https://doi.org/10.2298/TSCI2006923Y

The study of gas seepage under the condition of multifield coupling has always been an important topic in coal mining. Based on the theory of multifield coupling and the research method of numerical simulation, the influences of the stress and temperature fields on the seepage field under the conditions of deep coal mining are studied. With the example of the J15-31030 deep working face from mine No. 12 in the Pingdingshan Coal Mine, modeling and finite element analysis are carried out. The influences of the mining stress field and temperature field on the gas seepage field are preliminarily revealed. The results show that the closer to the working face, the greater the velocity of the seepage field is, and the greater the gradient of velocity change. There is a clear negative correlation between the mining stress field and the permeability of the seepage field. The larger the excavation length is, the greater the change gradient of the rock permeability near the working face is. The temperature field has a significant impact on the adsorbed gas in the seepage field. These research results provide the corresponding basis for the safety control and effective mining of coal mine gas.

Key words: *coal seam gas, mining induced stress field, temperature field, gas migration, multi physical field coupling, COMSOL multiphysics*

Introduction

With the exploitation of the Earth's shallow resources exhausted, the exploitation of coal resources gradually goes to greater depths [1-3]. Deep mining engineering involves some problems, such as high stress, high temperature and low permeability of coal [4, 5], which lead to the frequent occurrence of coal mine engineering disasters such as coal and gas outbursts and rock bursts, which greatly increase the difficulty of mining safety in deep coal mines [6-9]. At the same time, coalbed methane is also a kind of precious unconventional natural gas, and realizing the safe and efficient mining of coalbed methane has great economic value and safety benefits [10]. Therefore, exploring the multiphysical field coupling of the temperature field and seepage field under the mining conditions of deep coal mines [11], exploring the migration law

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of coal mine gas under the multiphysical field conditions and studying the mutual coupling and interactions of dynamic disaster-inducing factors such as different mining intensities, ground temperatures and gas pressures are urgent.

Many scholars have performed much research on multifield coupling in the process of coalbed gas seepage and have made substantial progress to date. Liang [12] obtained the gas adsorption curve of coal and the mathematical relationship between the adsorption constant and temperature when the temperature and gas pressure changed. Liu *et al.* [13] established a gas-solid coupling mathematical model considering the swelling deformation of gas coal. Qin *et al.* [14] established a coupled thermal-fluid-solid numerical model of a gas-bearing coal rock mass and studied the changes in gas pressure, gas seepage velocity and coal rock displacement under different temperature conditions. Zhu *et al.* [15] established the relationship between coal permeability and temperature according to the influences of temperature change, adsorption and effective stress on the coal volume strain. Qin *et al.* [16] established a multiphysical field coupling model of gas migration among the stress field, seepage field and temperature field and used the model to study the change patterns of gas pressure and content with burial depth. Tao [17] established thermal-fluid-solid coupling to describe the gas flow in a coal seam by introducing desorption differential thermal energy and verified the correctness of the model by comparing the measured gas pressure and temperature with the numerical calculation results under laboratory conditions. Liang and Ye [18] established a gas-solid coupling model of different mining methods and found that when the gas-solid coupling effect is considered, the coal strain is larger. In the work [19], based on the thermal-fluid-solid coupling model of gas migration in deep coal seams, the factors influencing gas pressure and the content distribution were studied, and the gas content in a coal seam was affected by the gas pressure and coal temperature together. The gas content result obtained without considering the prediction of coal temperature was larger. Peng *et al.* [20] used the method of physical similarity simulation to study the changes in coal seam temperature during the process of coal seam gas desorption under the condition of extraction and obtained the influence pattern of the initial gas pressure, gas desorption speed and ground stress on coal seam temperature. Xia *et al.* [21] established a fully coupled finite element model of non-Darcy gas flow and coal deformation processes considering adsorption and the Klingenberg effect. Yin *et al.* [22] studied the law of gas seepage under gas pressure and confining pressure by using a self-designed multifield coupling experimental device. Valliappan *et al.* [23] set up a fluid-solid coupling model of coalbed methane flow, compiled the corresponding finite element computer program, and simulated the processes of coal and gas outbursts.

Although great progress has been made in the study of coal seam gas seepage, few studies have been performed on the multifield coupling of coal mine gas under deep conditions. Based on the theory of multifield coupling, this paper selects the COMSOL Multiphysics finite element analysis software and takes a working face mine No. 12 in the Pingdingshan Coal Mine as an example to study and analyze the law of the action of the mining stress field and temperature field on the seepage field in the deep coal mine to provide the basis for the safe control and effective utilization of the coal seam gas.

Geological conditions of the working face

Coal seam, roof and floor conditions

The design workable strike length of the J15-31030 working face of mine No. 12 in the Pingdingshan Coal Mine is 932.8 m, the average mining length is 206 m, the reserve is 909000 tons, the mining face elevation is –762~–798 m, and the ground elevation is +230~+320 m.

The J15-31030 working face has a good overall occurrence, with relatively well-developed fissures. The coal seam structure is a simple coal seam, and the coal body structure is mostly primary structural coal. The average thickness of the coal is 3.2 m. The old roof of the J15 coal seam consists of gray-white fine sandstone and a muddy strip in a moderately thick layer, approximately 2.5 m thick. The direct roof is gray-black sandy mudstone 4 m-5 m thick, containing plant fossils, and the pseudo roof is 0.5-2 m black mudstone. The pseudo bottom is black mudstone with a thickness of approximately 0.2-1.3 m. The bottom plate is gray sandy mudstone or mudstone; the old bottom is dark gray sandy mudstone, and part of it is fine-grained sandstone.

General situation of the stress, temperature and gas fields

The maximum horizontal principal stress in the coal seam of the J15-31030 working face is 42.07 MPa, the minimum horizontal principal stress is 21.79 MPa, the vertical stress is 25.63 MPa, and the maximum principal stress gradient is 2.16 MPa/hm. In general, the vertical stress in the Pingdingshan Coal Mine area increases linearly with increasing depth. The horizontal stress shows a nonlinear trend with increasing depth. The tectonic movement in the mining area is significant and occurs within the stress field dominated by horizontal structural stress [24]. The original ground temperature of mining face J15-31030 is 45 °C, and the mine temperature gradient is 2.73 °C/hm. The J15 coal seam is an outburst coal seam, and the outburst area is below the level of –350 m. The elevation of the mining face is –762~–798 m, the original gas pressure of the coal seam is 2.6 MPa, the original gas content is 11.18 m^3/t, the gas pressure gradient is 0.62 MPa/hm, and the absolute gas emission is 2.23 m^3 per minute.

Establishment of the model and the boundary conditions

Mathematical model of the deformation, temperature and seepage fields

To study and analyze the effects of the deformation field and temperature field on the seepage field under mining conditions, this paper uses steady-state numerical simulation research and solves the corresponding theoretical formula.

Governing equations of the deformation field

Due to the effect of its own gravity and the gravity of the overlying rock layer, the model itself produces a certain settlement. To eliminate the influence of this settlement on the final steady-state deformation, the second Piola-Kirchhoff stress of the stratum before excavation is used as the external stress, which is applied to the model to be solved.

The burial depth of the working face is 1050 m. The deep rock layer is located within a high-temperature and high-pressure environment and easily shows plastic properties. Therefore, the constitutive equation of the deformation field adopts the elastoplastic constitutive equation and the Drucker-Prager yield criterion.

Affected by the mining stress field, the evolution equation of rock layer porosity [25] is:

$$\phi = 1 - \frac{1-\phi_0}{1+\varepsilon_v}\left(1 - K_Y \Delta p\right) \tag{1}$$

where ϕ and ϕ_0 are the porosity and initial porosity of the rock layer, respectively, K_Y – the volume compression constant, Δp – the change in gas pressure, and ε_v – the volume strain of the formation.

The evolution equation of permeability [25] is:

$$k = \frac{k_0}{1+\varepsilon_v}\left[1+\frac{\varepsilon_v}{\phi_0}+\frac{\left(1-\phi_0 K_Y \Delta p\right)}{\phi_0}\right] \tag{2}$$

where k and k_0 are the permeability and initial permeability of the formation, respectively.

Governing equation of the temperature field

The governing equation of heat conduction considering the effect of fluid permeability is expressed:

$$\rho_L c_{pL} u \nabla T = \nabla (k_{\text{eq}} \nabla T) + Q_G \tag{3}$$

where ρ_L is the density of the heat conducting medium, ρ_{pL} – the atmospheric heat capacity, u – the Darcy velocity, k_{eq} – the thermal conductivity, and Q_G – the heat source.

Governing equations of the seepage field

Assuming that the flow of gas in porous media conforms to Darcy's law, the governing equations of the seepage field are:

$$\nabla (\rho u) = Q_m \tag{4}$$

and

$$u = -\frac{k}{\mu}\nabla p \tag{5}$$

where ρ is the gas density, Q_m – the mass source, and μ – the dynamic viscosity.

Applying the equation of state for an ideal gas yields:

$$\rho = \frac{p T_a \rho_a}{p_a T} \tag{6}$$

where $T_a = 273.15$ is the standard temperature, $\rho_a = 0.717$ – the density of gas in the standard state, and $p_a = 0.1$ – the gas pressure under the standard state.

According to the Langmuir formula and related literature [16, 26], the content of adsorbed gas, denoted by m, is defined:

$$m = \rho_a \rho_c \frac{V_L p}{p + p_{L2}} \exp\left[-\frac{0.02}{0.993 + 0.07 p}\left(T_0 + T\right)\right] \tag{7}$$

where ρ_c is the density of the coal seam, V_L – the Langmuir volume constant, p_{L2} – the Langmuir pressure constant, T_0 – the coal seam temperature, and T – the experimental temperature.

Model establishment

A 2-D numerical model is established, and the selected model involves the plane strain problem. As shown in fig. 1, six stratigraphic models are established, and on the left side of the rock formation is the working face. The model is 60 m long and 31 m high, the upper rock layer is 6.3 m thick, the old roof is 2.5 m thick, the direct roof is 5 m thick, the coal layer is 3.2 m thick, the floor thickness is 4 m, and the lower rock layer is 10 m thick. The material parameters assigned to each stratum are shown in tab. 1.

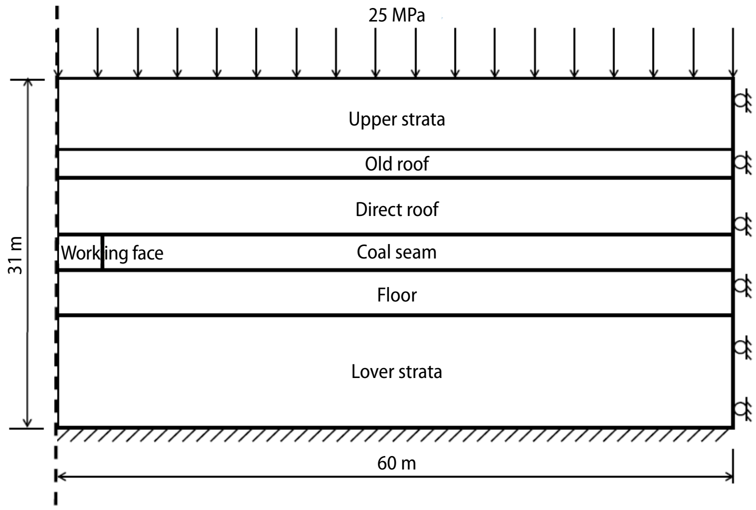

Figure 1. The numerical calculation model

Table 1. Variable settings

Variable	Coal seam	Direct roof	Old roof	Upper strata	Floor	Lower strata	Gas
Poisson's ratio	0.4	0.31	0.31	0.3	0.3	0.3	–
Young's modulus, [GPa]	6	7	8	9	8	9	–
Density, [kgm^{-3}]	1400	2600	2700	2800	2700	2800	ρ
Thermal conductivity, [Wm^{-1}K^{-1}]	0.443	2.035	2.035	2	2.035	2	0.029
Atmospheric heat capacity, [Jkg^{-1}K^{-1}]	1300	690	690	600	690	600	1000
Initial permeability, [10^{-17} m^2]	2.449	0.2669	–	–	–	–	–
Initial porosity	0.0725	0.08	–	–	–	–	–
Cohesion, [MPa]	3	3.5	1.3	10.2	3	10.2	–
Internal friction angle, [°]	30	38	36	35	38	35	–
Dynamic viscosity, [10^{-5} Pas]	–	–	–	–	–	–	1.34
Specific heat rate	–	–	–	–	–	–	1.3

Boundary conditions

As shown in fig. 1, the top of the model is under pressure from the overburden, the boundary load is 25 MPa, the right side of the model is set to roller support, the bottom is set to fixed conditions, and the left side of the model is symmetric. The initial value of the rock layer temperature is set to 318.15 K, the model boundary temperature is set to 333.15 K, and the working face and roadway temperature is set to room temperature, *i. e.*, 293.15 K. The Langmuir volume constant V_L is 0.026 m^3/kg, and Langmuir pressure constant p_{L2} is 1.4 MPa. Assuming that the gas can be transported in the coal seam and the direct roof, the initial gas pressure in the rock layer is set to 2.6 MPa, there is no gas flow at the upper and lower boundaries, the gas pressure at the right boundary of the model is set to 2.6 MPa, and the excavation roadway pressure is equal to the atmospheric pressure.

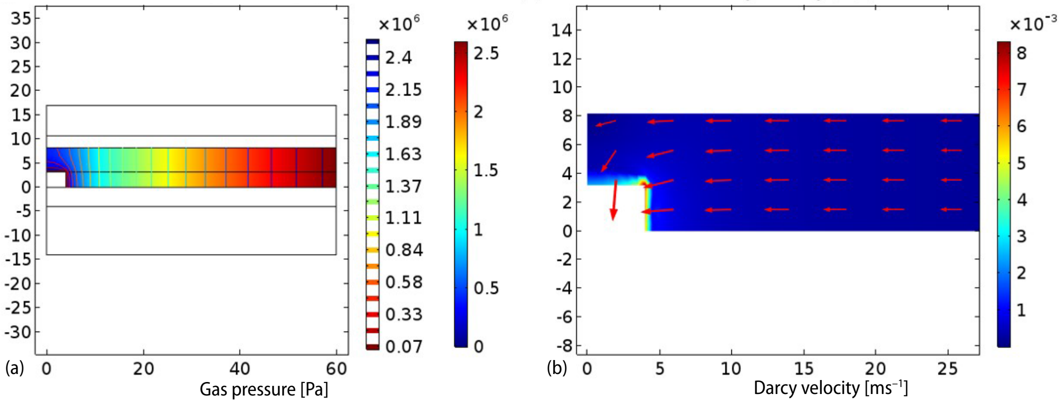

Figure 2. Schematic diagrams of the seepage field; (a) gas pressure distribution and contours and (b) schematic of gas Darcy velocity

Analysis of gas migration under the temperature field in mining coal

Simulation result for the seepage field

As shown in fig. 2, in general, the gas pressure in the model gradually decreases from right to left. The pressure contours show that the closer to the working surface, the greater the gas pressure gradient is and the smaller the pressure gradient away from the working surface. The local Darcy velocity field of the model illustrates that the velocity near the gas working surface is greater than the velocity away from the working surface, and the closer to the working surface, the faster the velocity is.

Influence of mining face on seepage field

As shown in fig. 3, the permeability of the roof behind the working face is large, and the closer it is to the roadway, the greater the permeability of the roof; the permeability at the top and bottom of the working face decreases abruptly. Compared with the mining stress field near the working face, as shown in fig. 4, the distribution of seepage and dew near the working face is similar to the mining stress field to some extent. The greater the stress in the rock mass is, the smaller the permeability. Excavation leads to the redistribution of mining stress and the stress in the rock

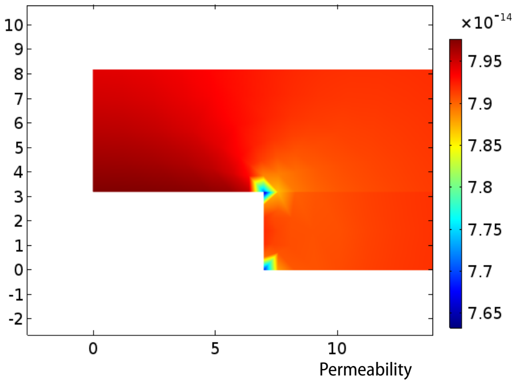

Figure 3. Permeability distribution near the working face

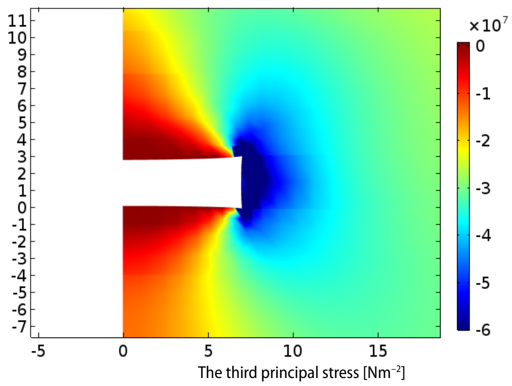

Figure 4. Mining stress field near the working face

strata. In places with high stress, the strata are compressed, and the porosity decreases, which leads to a decrease in permeability.

As shown in fig. 5, regardless of the steeply increasing stage of the rock stratum near the working face, the permeability increases significantly as the distance increases. As the distance from the working face increases, the permeability of the rock stratum increases significantly. At 20 m from the working face, the permeability change tends to be gentle. The larger the excavation length is, the faster the permeability increase in the first 20 m. For the rock layer 20 m from the front of the working face, the influence of the excavation length on the permeability is very small.

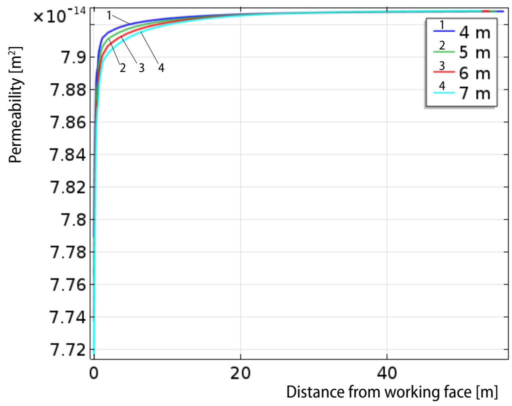

Figure 5. Permeability change in front of the working face at the different excavation distances

Influence of temperature on seepage field

As shown in fig. 6, when the temperature in the roadway is 313.15 K, the distribution of the adsorbed gas content is representative, and the adsorbed gas content approaches zero near the working face. As the distance from the working surface increases, the content of adsorbed gas gradually increases. The rock layer closer to the working surface has a larger gradient of the change in adsorbed gas content.

As shown in fig. 7, under different roadway temperature conditions, the contents of adsorbed gas in the rock layer in front of the working face are significantly different. The lower the temperature of the roadway is, the greater the change gradient of the adsorbed gas content near the working face is. The difference in the change gradient is mainly in the 20 m rock layer in front of the working face. After 20 m, the slopes of the curves corresponding to different temperatures are almost the same, indicating that the temperature has very little further effect.

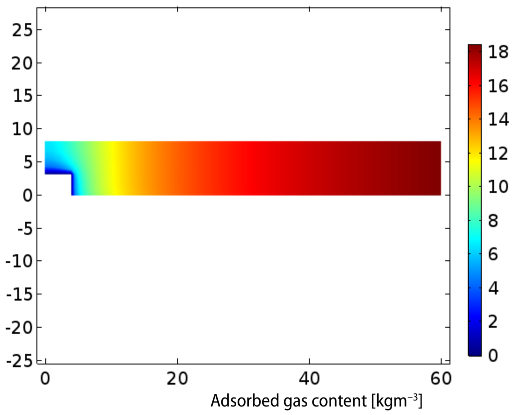

Figure 6. Distribution map of adsorbed gas content

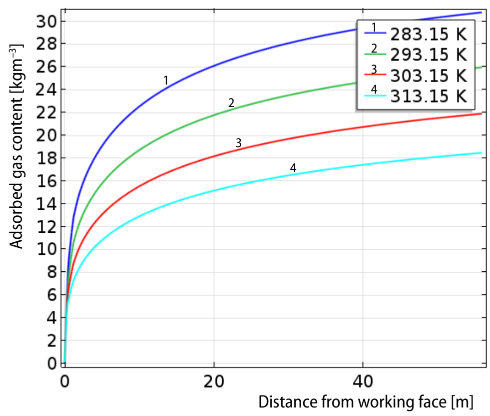

Figure 7. Adsorption gas content in front of working face at different roadway temperatures

Conclusion

Based on the solid mechanics theory, porous medium heat transfer theory and seepage theory, the deep mining face from mine No. 12 in the Pingdingshan Coal Mine was considered to analyze the effects of the mining stress field and the temperature field on the seepage field. The closer to the working surface, the greater the velocity of the seepage field is, and the greater the gradient of velocity change. The mining stress field has an important influence on the seepage field. The area with greater mining stress corresponds to the area with lower permeability, and the two factors are inversely related. Different excavation distances also have an effect on the seepage field. The influence range is within 20 m in front of the working face. The greater the excavation length is, the greater the gradient of the rock permeability near the working face. The temperature of the roadway and working face has an influence on the seepage field. At the same temperature, the rock layer closer to the working face has a larger gradient of change in adsorbed gas content. The difference in the change gradient occurs mainly within the 20 m rock layer in front of the working face.

Acknowledgment

The study was financially supported by National Natural Science Foundation of China (Grant No. 51822403. 51827901).

Nomenclature

c_{pL} – atmospheric heat capacity, [Jkg^{-1}K^{-1}]
K_Y – volume compression constant, [–]
k_0 – initial permeability, [m^2]
k_{eq} – thermal conductivity, [Wm^{-1}K^{-1}]
k – permeability, [m^2]
m – adsorbed gas content, [kgm^{-3}]
p_a – gas pressure in standard state, [MPa]
p_{L2} – Langmuir pressure constant, [MPa]
p – gas pressure, [MPa]
T_0 – coal seam temperature, [K]
T_a – Temperature in standard state, [K]
T – Experimental temperature, [K]
u – Darcy velocity, [ms^{-1}]
V_L – Langmuir volume constant, [m^{3}kg^{-1}]

Greek symbols

ε_v – volume strain, [–]
μ – dynamic viscosity, [Pas]
ρ_a – gas density in standard state, [kgm^{-3}]
ρ_c – coal density, [kgm^{-3}]
ρ – gas density, [kgm^{-3}]
ϕ_0 – initial porosity, [–]
ϕ – porosity, [–]

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Paper submitted: March 15, 2020
Paper revised: April 20, 2020
Paper accepted: May 1, 2020