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Gas-solid coupling laws for deep high-gas coal seams

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ABSTRACT

A better understanding of gas-solid coupling laws for deep, gassy coal seams is vital for preventing the compound dynamic disasters such as rock burst and gas outburst. In this paper, a gas-solid coupling theoretical model under the influence of ground stress, gas pressure, and mining depth is established and simulated by using COMSOL Multiphysics software. Research results indicate that under the influence of factors such as high ground stress and gas pressure, the mutual coupling interaction between coal and gas is much more significant, which leads to the emergence of new characteristics of gas compound dynamic disasters. Reducing the ground stress concentration in front of the working face can not only minimize the possibility of rock burst accidents, which are mainly caused by ground stress, but also can weaken the role of ground stress as a barrier to gas, thereby decreasing the number of outburst accidents whose dominant factor is gas. The results have a great theoretical and practical significance in terms of accident prevention, enhanced mine safety, disaster prevention system design, and improved accident emergency plans.

1. Introduction

Most coal mines in China have reached deep deposits, and thus, the interaction between the constantly increasing coal seam ground stress, gas content, and gas pressure is blamed for the increased occurrence of gas compound dynamic catastrophes, as well as some new emergent disaster characteristics [1–5]. Based on investigations concerning gas compound dynamic catastrophes in high-gas coal seams that have occurred in recent years, it has been discovered that there are obvious rock burst manifestations such as roof collapse, floor heave, and roadway deformation (often accompanied by high levels of gas gushing) at the scene of this new type of gas compound dynamic disasters [6–9]. Moreover, there are some gas outburst holes at the scene and coal rock is ejected far away from these holes. Several distinctive features of gas outburst can be found in these accidents. All these illustrate that the coupling interaction between coal and gas in deep high-gas coal seams is more significant, which results in the emergence of new features of gas compound dynamic disasters [10–15].

Investigations aimed at coupling laws were made by domestic and foreign scholars. Litwiniszyn et al. studied the coupling interaction between coal and gas as well as gas migration law from different angles [16]. Liu et al. built a mathematical model for gas-solid coupling which takes gas-coal swelling deformation into account [17]. Zhao et al. took the lead in proposing a new mathematical model of the coupling reaction between coal rock and gas and further analyzed the numerical method [18]. Zhao et al. came up with the instability theory of gas outburst, and established a mathematical model based on the coupling relationship of a gas-solid two-phase medium [19]. Liang et al. set up a coal rock constitutive model which takes the gas interaction into account from the intrinsic time angle [20]. Meanwhile, they proposed a destabilization theory of gas outburst/rock burst and established the mathematical model. Considering the fracture evolution process in coal, Yang et al. developed a gas-solid coupling model of coal seam containing damage, and then simulated the gas drainage process in a deep coal seam [21]. Xu et al. studied the numerical simulation of coal and gas outburst by using the relevant theory of fluid-solid coupling [22]. Valliappan et al. established a fluid-solid coupling model for the flow of coal-seam gas and compiled the corresponding finite element computer program to simulate the process of coal and gas outburst [23].

Mainly aimed at the characteristics of high-gas coal seams in deep mining, this paper simulates the laws of gas-solid coupling

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in coal-bed gas under the influence of gas pressure, mining depth, and other factors. The influencing factors of gas compound dynamic disasters of coal rock in gassy seams are then analyzed. The results have a great theoretical and practical significance in terms of accident prevention, enhanced mine safety, disaster prevention system design, and improved accident emergency plans.

2. Gas-solid coupling theory of coal-bed theory

For ideal gas, the content of adsorbed gas satisfies the Langmuir equation and the gas seepage process conforms to Darcy's law. Per the law of conservation of mass at the same time, the following equations can be written, ignoring the effect of gravity.

(1) State equation of gas

The state equation of gas is obtained based on the state equation of ideal gas.

$$\rho_g = \frac{M_g p}{RTZ} \tag{1}$$

With temperature being constant, then

$$\rho_g = \frac{\rho_n}{p_n} p \tag{2}$$

where p is gas pressure, MPa; ρ_g the gas density, kg/m^3, when the pressure is equal to p; M_g the molar volume of gas, mol/L; R the molar gas constant, kg/(m^3·MPa); Z the compressibility factor, and the value is approximately equal to 1 when the temperature variation is not vast; T the absolute temperature, K; p_n the gas pressure in standard state, MPa; and ρ_n the gas density in standard state, kg/m^3.

This can be simplified as:

$$\rho_g = \beta p \tag{3}$$

(2) Gas content model

Gas in coal beds can be divided into two states; absorbed gas (Q1), that is absorbed between micropore surface and coal particles, free gas (Q2), which flows freely in pore fissure space. When adsorbed gas content satisfies the Langmuir equation, then absorbed gas content formula of unit coal can be written as

$$Q_1 = c\rho_c\rho_0 \frac{abp}{1+bp} \tag{4}$$

where ρ_c is the density of coal, kg/m^3; ρ_0 the density of gas under normal atmospheric pressure, kg/m^3; a and b are Langmuir adsorption coefficient, the value of a ranges from 10 to 60 with the dimension of m^3/t, and the value of b ranges from 0.5 to 5 with the dimension of MPa^{-1}; c the correction coefficient when considering factors such as coal moisture and ash temperature, and the value of c ranges from 0 to 1.

Free gas content of unit coal can be expressed as:

$$Q_2 = \phi\rho_g \tag{5}$$

where ϕ is the coal porosity, which is dimensionless.

The total gas content of unit coal is:

$$Q = Q_1 + Q_2 = c\rho_c\rho_0 \frac{abp}{1+bp} + \phi\rho_g \tag{6}$$

The operator form is shown as follows:

$$\frac{\partial Q}{\partial t} = -\nabla(\rho_g u) + Q_m \tag{7}$$

Gas seepage process conforms to Darcy's law and ignores the effect of gravity. Thus,

$$u = -\frac{k}{\mu}\nabla p \tag{8}$$

where is the permeability of coal seam, m^2; and μ the gas viscosity, Pa·s.

(3) Porosity evolution model

Ignoring the change of temperature and gas adsorption, the evolution equation for coal porosity is

$$\phi = 1 - \frac{1-\phi_0}{1+\varepsilon_v}(1 - K_Y\Delta p) \tag{9}$$

where ϕ and ϕ_0 are the coal porosity and original porosity, dimensionless; K_Y the coefficient of volume compressibility, dimensionless; Δp the pressure changes of gas, MPa; and ε_v the volumetric strain of coal, dimensionless.

(4) Permeability evolution model

Coal is a dual-porosity reservoir where gas is mostly stored in the coal matrix and Darcy fluid flow occurs in the natural fracture system. The flow capacity of fracture media depends almost entirely on the number and width of fractures and their continuity in the direction of flow. Permeability, a measure of the flow capacity, is directly related to a range of pore characteristics including pore size, continuity, and connectivity. It is generally believed that the change of coal permeability is dictated by coal porosity. The Kozeny-Carman equation, which is based on the capillary model, is most widely used [24]. The permeability evolution model is

$$k = \frac{k_0}{1+\varepsilon_v}\left[1 + \frac{\varepsilon_v}{\phi_0} + \frac{(1-\phi_0(K_Y\Delta p)}{\phi_0}\right]^3 \tag{10}$$

3. Numerical simulation of gas-solid coupling in deep high-gas coal seams

The general purpose, finite element analysis using COMSOL Multiphysics software was adopted to calculate the established gas-solid coupling model. The geometry of the numerical model is 80 m long, 30 m high, and its roof height, floor height and coal seam height is 15, 10, and 5 m. The roadway was excavated from the left to the right in the coal seam, the displacements in the floor of the model as well as the both sides were zero, the vertical stress of 16.4 MPa was applied to the model.

3.1. Model input parameters

Taking the actual situation of high-gas coal mines in China as an example, the model input parameters are selected, as shown in Tables 1 and 2.

Table 1
Parametric values of coal and surrounding rock.

Variable	Value
Coal density ρ_1 (kg/m^3)	1250
Coal elastic modulus E_1 (MPa)	2713
Coal Poisson's ratio v_1	0.339
Coal cohesion c_1 (MPa)	1.25
Coal internal friction angle θ_1 (rad)	37π/180
Surrounding rock density ρ_2 (kg/m^3)	2640
Surrounding rock elastic modulus E_2 (MPa)	33,400
Surrounding rock Poisson's ratio v_2	0.235
Surrounding rock cohesion c_2 (MPa)	3.2
Surrounding rock internal friction angle θ_2 (rad)	π/6