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Numerical analysis on the influence of gas extraction on air leakage in the gob

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ABSTRACT

Air leakage volume from the working face to the gob is affected by gas extraction. This paper focuses on the numerical study of the flow field at the working face in a coal mine. Results show that the distribution of air volume at the working face, the pressure difference between the upper and lower corners, and the negative pressure of gas extraction from high drainage roadway obtained by the simulation are in good agreements with the actual field data. Furthermore, the influences of gas extraction on air leakage in the gob were studied. The results show that the gas extraction of high drainage roadway has negative effects on controlling the air leakage into the gob. The gas extraction not only affects the air leakage volume, but also affects the range of air leakage. The relations between the gas extraction volume and the air leakage volume were also studied. Results show that the air leakage volume in the gob and the air volume at working face have a third-order polynomial relation, while the air leakage volume in the gob and the gas extraction volume have an exponential relation, and the critical gas extraction volume was obtained through the relations. The result of the simulation provides useful information for the mining safety of coal mines.

1. Introduction

The coal mine fire is a hazard during mining, which not only affects mine production and results in great economic and resource losses, but also leads to gas explosion and even heavy casualties (Lu and Qin, 2015). Among the coal mine fires, the spontaneous combustion of the residual coal in gob is the most serious. According to the statistics, more than 60% of coal mine fires in China resulted from spontaneous combustion in gob (Qin et al., 2012). Air leakage into the gob is one of the major causes of the spontaneous combustion of residual coal (Wu and Liu, 2011; Yuan and Smith, 2012; Yang et al., 2014). Therefore, studying the air leakage in gobs is important to control the spontaneous combustion of residual coal for security. The main factors that affect air leakage in gobs are in two aspects. On the one hand, they are internal factors, such as the distribution of air leakage resistance coefficient, which are related mainly to the lithology of the top and bottom of working face and the advanced rate of the working face (Karacan et al., 2007; Li, 2007; He et al., 2008; Taraba and Michalec, 2011; Tang et al., 2012). On the other hand, they are external factors, which are related to the ventilation resistance at the working face and the distributions of the source and sink of air leakage at the boundary of the gob (Qin et al., 2009; Li, 2008; Zhu and Liu, 2012; Xia et al., 2015). The pressure difference between the upper and lower corners at the working face is the main force for air leakage into the gob, which is affected by air volume at the working face. Field engineers design the working face with the consideration of the parameters of the working face and its effects on air leakage in the gob. Most mines in China are rich in gas. For security against gas accidents, most working faces extract gas by using high-drainage roadways. In this manner, the high drainage roadway becomes the sink of the air leakage in the gob under the negative pressure of gas extraction. Therefore, high drainage roadways affect air leakage in the gob. Field engineers should also focus on the suitable volume of gas extraction and its effects. Several studies have focused on the

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influence of air volume at the working face on air leakage in the gob by using numerical simulations of air leakage flow fields. For example, Zhu et al. (2011) compared the influences of different air volumes on spontaneous combustion “three zones” and concluded that a higher air volume at the working face corresponds to deeper oxidation zones in the gob and the larger range of the oxidation zone. Shao et al. (2011) simulated and analyzed the relationship of the air volume and air leakage volume in the gob and found that a higher air volume leads to higher air leakage volume in the gob. Yang et al. (2013) studied the law of air leakage in the gob in stereo gas extraction systems by numerical simulation and found that high drainage roadways can increase the air leakage volume. Zhu and Liu (2012) simulated and analyzed qualitatively the influence of tail methane drainage pattern on easily spontaneous combustible region in gob. However, they did not manage to analyze the degree of the influence of gas extraction by using the allowed high drainage roadway and the most gas extraction volume.

For the modeling of the gob, the distribution of porosity and permeability has the characteristic of “O” style carving and compaction, and the porosity and permeability are the largest behind the working face and smallest at the middle of the gob (Taraba and Michalec, 2011; Zhu and Liu, 2012; Yuan and Smith, 2008). The degrees of compaction of the residual coal and caving gangue in the gob are significantly different, thus, the speed and the airflow pattern vary at different places of the gob. The nonlinear seepage model proposed by Bachmat is popular in studying the air leakage flow field (Bachmat, 1965; Di et al., 1993). On the basis of the characteristic of “O” type caving and compaction and the nonlinear seepage model by Bachmat, this study also uses FLUENT, which is a commercial CFD software, to simulate the air leakage flow field at the working face in Liuzhuang Mine in China (ANSYS, 2012). And the gas emission is taken into consideration in this study. On this basis, the influences of gas extraction volume of high drainage roadway are studied. These studies provide important basis for gas extraction and the technology of fire prevention during coal production.

2. Mathematical models

2.1. Basic flow equations

The airflows at the tail airway, return roadway, high drainage roadway, and working face are simulated as fully developed turbulent flow by using an RNG k-ε model (Taraba and Michalec, 2011; Sasmito et al., 2013). Because laminar flow, transition flow and turbulent flow coexist in the gob, the flow pattern of the air leakage in the gob is treated as a non-darcy flow. By taking incompressible air into consideration, the simplified steady balance equations of mass and momentum in the gob are expressed as follows (Wang et al., 2012; Xia et al., 2014):

$$\begin{cases} \dfrac{\partial(\rho V_x)}{\partial x}+\dfrac{\partial(\rho V_y)}{\partial y}+\dfrac{\partial(\rho V_z)}{\partial z}-q_{e(x,y,z)}=0 \\ -\dfrac{\partial p}{\partial x}=C_1\mu V_x+C_2\dfrac{1}{2}\rho|V|V_x \\ -\dfrac{\partial p}{\partial y}=C_1\mu V_y+C_2\dfrac{1}{2}\rho|V|V_y \\ -\dfrac{\partial p}{\partial z}=C_1\mu V_z+C_2\dfrac{1}{2}\rho|V|V_z \end{cases}, \tag{1}$$

where p is the static pressure in Pa, V_x, V_y and V_z are the air velocity of the unit body at the x, y and z direction respectively in m/s, C_1 is the factor of viscous resistance in 1/m^2, C_2 is the factor of inertial resistance in 1/m, ρ is the fluid density in kg/m^3, μ is the dynamic viscosity in Pa·s, and q_e is gas emission volume, kg/(m^3·s). When C_2 approaches 0, the equation is darcy flow.

2.2. Model of air leakage resistance coefficient in the gob

According to the nonlinear equations of seepage motion in porous media by Bachmat (1965), the following expression is obtained (Bachmat, 1965; Di et al., 1993):

$$-\nabla h=(a+b|V|)\overrightarrow{V}, \tag{2}$$

where h is the pressure head in m, V is the fluid velocity in m/s, a and b are scalar coefficients in Eq. (2) and can be expressed by Eq. (3):

$$\begin{cases} a=\nu/(g\cdot k) \\ b=\beta\cdot D_{\mathrm{m}}/(g\cdot n\cdot k) \end{cases}, \tag{3}$$

where g is the acceleration of gravity in m/s^2, n is the porosity, ν is the kinematic viscosity in m^2/s, k is the permeability of porous media in m^2, β is the shape factor of the media particles, and D_{m} is the harmonic average particle size in m. In this paper, the value of g is 9.81 m^2/s, the value of β is 1.5 obtained on the basis of the field mining conditions. The simulation result is in good agreement with the field mining conditions when the value of D_{m} is set to 0.1 m. Therefore, the value of D_{m} is 0.1 m (Zhang et al., 2016).

The permeability k is the function of porosity n, using the Blake-Kozeny formula (Macdonald et al., 1991; Luo et al., 2012; Byon and Kim, 2013):

$$k=\frac{D_{\mathrm{m}}^2}{150}\cdot\frac{n^3}{(1-n)^2}, \tag{4}$$

The porosity can be obtained by K_p, which is the coefficient of the bulk increase of caving rocks in the gob:

$$n(x,y)=1-\frac{1}{K(x,y)}. \tag{5}$$

According to the general law of mine pressure, the coefficient K_{p} follows the law of attenuation of the negative exponent (Li, 2007):

$$K_{\mathrm{p}}(x,y)=K_{\mathrm{p}}'+\left(K_{\mathrm{p}}^0-K_{\mathrm{p}}'\right)\cdot e^{-a\cdot d}, \tag{6}$$

where K_{p}^0 is the coefficient of the bulk increase of caving before compacting, K_{p}' is the coefficient of the bulk increase after compacting, a is the decay rate in m^{-1}, d is the distance from the coordinate in the gob to the boundary in m. In this paper, the value ofK_{p}^0 is 1.45 and the value of K_{p}' is 1.15. This means that the differences of blackness and intensity of the rock in the caving zone cause the differences of the distribution of these coefficients. The compaction degree in the gob behind the working face is significantly different from the compaction degree in the deep gob because the compaction degree of caving rocks is not only related to mine pressure but is also related to the carving time. In this paper, the compaction degree is 0.037 in the gob behind working face and 0.268 in the deep gob.

Combined with Eq. (1), the viscous resistance coefficient C_1 and the inertial resistance coefficient C_2 in FLUENT are obtained as follows: