International Journal of Mining Science and Technology 26 (2016) 637–643

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Effect of protective coal seam mining and gas extraction on gas transport in a coal seam

Yao Banghua [a,b,c], Ma Qingqing [a,b], Wei Jianping [a,b,c,*], Ma Jianhong [c], Cai Donglin [a,b]

[a] State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo 454000, China
[b] School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China
[c] Collaborative Innovation Center of Coal Work Safety of Henan Province, Jiaozuo 454000, China

ARTICLE INFO

Article history:
Received 20 November 2015
Received in revised form 7 January 2016
Accepted 18 March 2016
Available online 24 May 2016

Keywords:
Protective coal seam mining
Seepage characteristic
Coal and gas outburst
Numerical simulation

ABSTRACT

A gas–solid coupling model involving coal seam deformation, gas diffusion and seepage, gas adsorption and desorption was built to study the gas transport rule under the effect of protective coal seam mining. The research results indicate: (1) The depressurization effect changes the stress state of an overlying coal seam and causes its permeability to increase, thus gas in the protected coal seam will be desorbed and transported under the effect of a gas pressure gradient, which will cause a decrease in gas pressure. (2) Gas pressure can be further decreased by setting out gas extraction boreholes in the overlying coal seam, which can effectively reduce the coal and gas outburst risk. The research is of important engineering significance for studying the gas transport rule in protected coal seam and providing important reference for controlling coal and gas outbursts in deep mining in China.

1. Introduction

Coal and gas outburst is a dynamic disaster in which broken coal and gas erupt into the working face from a coal body under the combined action of ground stress and coal gas pressure. Presently, as mining activity has rapidly developed to increasingly deeper ground, there have been an increasing number of coal and gas outburst accidents in China. According to statistics, there are 576 state-owned key coal mines which include 277 gassy coal mines which are prone to gas outburst and which account for over 48% of total accidents. In 1976, about 20.2% of deaths in coal mining accidents were caused by coal and gas outbursts, while this number sharply increased to 54% in 2000, and in 2013 alone, there were 69 severe coal and gas outburst disasters in China, causing 1326 fatalities. Therefore, coal and gas outburst accidents have become a serious problem which threatens and influences the safety of mining in many areas of China.

In order to safely, economically and effectively prevent coal and gas outburst, many researchers in China have performed much useful work and proposed many useful preventive measures, in which protective coal seam mining is the most cost-effective method of preventing coal and gas outburst. Fig. 1 is a schematic diagram illustrating the application of protective coal seam mining, in which d denotes the working face advance distance, L_1 illustrates the depressurization area in the protected coal seam, H is the distance between protective coal seam and protected coal seam, while θ is the depressurization angle, where $\theta = \arctan(H/l)$.

In 1933, coal mines in France successfully adopted protective coal seam mining as a measure to prevent coal and gas outburst, and from then on, this method has been widely applied in countries such as the former Soviet Union, Poland, and Germany. Since 1958, many coal mines in China have carried out studies on protective coal seam mining in coal fields including Beipiao, Nantong, Tianfu, Zhongliangshan, and Songzao, and have made good progress in improving this method. Recently, many researchers in China have carried out many studies on the effectiveness of protective coal seam mining on coal and gas outburst prevention from various aspects including: overlying rock mass deformation and movement characteristics, depressurization range, coal and gas co-mining, gas transport rules. For instance, Yang et al. established a coupled stress-damage-flow model, which combined the evolution of stress, damage, gas permeability and deformation of coal and rock, and investigated the deformation and fracture characteristics of the overburden strata, the evolution of gas permeability and gas flow in target coal seams [1]. Yang et al. developed an equation correlated with normal stress and permeability and used FLAC (3D) software to investigate rock mass stress evolution and distribution to understand the methane flow characteristics, obtaining the division of "three belts and five zones" as well as

* Corresponding author. Tel.: +86 391 3987885.
E-mail address: hpuwjp@163.com (J. Wei).

http://dx.doi.org/10.1016/j.ijmst.2016.05.016
2095-2686/

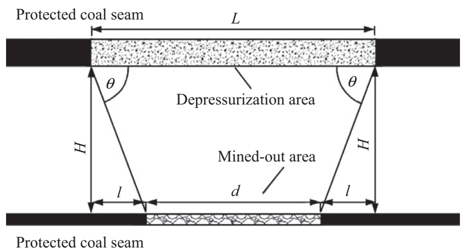

Fig. 1. Schematic diagram of protective coal seam mining.

the rock mass stress and permeability distribution and evolution [2]. Liu et al. studied and analyzed the simulation of far-distance-lower-protective-layer mining by using the similar material simulation test in the laboratory and found the dynamic evolution law of overlying coal fractures, analyzing the progress of fracture evolution including cracking, extensional cracking, fracture shrinking and turning small, fitting, and closing [3]. Hu et al. carried out numerical simulations of protective coal seam mining and analyzed the protected coal seam gas pressure distribution, obtaining the depressurization range in the protected coal seam [4]. According to the damage characteristics of coal and rock, Gao et al. defined the damage variable of coal and rock structures, and established the corresponding elastic–plasticity damage constitutive equation, and completed the secondary development of the finite element program. The example of Wulan coal mine with double protective seam mining was then calculated and analyzed by this new program, and the change laws of damage degree and permeability coefficient in protected coal seams were given [5]. Other papers also provided useful references for our study [6–13]. However, these investigations were mainly carried out with respect to structural failure, and only a small number of researchers have investigated this problem from the perspective of gas–solid coupling, and few of them consider the effective combined action of protective coal seam mining and borehole drainage on coal and gas outburst risk of protected coal seams.

In this paper, based on the corresponding research results and theory, a gas–solid coupling model involving coal seam deformation, gas diffusion and seepage, gas adsorption and desorption was built and then applied to the engineering practice of protective coal seam mining, thus obtaining the gas transport characteristics under the depressurization effect of protective coal seam mining. Our research has significant meaning for revealing the mechanism of the depressurization effect of protective coal seam mining and preventing future coal and gas outburst accidents involving protective coal seam mining.

2. Coupling model development

2.1. Basic assumptions

Before the fluid–solid coupling model, which includes coal deformation and gas transport, is established, some assumptions are made as follows:

(1) Coal is an isotropic and elastic porous medium.
(2) Strains are much smaller than the length scale.
(3) Gas contained within the pores is in an ideal state, and its seepage in coal obeys Darcy's law.
(4) Gas in coal seam obeys the Langmuir sorption equation.

2.2. Coal deformation equation

The equilibrium differential equation with self-weight and neglecting inertial effects can be expressed as:

$$\sigma_{ij,j} + f_i = 0 \quad (i = 1,2,3;\ j = 1,2,3) \tag{1}$$

where σ_{ij} is the component of stress tensor, and f_i is the component of body force.

The strain component and displacement should satisfy the geometrical equation:

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

where ε_{ij} is the component of strain tensor, and u_i are displacement components.

According to the elastic theory of a porous medium, the constitutive equation for coal under a sorption effect can be expressed as:

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij} + \frac{\alpha}{3K}p\delta_{ij} + \frac{\varepsilon_s}{3}\delta_{ij} + \frac{\alpha_s \Delta T}{3}\delta_{ij} \tag{3}$$

where ε_{ij} is a component of the strain tensor, σ_{ij} is a component of the stress tensor, G is the shear stiffness, δ_{ij} is the Kronecker delta (i, $j = x, y, x$), α is the Biot coefficient [14] where $\alpha = 1 - K/K_s$, K_s is the grain elastic modulus, K is the bulk modulus of coal, $\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}$ are the components of the mean stress, α_s is the thermal expansion coefficient, ΔT is the temperature increment, ε_s is the gas sorption-induced strain, and its expression is [15–17]:

$$\varepsilon_s = \frac{\varepsilon_L p}{P_L + p} \tag{4}$$

where ε_L is the Langmuir-type swelling/shrinkage constant and P_L is the Langmuir pressure constant.

According to Eqs. (1)–(4), the coal seam equilibrium differential equation can be expressed as:

$$Gu_{i,kk} + \frac{G}{1-2v}u_{k,ki} - \alpha_s KT_{,i} - \alpha p_{,i} - K\frac{\varepsilon_L P_L}{(p+P_L)^2}p_{,i} + f_{,i} = 0 \tag{5}$$

Eq. (5) is the governing equation for coal deformation in which $\alpha p_{,i}$, $\alpha_s KT_{,i}$ and $K\frac{\varepsilon_L P_L}{(p+P_L)^2}p_{,i}$ reflect the effect of gas flow, temperature and gas adsorption on coal deformation respectively.

2.3. Gas flow equation

The mass balance equation for the gas phase is defined as:

$$\frac{\partial m}{\partial t} + \nabla \cdot (\rho_g q_g) = Q_s \tag{6}$$

where ρ_g is gas density, q_g denotes the Darcy velocity vector, Q_s is the gas source, t is the time and m represents the gas mass in unit volume (including free and absorbed gas) and can be expressed as:

$$m = \rho_g \phi + \rho_{ga}\rho_c \frac{V_L p}{p + P_L} \tag{7}$$

where ρ_{ga} is the gas density under normal atmospheric conditions, ρ_c is the coal density and ϕ is the porosity.

According to the ideal gas law, the density of free gas can be expressed as:

$$\rho_g = \frac{M_g}{RT}p \tag{8}$$

where M_g is the gas molecular mass, R is a gas constant, T denotes the absolute gas temperature. Neglecting the gravity effect, the Darcy velocity q_g can be expressed as:

$$q_g = -\frac{k}{\mu}\nabla p \tag{9}$$

where k is the coal permeability and μ is the coefficient of dynamic viscosity of the gas.