THE DYNAMIC EVOLUTION ANALYSIS OF GAS SEEPAGE FIELD DURING THE MINING PROCESS OF PROTECTIVE LAYER

by

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The process of gas extraction by the protective layer mining is actually the multi-field coupling process. In this paper, the governing equations of the gas diffusion and seepage in the damaged coal and rock mass under the condition of the coupling action of gas and solid are established. A multi-field coupling analytical program is compiled by the FORTRAN language. The distribution and dynamic evolution law of the gas seepage field of the protected layer are calculated and analyzed. The result will provide the data support for the gas extraction design.

Key words*: gas-solid coupling model, gas seepage field, protective layer, FORTRAN program*

Introduction

Coal is the main source of energy in China, The gas disaster is the most frequent mine disaster in China's coal mines with the biggest casualties and losses accidents [1]. coal bed gas is a kind of harmful gas to the environment [2]. In addition, coalbed methane is also an economic, clean, convenient, efficient and non-renewable green energy. Therefore, the realization of simultaneous extraction of coal and gas is an important way to realize the efficient and green mining of coal resources and to ensure the security of energy in China [3].

Coal is a porous medium, mainly composed of solid particles, pores and fissures, and the pores and cracks in the coal are not only the storage places of gas, but also the flow passage of the gas. The process of gas extraction by the protective layer mining is also the multi-field coupling process of the damage field, stress field and gas seepage field of coal and rock. Therefore, it is necessary to study the dynamic evolution process of coal and rock damage field and the distribution law of gas seepage field under the condition of gas-solid coupling action in order to effectively guide the gas extraction. At present, many scholars have studied the gas-solid coupling mechanism. For example, Cheng *et al*. [4] studied the mechanism of gas-solid coupling and analyzed the distribution of the gas pressure. Zhang *et al*. [5] obtained the evolution process of the porosity and permeability as a result of the competition between the effective stress and gas adsorption. Zhao *et al*. [6] solved the problem of the gas migration in porous media by the finite element method. Wu *et al*. [2] proposed a theoretical model of the gas-solid coupling based on the relationship between the gas diffusion, seepage movement and

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coal seam deformation. In the engineering practice, it is difficult to directly measure the change of the porosity and permeability caused by the fracture and damage of the mining coal and rock mass, and the fracture and damage of the coal and rock materials have great influence on the gas migration state. In this paper, according to the degree of fracture and damage of coal and rock mass, the differential equation of the gas diffusion and seepage movement in damaged coal and rock mass is established. On the basis of this theory, a 3-D elastic computational program for the analysis of gas seepage law of the damaged coal and rock mass under the condition of the gas-solid coupling action is presented. Using this program, the dynamic mining process of the protective layer and gas seepage process is analyzed, and the distribution and dynamic evolution process of the damage field and gas seepage field are given.

The gas diffusion and seepage theory in damaged coal and rock mass

Deformation control equation of damaged coal and rock mass

In order to describe the dynamic evolution process of the damage in the coal and rock mass, the damage variable related to the strain in the unidirectional stress state, introduced in [7], is expressed:

$$\omega = \frac{\varepsilon_u(\varepsilon - \varepsilon_f)}{\varepsilon(\varepsilon_u - \varepsilon_f)} \quad \varepsilon_f < \varepsilon < \varepsilon_u \tag{1}$$

where ε_f is the threshold strain of coal damage evolution, and ε_u is the ultimate strain of damage evolution of coal and rock.

For the three direction stress state [8], the equivalent total strain can be expressed:

$$\varepsilon = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2}$$

the equivalent tensile strain:

$$\varepsilon_t = \sqrt{\sum \varepsilon_i^2}\,(\varepsilon_i > 0)$$

the equivalent pressure strain:

$$\varepsilon_c = \sqrt{\sum_j \varepsilon_j^2}\,(\varepsilon_j < 0)$$

and the total damage of the 3-D body can be given:

$$\omega = \alpha_t \omega_t + \alpha_c \omega_c \tag{2}$$

where $\alpha_t = (\varepsilon_t/\varepsilon)^2$ and $\alpha_c = (\varepsilon_{tc}/\varepsilon)^2$.

It is assumed that the damage of rock mass is mainly caused by the partial stress, and the constitutive equation of the damage of rock mass [9] can be suggested:

$$\sigma ij = (1-\omega)E_{ijkl}\varepsilon_{kl}^e + \frac{\omega}{3}\delta_{ij}E_{ppkl}\varepsilon_{kl}^e \tag{3}$$

where E_{ijkl} is the material parameter of coal and rock mass, ε_{kl}^e – the elastic strain, ω – the damage variable, and δ_{ij} – the Kronecker symbol.

The total stress of coal and rock mass is composed of two parts of gas pore pressure and effective stress, and the deformation and strength characteristics of the coal and rock mass containing gas is determined by the effective stress. According to the Terzagzhi effective stress principle, the effective stress can be given:

$$\sigma'_{ij} = \sigma_{ij} - \alpha p \delta_{ij} \tag{4}$$

where σ'_{ij} is effective stress, σ_{ij} – the total stress, and p – the pore pressure.

In 3-D equilibrium state, the differential equation of the coal and rock mass:

$$\sigma_{ij,j} + F_i = 0 \tag{5}$$

Substituting the effective stress eq. (4) into eq. (5) to obtain the differential equation of the skeleton deformation of the coal and rock mass:

$$\sigma_{ij,j} + F_i - (\alpha p \delta_{ij})_{,j} = 0 \tag{6}$$

Migration theory of gas in coal seam

Gas exists in two states of the adsorption and free states in coal seam. The adsorption gas obeys the Langmuir equation, and the free gas obeys the ideal gas state equation [2], *e. g.*

$$C' = \frac{abcpp_n M_g}{(1+bp)\mathrm{R}T} \tag{7}$$

$$\rho = \frac{pM_g}{\mathrm{R}T} \tag{8}$$

The total gas mass concentration in the coal seam is the sum of the mass concentration of the adsorbed gas and the mass concentration of the free gas, which can be written:

$$M = \frac{abcpp_n M_l}{(1+bp)\mathrm{R}T} + \frac{\varphi p M_g}{\mathrm{R}T} \tag{9}$$

where C' is the mass concentration of the absorbed gas in coal seam, p – the absorption equilibrium pressure, a – the limit adsorption capacity for unit mass combustibles under reference pressure, b – the absorption constant, c – the quality of combustibles in unit volume coal, p_n – reference pressure for measuring the content of gas (the standard atmospheric pressure or the air pressure in the roadway), R – the gas constant of the CBM, T – the temperature of coal seam, ρ – the density of free gas, M – the total mass concentration of gas, φ – porosity of coal seam, and M_g – mole mass of CH_4.

Control equation of gas diffusion motion in pore system of coal body

In the pore system of the coal body, the pore diameter is very small so that both the adsorbed gas and free gas are involved in the diffusion movements. The study shows that the Fick diffusion law is suitable for describing the process of the gas diffusion in the pore system, and the process of the gas emission from the coal particles is regarded as the diffusion of the gas in the porous medium. The migration law, which accords with the Fick diffusion law [10], can be given:

$$\mathbf{m}_f = -D_f \nabla C' \tag{10}$$

where $\mathbf{m}_f$ is the mass diffusion flux vector of the adsorbed gas, and D_f – the Fick diffusion coefficient.

The coal unit body is taken out of the coal seam per unit volume. According to the law of conservation of mass, the continuity equation of the gas diffusion in the coal seam can be given:

$$\frac{\partial C'}{\partial t} = -\nabla(\mathbf{m}_f) - q \tag{11}$$

where q is a negative exchange quality source.

If the quality source is $q = 0$, according to the eqs. (7), (10), and (11), the differential equation of the gas diffusion motion in the pore system of the coal body can be obtained:

$$\frac{abcp_n Mg}{(1+bp)^2 \mathrm{R}T}\frac{\partial p}{\partial t} = \nabla\left[D_f \frac{abcp_n M_g}{(1+bp)^2 \mathrm{R}T}\nabla p\right] - q \tag{12}$$

Control equation of gas seepage motion in the coal fractured system

In the fracture system of coal seam, the pore diameter of coal seam is larger, so it does not consider the diffusion motion of gas in pore surface, and the adsorption state of gas is desorbed instantaneously. Therefore, the gas both in the adsorption state and in the free state conforms to the Darcy's law of seepage flow, the equation can be given:

$$\mathbf{V} = -\frac{k}{\mu}\nabla p \tag{13}$$

where $\mathbf{V}$ is the seepage velocity vector of free gas, k – the permeability of the fracture system in the coal seam, μ – the dynamic viscosity of the gas in the coal seam, and p – the pressure of the free gas in the fracture system.

The coal unit body is taken out of the coal seam per unit volume. According to the law of conservation of mass, the quality variation of element volume per unit time is equal to the quality of unit time seepage into the element minus the quality of the outflow, coupled with the production of quality source. The continuity equation of the seepage motion in the fracture system can be written:

$$\frac{\partial(\varphi\rho)}{\partial t} = -\nabla(\rho\mathbf{V}) + q \tag{14}$$

According to the eqs. (8), (13), and (14), the differential equation of the seepage motion of the gas in the fracture system is obtained:

$$\frac{Mg}{\mathrm{R}T}\frac{\partial(\varphi p)}{\partial t} = \nabla\left(\frac{Mgkp}{\mathrm{R}T\mu}\right)\nabla p + q \tag{15}$$

Coupling action between the gas diffusion and seepage motion

If the coal is considered as the double medium of pore and crack, the two systems achieves the mass transfer through the mass exchange source. The diffusion and seepage motion of the gas are controlled by the concentration and influence each other, so that there is the coupling effect between the gas diffusion and the seepage. Adding the eqs. (11) and (14), and the continuity equation of the coupling effect of the gas diffusion and seepage motion can be given:

$$\frac{\partial(\varphi\rho)}{\partial t} + \frac{\partial C'}{\partial t} + \nabla(\rho\mathbf{V} + \mathbf{m}_f) = 0 \tag{16}$$

The differential equation of the mixed motion of the gas diffusion and seepage motion is derived:

$$\frac{abcp_n M_g}{(1+bp)^2 \mathrm{R}T}\frac{\partial p}{\partial t} + \frac{M_g}{\mathrm{R}T}\frac{\partial(\varphi p)}{\partial t} = \nabla\left(D_f^{\mathrm{eff}}\frac{abcp_n M_g}{(1+bp)^2 \mathrm{R}T}\nabla p + \frac{M_g kp}{\mathrm{R}T\mu}\nabla p\right) \tag{17}$$

Numerical simulation of engineering examples

Numerical model

The Wulan coal mine is one of the more serious coal and gas outburst mines. The mine has 17 minable layers, the main mining coal seams are 2#, 3#, 7#, and 8# coal seam. The 2# and 8# coal seams are outburst coal seams, and 3# and 7# coal seams are non-outburst coal seams.

According to the China's *coal mine safety regulations* stipulates: *no outburst and dangerous coal seam should be chosen as a protective layer with priority*, the 7# coal seam is first chosen as the mining protection layer, and it is not only the long distance protection layer of the 2# and 3# coal seam, but also the upper protective layer of the 8# coal seam. Then the 8# coal seam is mined so that it can be used as the lower protective layer of the 2# and 3# coal seams for two protections.

According to the actual situation of the mine as shown in fig. 1, a 3-D finite element model is established. The conditions of the numerical model are represented as follows: the alignment length of coal seam is 200 m, the sloping length of coal seam is 350 m, the length of model in the vertical direction is 300 m, and the dip angle of coal seam is about 20°. In the sloping direction, the working face width of the protective layer is 200 m, and there are 75 m coal pillars at each end of the working surface. Based on the above model, we use an eight-node hexahedral element to divide the grid. The total number of model units is 84240, and the total number of nodes is 90280. Before the coal seam is mined, the initial stress field is formed by the self-weight of the overlying strata.

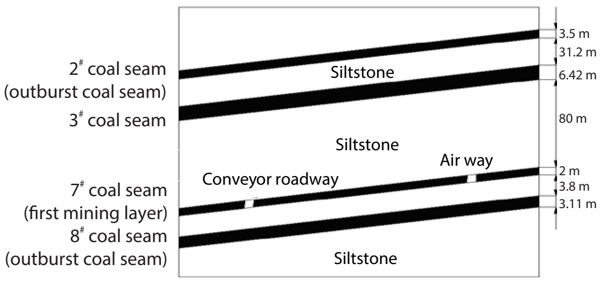

Figure 1. Geological distribution map of coal and rock mass

Permeability distribution and evolution characteristics of the protected layer

After the protective layer is mined, the collapse, bending and sinking of the overlying coal strata or the rupture, heaving of the underlying coal and rock layer are caused. The original fracture of the coal and rock mass is opened and expanded, and a large number of the new cracks are produced. It results in the remarkable increase of the permeability of the coal and rock mass. The changes in the permeability of the protective layer will directly affect the release of the gas pressure. Therefore, it is particularly important to study the change of the permeability of the protected layer with the mining of the protective layer. The permeability ratio curves along the sloping directions of the 2# and 3# coal

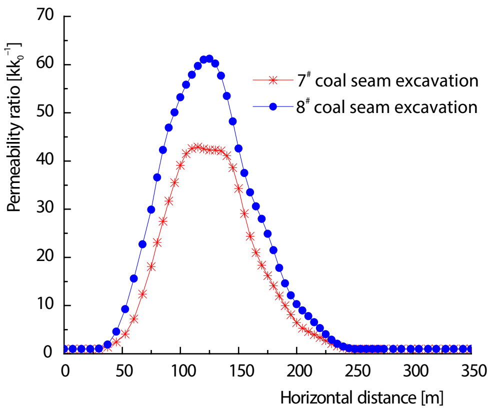

Figure 2. The permeability change curve of 2# coal seam along the sloping direction

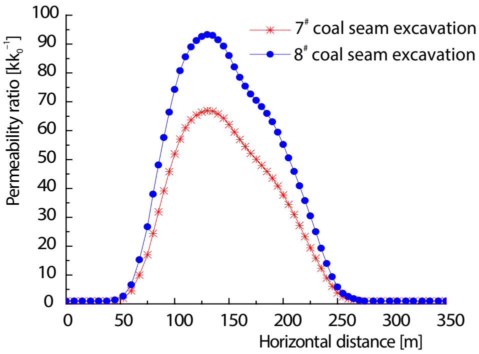

Figure 3. The permeability change curve of 3$^{\#}$ coal seam along the sloping direction

seams are shown in figs. 2. and 3, respectively. The permeability ratio curves of the 2$^{\#}$ and 3$^{\#}$ coal seams along the alignment direction are shown in figs. 4. and 5, respectively.

As illustrated in fig. 2, when the 7$^{\#}$ coal seam is mined, the permeability of the 2$^{\#}$ coal seam is increased, the maximum permeability ratio is up to 42. When the 8$^{\#}$ coal seam is mined, the permeability of the 2$^{\#}$ coal seam is further increased, the maximum permeability ratio increases to 64, which is 52.38% more than that of the 7$^{\#}$ coal seam. As shown in fig. 3, when the 7$^{\#}$ coal seam is mined, the maximum permeability ratio of the 3$^{\#}$ coal seam is increased to 65. When the 8$^{\#}$ coal seam is mined, the permeability ratio of the 3$^{\#}$ coal seam continues to increase, the maximum permeability ratio increases to 97, which is 49.2% more than that of the 7$^{\#}$ coal seam. From the above two diagrams, it can be seen that the pressure relief mining of the protective layer can significantly improve the permeability of the long distance-unloaded coal seam.

As shown in fig. 4, before the mining 50 m in the 7$^{\#}$ coal seam, the increase of the permeability of 2$^{\#}$ coal seam is not obvious. When the 7$^{\#}$ coal seam is mined for 100 m, the maximum permeability ratio of the 2$^{\#}$ coal seam increases to 39, and the permeability increases obviously. When the 8$^{\#}$ coal seam mined for 50 m, the maximum permeability ratio of 2$^{\#}$ coal seam is 49. With the mining time going on, when the 8$^{\#}$ coal seam mined for 100 m, the maximum permeability ratio of 2$^{\#}$ coal seam is 54, and the maximum value is located in the middle part of the goaf. As depicted in fig. 5, when the 7$^{\#}$ coal seam is mined for 75 m, the permeability ratio of 3$^{\#}$ coal seam has a small increase, the maximum permeability ratio is about 10. When the 7$^{\#}$ coal seam is mined for 100 m, the maximum permeability ratio of the 3$^{\#}$ coal seam increases to 29, and the permeability ratio increases obviously. When the 8$^{\#}$ coal seam is mined for 50 m, the permeability ratio is obviously increased to 68. When the 8$^{\#}$ coal seam is mined for 100 m, the maximum permeability ratio of the 3# coal seam is 89, which is 1.82 times of the 2$^{\#}$ coal seam.

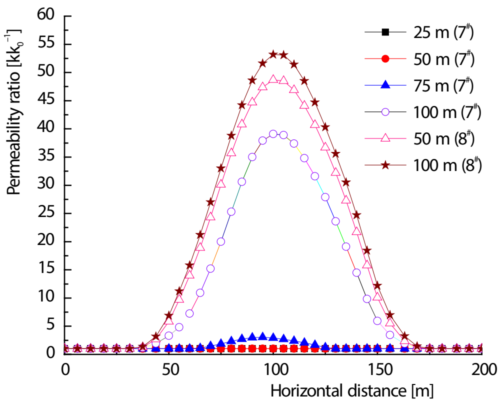

Figure 4. The permeability change curve of 2$^{\#}$ coal seam along the alignment direction

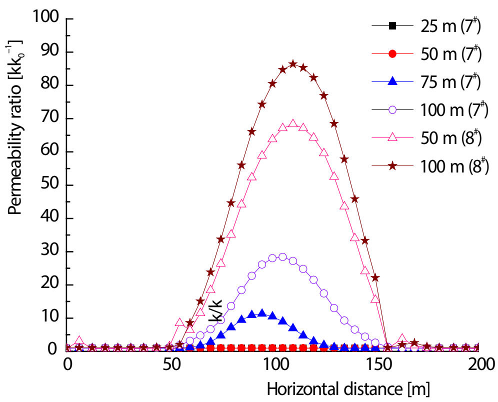

Figure 5. The permeability change curve of 3$^{\#}$ coal seam along the alignment direction

Analysis of pressure relief effect of protected layer

After the mining of the protective layer, the mining fissures are produced in the overlying strata and the long distance protected layer, these fractures provide a channel for gas migration. Under the action of gas pressure gradient, the gas gradually flows from the coal seam to the surrounding rock strata, resulting in the reduction of the gas pressure in the seam and the realization of the safe production of the outburst coal seam. The gas pressure distribution curves along the alignment direction of the 2# coal seam and the 3# coal seam are given in figs. 6 and 7, respectively.

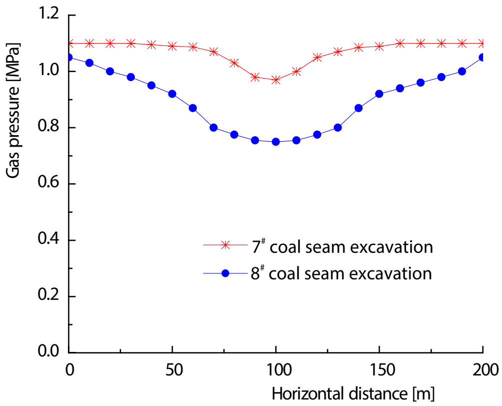

Figure 6. Gas pressure distribution curve of 2# coal seam along the alignment direction

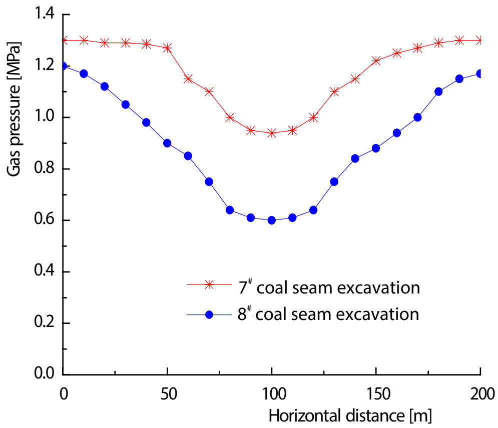

Figure 7. Gas pressure distribution curve of 3# coal seam along the alignment direction

As demonstrated in fig. 6, we can see that after the first mining of 7# coal seam, there are small cracks in the 2# coal seam, and some of the gas-flow into the rock layer, it leads to a certain reduction of gas pressure in coal seam, the minimum value is reduced to 0.98 MPa. With the continuous mining of 8# protective layer, the fracture field of the 2# coal seam and the surrounding rock layer is further expanded, the gas pressure of 2# coal seam is further reduced and the lowest is 0.75 MPa. As shown in fig. 7, it can be seen that after the first mining of the 7# coal seam, there are a lot of fractures in the 3# coal seam, the gas in the coal seam enters the rock stratum through the fissure, which reduces its own gas pressure. The minimum value of gas pressure appears in the middle part of the goaf, and the minimum value is 0.92 MPa. With the mining of 8# protection layer, the cracks in the 3# coal seam and the surrounding rock layer continue to expand, and the gas pressure decreases further. After the 8# coal seam is mined, the minimum gas pressure of 3# coal seam is reduced to 0.6 MPa. The results show that the mining of the protective layer is beneficial to the gas pressure relief of the remote protected layer, and the safe mining of the protected layer can be realized.

Conclusion

In our work, the finite element program for the analysis of the damage and gas pressure distribution in the coal and rock mass under the condition of the coupling action of the gas and solid was developed. Making use of the program, the dynamic evolution law of gas seepage field of the protected coal seam under the condition of double protective layer mining in the Ulan coal mine was calculated and analyzed. It provides a certain theoretical guidance for the simultaneous extraction of the coal and gas in the engineering. The main conclusions are as follows.

- The permeability of the 2# and 3# coal seams is greatly increased by the disturbance of the protection layer mining. After the first mining of 7# coal seam, the maximum permeability ratios of 2# and 3#coal seams reached 42 and 65, respectively. When 8# coal seam is mined, the maximum permeability ratios of 2# and 3# coal seams increased to 64 and 97.
- The increase of permeability is beneficial to the desorption and migration of the gas in coal seam.
- With the mining of the protective layer, there are a lot of the cracks in the protected coal seam and sorrounding rock mass.
- The gas in the coal seam flows into the surrounding rock layer, and the gas pressure of the coal seam is reduced. However, the gas content of the rock layer is gradually increased.
- According to the analysis results, the gas extraction in the rock layer can be effectively realized, and the simultaneous extraction of the coal and gas in the outburst coal seam can be realized.

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Nomenclature

E_{ijkl} – material parameter of coal and rock mass, [MPa]
k/k_0 – permeability ratio of coal seam, [–]
p – gas pore pressure, [MPa]

Greek symbols

φ – porosity of coal seam, [–]
ω – damage variable, [–]

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