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Numerical simulation on the coupling law of stress and gas pressure in the uncovering tectonic coal by cross-cut

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ABSTRACT

During the process of cross-cut coal uncovering, the stress and gas pressure of the coal mass change with time and even lead to coal and gas outburst. This paper establishes a coupled model that includes the equation of coal deformation, gas diffusion, gas seepage and permeability evolution based on the dual poroelastic theory. This model is applied into COMSOL Multiphysics numerical software. The distribution and evolution of the stress and gas pressure in front of the working face can be obtained from the numerical results. The stepped increase mechanism of the combined potential energy in the tunneling process is proposed, which is used to analyze the evolution of elastic potential energy and gas potential energy. The results can be summarized as follows: under natural conditions, an obvious abnormal stress area occurs near the fault, and the stress of the coal seam is greater than that of the rock stratum. Under tunneling conditions, a original stress (OS), stress concentration (SC) and stress reduction (SR) are formed successively in the front of the working face. And correspondingly, the gas accumulates in SC due to the closure of cracks. The distributions of gas pressure p_f and p_m are approximately the same during tunneling, and they can reach an equilibrium state after 300 days. The coupled effects of stress and gas pressure gradually intensify, so the elastic potential energy and the gas potential energy of the coal continuously accumulate. The combined potential energy of coal increases with tunneling length, and an outburst is very likely to occur when the combined energy exceeds the surface energy of the coal body at the "Key point". This research is helpful to understand the evolution mechanism of stress and gas pressure of coal seam in the process of cross-cut coal uncovering, and to know the effects of it to the dynamic disaster.

1. Introduction

Gas outbursts are sudden, violent blowouts of coal and gas from a solid coal seam into a mine entrance. These dangerous incidents have occurred in most coal producing countries.[1] In China, coal and gas outbursts have always been major disasters that influence safe coal production.[2] Due to the different types of roadways, the conditions of outbursts are not always the same. Although cross-cut coal uncovering does not have the largest quantity of outbursts, it does result in the greatest outburst intensity.[3] Currently, Chinese coal mines are being deepened at an annual rate of 20–50 m. The depths of many coal mines are predicted to reach 1000–1500 m in 20 years.[4–7] With increasing mining depth, the risk of cross-cutting increases, which seriously threatens the safety and economic benefits of coal mines.

In recent years, many scholars have used numerical simulations to study the mechanisms of coal and gas outbursts. Paterson[8] established the gas flow equation, stress equation and failure criterion and used a finite element program to research the influence of gas flow in one-dimensional and two-dimensional coal seams, coal face propulsion, and coal seam permeability and strength on coal and gas outbursts. Valliappan and Zhang[9] and Dziurzyński and Krach[10] proposed the solid-fluid coupled model of coal and gas outbursts based on the relevant theory and conducted numerical analysis on the coal bed gas flow. Based on the unified theoretical model of outbursts and rock bursts,[11] Zhao[12] and Zhao et al.[13] presented a mathematical model and numerical solution for a coal-gas coupled model. Liang[14] conducted a numerical analysis on the solid-fluid instability in coal and gas outbursts. Many studies[15–21] show that stress or gas pressure plays an important role in outburst disasters. These studies have inspired scholars to study the mechanisms of coal and gas outbursts induced by cross-cut coal uncovering. Han and Shi[22] used the FLAC3D software to simulate the changes in underground stress during the process of cross-cut coal

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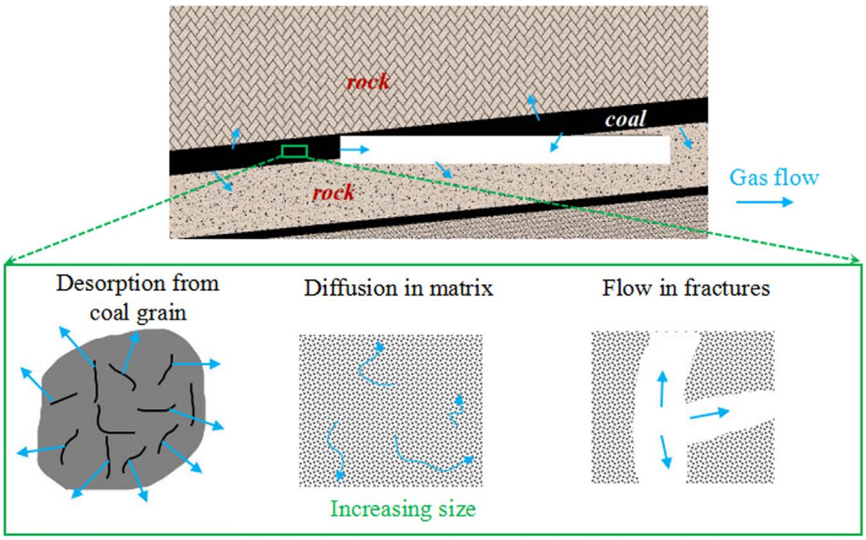

Fig. 1. Flow process of gas in the coal above the roadway.

uncovering and analyzed the stress distribution around the roadway. Gao et al.[23] used COMSOL Multiphysics software to analyze the role of underground stress in the process of cross-cut coal uncovering. Yu et al.[24] used MATLAB software to analyze the effect of releasing gas expansion energy on outbursts during the process of cross-cut coal uncovering. Tang and Liu[25] used the PFPA2D system to numerically simulate outbursts in steep coal seams during the process of cross-cut coal uncovering and analyzed the effects of underground stress and gas pressure on inducing outbursts.

Although the above models have achieved a certain degree of success in analyzing the stress or gas pressure distributions and trends during the process of cross-cut coal uncovering, few studies have considered the dual porosity of coal. There are many porosities and fractures in natural coal, and most of the gas is stored in the form of an adsorbed layer in the micropores rather than as free gas in the pore space.[26,27] The coal above the roadway is destroyed by tunneling in the cross-cut of the coal seam; then, the gas moves into nearby rock formations or mined-out areas in two stages (Fig. 1): (1) gas flows through the cleat system in a laminar pattern, as described by Darcy's law of fluid flow; (2) diffusion occurs within the coal matrix due to the concentration gradient, following Fick's law of diffusion. This process leads to the changes in the gas pressure of the fractures and the matrix.[28]

Therefore, this study establishes a coupled model that includes the coal seam deformation equation, gas seepage equation, gas diffusion equation and permeability evolution equation. The stress and gas pressure during the process of cross-cut coal uncovering are numerically simulated and analyzed using COMSOL Multiphysics software based on the complex geologic conditions of Qianjiaying Mine. In addition, the influences of stress and gas pressure on coal and gas outbursts are analyzed from the energy perspective. A new viewpoint is proposed to describe the variation of the combined energy in front of the face during the process of cross-cut coal uncovering.

2. Coupled model

2.1. Basic assumptions

The following assumptions are considered in the model: (1) coal and rock have dual poroelastic and isotropic continuums, and the coal skeleton experiences elastic deformation; (2) the movement of gas in the coal and rock mass is regarded as an isothermal process; (3) coal is saturated with gas, and the original gas pressure in the coal is evenly distributed; (4) the coal fractures are filled with free gas, and the gas in the matrix exists in both the free state and the adsorbed state; and (5) the gas seepage in the fracture satisfies Darcy's law, and the gas diffusion in the matrix satisfies Fick's law (assuming that the amount of gas directly entering the borehole or roadway by diffusion is small).

2.2. Equations

2.2.1. Coal seam deformation

The deformation field equation is composed of the stress balance equation, geometric equation and constitutive equation. The stress balance equation can be expressed as:

$$\sigma_{ij,j} + F_i = 0 \tag{1}$$

where F_i is the body force, MPa, and subscripts i and j indicate the main directions.

The geometric equation is defined as:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{2}$$

where ε_{ij} is the strain component ($i, j = 1, 2, 3$) and u_i is the displacement component in the i-direction. Based on Hooke 's law, the constitutive equation can be expressed as[29]:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \frac{2Gv}{1-2v}\varepsilon_V\delta_{ij} - \beta_f p_f \delta_{ij} - \beta_m p_m \delta_{ij} \tag{3}$$

where $G = E/2(1+v)$ and is the shear modulus of the coal, MPa; $\varepsilon_V = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$; E is the Young's modulus of the coal, MPa; v is the Possion's ratio of the coal; ε_V is the volumetric strain of the coal matrix; δ_{ij} represents the Kronecker variables (i = j take 1, i ‡ j take 0); p_f and p_m are the gas pressure of the fracture and the matrix, respectively, MPa; and β_f and β_m are the Biot coefficients for the fractures and the matrix, respectively. These Biot coefficients can be calculated as follows[30]: $\beta_f = 1 - K/K_m$ and $\beta_m = K/K_m - K/K_s$ where K, K_m and K_s are the bulk modulus of the coal, coal grains and coal skeleton, respectively, MPa. The bulk modulus can be calculated as follows[31]:

$$K = \frac{E}{3(1-2v)} \tag{4}$$

$$K_m = \frac{E_m}{3(1-2v)} \tag{5}$$

$$K_s = \frac{K_m}{1 - 3\varphi_m(1-v)/[2(1-2v)]} \tag{6}$$

where E_m is the Young's modulus of the coal grains, MPa, and φ_m is the porosity of the coal matrix, %. Combining Eqs. (1)–(3), the Navier-type equation for coal seam deformation can be expressed as: