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Gas seepage equation of deep mined coal seams and its application

HU Guo-zhong, WANG Hong-tu, TAN Hai-xiang, FAN Xiao-gang, YUAN Zhi-gang

Key Lab for Exploitation of China Southwestern Resources & Environmental Disaster Control Engineering, Ministry of Education, Chongqing University, Chongqing 400030, China

Abstract: In order to obtain a gas seepage law of deep mined coal seams, according to the properties of coalbed methane seepage in in-situ stress and geothermal temperature fields, the gas seepage equation of deep mined coal seams with the Klinkenberg effect was obtained by confirming the coalbed methane permeability in in-situ stress and geothermal temperature fields. Aimed at the condition in which the coal seams have or do not have an outcrop and outlet on the ground, the application of the gas seepage equation of deep mined coal seams in in-situ stress and geothermal temperature fields on the gas pressure calculation of deep mined coal seams was investigated. The comparison between calculated and measured results indicates that the calculation method of gas pressure, based on the gas seepage equation of deep mined coal seams in in-situ stress and geothermal temperature fields can accurately be identical with the measured values and theoretically perfect the calculation method of gas pressure of deep mined coal seams.

Key words: deep mining; in-situ stress field; geothermal temperature field; gas seepage equation of coal seam; gas pressure

1 Introduction

Investigations into coalbed methane seepage equations and laws have led to a number of research results[1–11]. These studies mostly aimed at either a single physical or in-situ stress fields or at geothermal temperature fields. However, they failed to take into account the Klinkenberg effect, these studies cannot reflect perfectly coalbed methane seepage in deep mined coal seams. Given the increasing exhaustion of the superficial resources of coal mines, the mining depth of most mines increases gradually. Coal can be regarded as a porous and tight medium contained gas due to the impact of the high in-situ stress in the process of mining deep coal seams. The Klinkenberg effect, which exists in coalbed methane seepage, is especially prominent in this case. For the Klinkenberg effect, scientists carried out a great deal of studies[12]. A gas field seepage model incorporating the Klinkenberg effect was established by Wang et al. in 2003[13]. The method confirming the critical conditions without Darcy seepage under low gas permeability, was proposed for mass test studies by Liu et al[14]. A few years earlier, Wu et al. in 1998 and Skjetne and Auriault a year later accounted for the Klinkenberg effect with theories and experiments[15–16], but due to the complexity of coalbed methane seepage, they ignored the common effect of in-situ stress and geothermal temperature fields.

Gas pressure is the basic parameter of coalbed methane. The distribution of gas pressure of coalbed methane plays an important role in studying coal and gas outburst, in the occurrence and emission law of coal seams and in evaluating gas content and gas extraction. Over the years the investigations into coalbed methane pressure have led to some experimental and theoretical results[17–19]. These research results indicated that coalbed methane pressure depends on in-situ stress. Some experimental linear relationships have been established between coalbed methane pressure and depth, with properties which facilitate applications for coal seams under normal geological conditions. Therefore, the distribution of in-situ stress and geothermal temperature fields of deep mined coal seams are uneven. In-situ stress and geothermal temperatures at different locations at one level or differ-

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Corresponding author. Tel: +86-23-65111237; E-mail address: gzhu@cqu.edu.cn

ent locations at one depth of coal seams may be very distinctive, which makes for a nonlinear distribution of coalbed methane pressure as a function of depth. The in-situ stress field, geothermal temperature field and the Klinkenberg effect should be considered when analyzing the changing law of gas pressure of deep mined coal seams. Hence, given the seepage properties of coalbed methane affected by in-situ stress and geothermal temperature fields, the primary purpose of our study was to derive theoretically the gas seepage equation of deep mined coal seams in in-situ stress and geothermal temperature fields when the Klinkenberg effect is taken into account and to analyze the application of this seepage equation on gas pressure calculation of deep mined coal seams.

2 Permeability of coalbeds

Besides structure and quality of coal[8], the gas seepage properties and flow laws of deep mined coal seams are related to the Klinkenberg effect, as well as to in-situ stress and geothermal temperature fields. It is a complex physical phenomenon, sharing mutual effect and infiltration that in-situ stress and geothermal temperature fields affected the substances occurring in geologic bodies. Previous research has shown that gas permeability of coal is sensitive to stress; at the same time, the gas permeability of coal depends on the change of coalbed temperature. Thus, gas permeability of coal is dependent on stress and temperature, i.e., conditions under which the Klinkenberg effect is negligible. By adopting the variable separation approach, the absolute gas permeability $K_\infty(\sigma,T)$ without the Klinkenberg effect can be expressed as[19–21]:

$$K_\infty(\sigma,T) = k(1+T)^{\alpha_3}\,\mathrm{e}^{-\alpha_2\sigma} \tag{1}$$

in which $\sigma = (\sigma_1 + 2\sigma_3)/3 - P$, where σ_1 and σ_3 are, respectively, the axial pressure and confining pressure of three-axis loading, (Pa); α_2, α_3 are constants confirmed by experiments and $k = k_0^\sigma k_0^T$, where k_0^σ is the permeability of coal seam when the effective stress σ is equal to 0, k_0^T is the permeability of coal seam when the temperature of the coalbed is theoretically equal to 0.

According to the Klinkenberg effect, the effective gas permeability, depending on gas pressure, is given by[22]

$$K_\mathrm{g} = K_\infty(1+\frac{b}{P}) \tag{2}$$

in which K_g is the effective gas permeability of coal seams (m^2), K_∞ is the absolute gas permeability under very large gas pressure (m^2), a condition under which the Klinkenberg effect is negligible, P is the coalbed methane pressure; $P = (p_1 + p_2)/2$, where p_1 and p_2 are the gas pressure of the top and bottom of the coal sample (Pa) and b is the Klinkenberg factor (Pa). As early as 1980, Jones and Owens[23] fitted b to be

$$b = \alpha_1 K_\infty^{-0.36} \tag{3}$$

in which α_1 is the Klinkenberg effect coefficient, fitted in 1998 to be 0.251 ($\mathrm{Pa\cdot m}^{0.72}$) [15].

Hence, substituting Eq.(2) into Eq.(1), the effective gas permeability $K_\mathrm{g}(\sigma, T, P)$ of coal with the Klinkenberg effect in in-situ stress and geothermal temperature fields can be expressed as

$$K_\mathrm{g}(\sigma, T, P) = k(1+\frac{b}{P})(1+T)^{\alpha_3}\,\mathrm{e}^{-\alpha_2\sigma} \tag{4}$$

3 Seepage equation

3.1 Basic assumptions

1) The state equation of coalbed methane is defined as

$$\rho = \frac{\rho_0 P \beta_0 T_0}{P_0 \beta T} \tag{5}$$

where ρ is gas density under the condition that temperature is equal to T and the gas pressure equal to P ($\mathrm{kg/m^3}$), β is a compressibility factor; β_0 is a compressibility factor under atmospheric norms,, generally equal to 1, T is the absolute temperature of coalbed methane and T_0 is the temperature of air.

2) Coalbed methane is composed of adsorptive gas and free gas and considering the time delay in the desorption process of coalbed methane, the methane content C_g flowing in a unit of coal can be expressed as[8]

$$C_\mathrm{g} = \phi\left(\frac{PT_0}{\beta_\mathrm{a} T_\mathrm{a}}\right) + \frac{acP\rho_\mathrm{c}}{1+cP} \tag{6}$$

where β_a is a compressibility factor when the coalbed temperature is equal to T_a; ϕ is porosity of the coal seam, a ($\mathrm{m^3/kg}$) and c ($\mathrm{Pa^{-1}}$) are Langmuir constants and ρ_c is the density of coal.

3) The gas flow in coal seams is assumed to be a linear flow and in agreement with Darcy's law, so that the coalbed methane flow equation with the Klinkenberg effect in in-situ stress and geothermal temperature fields can be defined by Eq.(4) as

$$V = -\frac{k(1+T)^{\alpha_3}\,\mathrm{e}^{-\alpha_2\sigma}}{\mu_\mathrm{g}}(1+\frac{b}{P})\cdot\nabla P \tag{7}$$

where V is gas flow velocity vector (m/s), and μ_g the dynamic gas viscosity (Pa·s).

3.2 Seepage equation

According to the law of mass conservation, the coalbed methane flow continuity equation[24] can be given by infinitesimal analysis as

$$\mathrm{div}(\rho V) = -\frac{\partial C_\mathrm{g}}{\partial t} \tag{8}$$