Mining Science, vol. 28, 2021, 33–45

www.miningscience.pwr.edu.pl

Mining Science

(Previously Prace Naukowe Instytutu Gornictwa Politechniki Wroclawskiej, ISSN 0370-0798)

ISSN 2300-9586 (print)
ISSN 2353-5423 (online)

Received September 12, 2020; Reviewed; Accepted March 6, 2021

NUMERICAL MODELLING OF GAS PUMPING IN INNER INTERLOCKED TAIL ROADWAY OF COAL MINE BASED ON COUPLED FRACTURE-SEEPAGE MODEL

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Abstract: This paper focuses on modelling of pumping high overrun gas in an upper corner and fully mechanized caving face of a coal mine with extra-thick seam. The process of roof fracture and fall in goaf is analyzed. Then the numerical model of the immediate roof and main roof collapse in goaf is established. On the basis of the numerical model, FLUENT is employed to simulate the gas seepage process in the accumulation of the rock and coal in goaf. In addition, the influence of the inner interlocked tail roadway at different positions for the gas concentration in goaf is analyzed. To calibrate the proposed numerical model, it is implemented to a coal mine. It is concluded that numrical results are similar to those in the coal mine.

Keywords: *goaf, collapse of roof, fluid-solid coupling, main roof, immediate roof*

1. INTRODUCTION

The problem of gas disasters in fully mechanized coal mining work face in high gas seam has always been one of the key points in terms of coal mine safety management (Xu, Yu et al. 2007; Wang, Cheng et al. 2015; Wang, Wu et al. 2017). In order to reduce the gas content in fully mechanized mining face, the gas has to be extracted in advance (Hu, Liang et al. 2007; Hou, Ji et al. 2010). However, due to the low perme-

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doi: 10.37190/msc212803

ability of coal seams and short gas extraction time, there are lots of high concentration gas in the working face, especially in upper corner of the goaf, during the mining process(Jian-zhong 2004; Jia, Liu 2008; Gang 2011; Li, Shan 2011; Lang, Xisheng et al. 2013). At present, the common treatment methods for prevention of the gas concentration in the mine is to drain the gas in the goaf, or drain the gas in the fracture zone(Lou 2008; Lin, Li et al. 2014). In addition, an inner interlocked tail roadway is commonly used to drain the gas in the goaf (Zhi-yu 2004, Yang, Cheng et al. 2011; Luo, Jiang et al. 2012). The technology of inner interlocked tail roadway is one of the important methods for the gas control in the upper corner in China. An inner interlocked tail roadway is a special gas drainage lane which is at a certain height of the coal seam and can used to drain gas in work face, surrounding rock, adjacent layers. This method is very popular in preventing gas concentration. However, there are rare researches on mechanism of controlling gas overrun in upper concern of goaf.

In this paper, the fluid-solid coupling model is proposed to study the effects of inner interlocked tail roadway at different spatial position in terms of reducing gas concentration in fully mechanized work face of coal mine. The proposed model is implemented in FLUENT (Ding, Jiang et al. 2008) to simulate this process. Then the proposed model is implemented in a coal mine to reduce gas concentration.

2. MATHEMATICAL MODEL OF ROOF FRACTURE

During fully mechanized caving mining, when the upper coal body is released, a goaf will be formed. In order to explain the failure process of the goaf roof, there are a few hypotheses, such as pressure arch hypothesis, cantilever beam hypothesis, articulated rock block hypothesis, and pre-cavity hypothesis (Chen, He et al. 2011). Although the content and form expressed by each hypothesis are quite different, they all indicate that there is a delay in the process of the roof plate fracture and fall. In addition, with the advancement of the working face, the upper rock will be under the effect of its own strength. A probe of a certain length is formed in the goaf. The formation and existence of this probe creates favorable conditions for the extraction of gas in the goaf in the inner tail channel and the reduction of the gas concentration in the upper corner.

2.1. INITIAL FRACTURE STEP OF COAL SEAM ROOF

The roof of the coal seam is under the condition of simple support and three-sided solid support in the goaf. When it is in the limit suspension state, the three solid supports form a negative bending moment zone, and the maximum principal bending moment Ma is in the middle of the long solid. A positive bending moment zone is formed at the center of the goaf, and the maximum principal bending moment is $M_c = \sqrt{M_x^2 + M_y^2}$. Thus the following solutions can be achieved according to the Marcus correction solution:

$$\left|M_a\right| = \frac{(1-\mu^2)(1+\mu\lambda_1^2)}{12(1+\lambda_1^4)} q a_1^2 , \tag{1}$$

$$M_c = \frac{(1-\mu^2)\lambda_1^2(\mu + m_1^2)}{12(1+\lambda_1^4)} q b^2 . \tag{2}$$

In addition, the following solutions can be achieved from the relationship between bending moment and stress:

$$M_a = \frac{h^2 \sigma_s}{6} . \tag{3}$$

Substituting the formula (3) into the formula (2), the relationship between the initial fracture step of the coal seam roof under the condition of simple support and three-sided solid support can be obtained as follows:

$$a = \frac{2h}{1-\mu^2} \sqrt{\frac{\sigma_s}{q} \frac{2+\lambda^4}{4+3\mu\lambda^2}} , \tag{4.1}$$

$$l_m = \frac{h}{1-\mu^2} \sqrt{\frac{2\sigma_s}{q}} . \tag{4.2}$$

By solving formula (4), the formula (5) can be obtained:

$$a = \begin{cases} b^4 \sqrt{\dfrac{l_m^2}{2(b^2 - l_m^2)}} & \left(l_m < b < \sqrt[4]{2 l_m}\right), \\[2ex] \dfrac{b}{l_m} \sqrt{b^2 - \sqrt{b^4 - 2 l_m^4}} & \left(b > \sqrt[4]{2 l_m}\right). \end{cases} \tag{5}$$

where: μ is the Poisson's ratio of the rock formation, q is the self-weight of the rock layer and its upper load, λ_1 is the geometry coefficient of the goaf $\lambda_1 = a_1/b$, a_1 is the working surface propulsion distance, b is the working surface length, h is the thickness of the old top rock layer, σ_s is the tensile strength of the old top rock stratum strength.

2.2. THE SEPARATION AND COLLAPSE OF MAIN ROOF AND IMMEDIATE ROOF

Whether the main roof and immediate roof will be separated from each other can be judged by the maximum disturbance.

The maximum distance for the main roof:

$$y_{\max-\text{MainRoof}} = \frac{(\gamma h_1 + q_1)L_1^4}{384E_1J_1}. \tag{6}$$

The maximum distance for the immediate roof:

$$y_{\max-\text{ImmediateRoof}} = \frac{\sum h\gamma L_1^4}{384E_2J_2}, \tag{7}$$

where q_1 is the load applied to the old top, γh_1 is the load per unit length of the old top, L_1 is the initial stepping distance, $\sum h$ is the direct top thickness, E_1 and E_2 are the modulus of the main roof and immediate roof seperately, J_1 and J_2, are the section inertia moment of the main roof and immediate roof separately.

According to the conditions of the separation phenomenon between the main roof and the immediate roof, it can be known that:

when

$$\frac{(\gamma h_1 + q_1)L_1^4}{384E_1J_1} \frac{\left(\sum h\gamma K_1^4\right)}{384E_2L_2},$$

the main roof and the immediate roof are prone to separate and fall. It can be approximated that when the immediate roof thickness is less than or equal to the main roof thickness, direct vertical separation is likely to occur.

3. GEOMETRIC MODEL BOUNDARY CONDITION

3.1. OVERVIEW OF FULLY MECHANIZED CAVING WORK FACE

As this research is on the basis of the 2306 work face of Luan coal mine, the overview of the fully mechanized caving work face is introduced first.

Figure 1 illustrates the cross-section of the working face before the main roof falls. As for the workface, the length, average thickness of coal seam, the mining height are 200 m, 5.85 m and 3.0 m, respectively. The gas content of the coal seam is 1.81–9.68 m^3/t, and the average is 5.49 m^3/t. The immediate roof is composed of gray-black mudstone, sandy mudstone, sometimes sand mud. The thickness is generally from 1.0 to 7.0 m and average thickness is 5.35 m. The main roof is comprised of medium-fine grain gray-white quartz feldspar sandstone, and some parts are coarse sandstone with an average thickness of 5.8 m. The height of the goaf is about 30 m. For the details can be seen in Table 1.

3.2 GEOMETRIC MODEL

Due to the simulation needs, some assumptions are made in the goaf.

1. It is assumed that the airflow in the simulated space is a three-dimensional isothermal incompressible flow;
2. The negative pressure of gas drainage is stable, and the gas-solid two-phase flow in the fallen rock mass in the goaf is constant.
3. The space formed by the main roof is a trapezoidal body;
4. Other factors are ignored.

Table 1. Parameters of the working face coal seam roof

Parameters	Immediate roof	Main roof	Unit
Thickness	5.35	5.8	m
Broken coefficient	1.2	1.2	Non
Poisson's ratio	0.25	0.25	Non
Elastic modulus	1.5 × 104	1.5 × 104	MPa
Compressive strength	13.5	13.5	MPa
Thickness of seam	5.58	5.58	m
Fall height	6.4	13.4	m

According to the assumptions and the parameters in Table 1, a numerical model for workface in goaf is established as shown in Fig. 2.

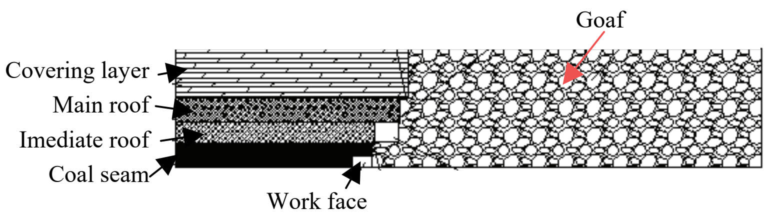

Fig. 1. The filling space section of the goaf before main roof fallen

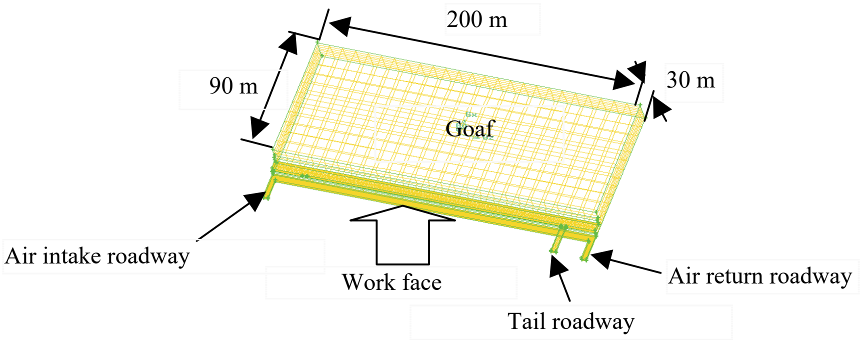

Fig. 2. Geometric model of work face in goaf before the main roof fallen

As illustrated in Fig. 2, the length and width of the model bottom are 200 m and 90.5 m., respectively. The height of the model is 30 m.

According to the data measured from work face 2306, the numerical parameters can be found in Table 2

Table 2. Parameters for numerical model

Boundary conditions	Parameters
Solver	separation solver
Turbulence model	κ–ε two-equation model
Component model	gas–air
Energy model	open
Convergence standard	10^{-3}
porous medium model	open
Void ratio	0.2
Inertial resistance coefficient	1.0e5 [1/m^2]
Injection source type	body jet
Material	methane
Density	0.716 [kg/m^3]
Jet source total mass flow rate	1.5e-7 [kg/m^3·s]

4. MODELLING RESULTS AND ANALYSIS

4.1. DETERMINATION OF HORIZONTAL DISTANCE

During the simulation, when the horizontal distance between the inner interlocked tail roadway and the return airway (referred to as the horizontal distance) is 10, 15, 20, 25 and 30 m, respectively, the height of the top floor of the inner interlocked tail roadway is 7.5 meters, and the negative pressure of extraction is 5 kPa. The gas migration vector of the goaf in the fully mechanized caving face is shown in Fig. 3. The gas concentration curve of the upper corner is shown in Fig. 4.

As illustrated in Fig. 3, a gas migration vortex zone is formed at the upper corner, and under the action of suction negative pressure, a large amount of gas is pumped away along the inner interlocked tail roadway. Thus the gas concentration at the upper corner is reduced.

It can be seen from Fig. 4 that in the range of 30 m, the influence of the gas concentration on the upper corner is gradually weakened as the inner interlocked tail roadway is far away from the return airway. However, the difference in position has little effect on reducing the gas concentration in the upper corner. The reason is that the main roof forms a large unfilled space below before it falls, and the existence of this space reduces the resistance of gas migration. The degree of influence of the flat distance of the inner interlocked tail road on the gas concentration of the upper corner is reduced.

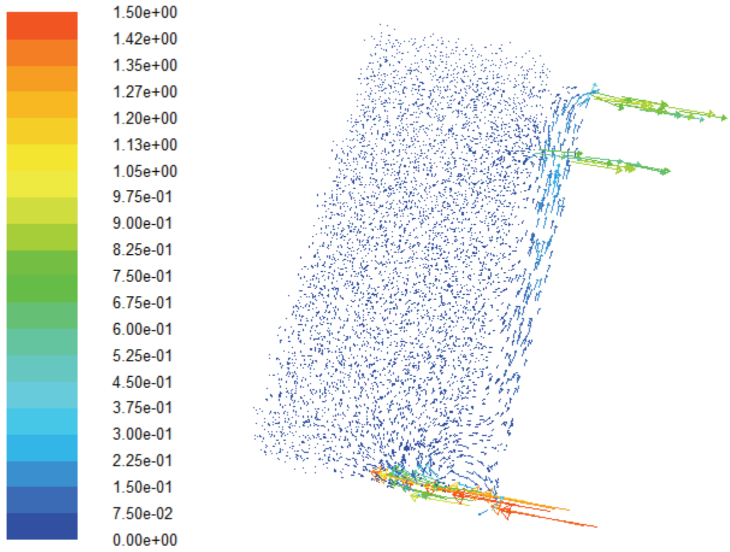

Fig. 3. Velocity vector diagram of methane migration working face goaf

It can be seen from Fig. 4 that the two curves for the horizontal distance of 15 m and 20 m are all most coincident, and the variation of the gas concentration curve is relatively stable. Therefore, 15~20 m from the horizontal distance between the inner interlocked tail road and return airway is the ideal parameter.

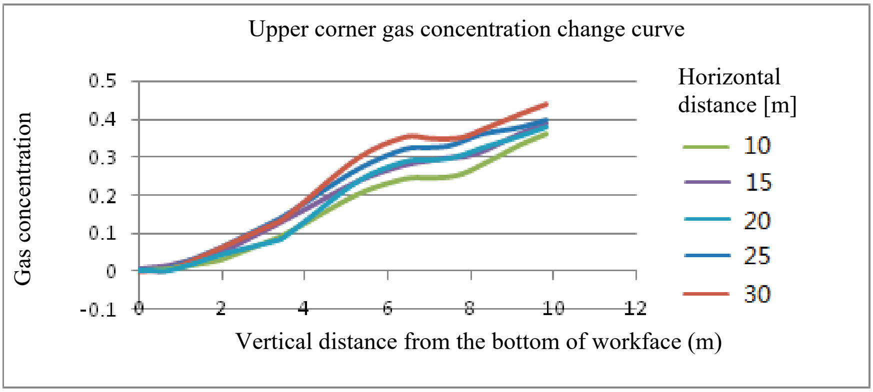

Fig. 4. The upper corner gas concentration change curve under different from the flat

4.2. DETERMINATION OF VERTICAL DISTANCE

The cloud concentration distribution in the goaf of the fully mechanized caving face is shown in Fig. 5. The gas concentration changes in the upper corner are shown in Fig. 6.

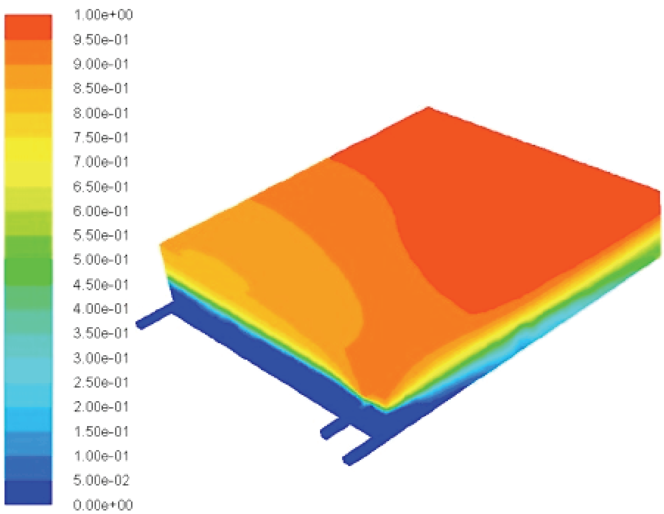

Fig. 5. Cloud map of gas concentration distribution in goaf

As illustrated in Fig. 5, the concentration of gas in goaf increases gradually with the distance from working face, and the stratification phenomenon is obvious. The influence range of inner interlocked tail road is limited, and the gas concentration in its control range decreases obviously.

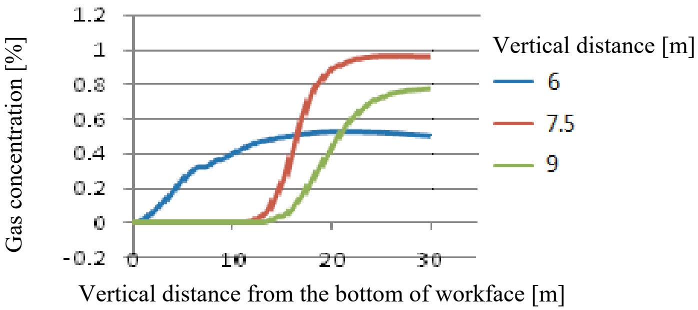

Fig. 6. The upper corner gas concentration change curves under the different vertical distance

From Fig. 6, it can be seen that the vertical height of the inner interlocked tail road has a significant effect on the gas concentration in the upper corner. When the top height of the inner interlocked tail road is 6 m, the gas concentration in the upper corner is almost unaffected. The reason is that the height of the accumulation of rock mass from the fall of immediate roof (6.4 m) is higher than the height of the inner interlocked tail road (6 m). The caved coal and rock mass will seal all the ports of the interlocked tail road.

When the roof height of the inner interlocked tail road is 7.5 and 9 m, the gas concentration in the upper corner decreases obviously, and its influence on the gas concentration in the upper corner is the same. The reason is that when the roof height of the inner interlocked tail road is 7.5 and 9 m, the inner interlocked tail road is not blocked, which can communicate with the unfilled space below the old roof. The eddy current zone is formed in the upper corner, and a large amount of gas is discharged along the inner staggered tail lane, which reduces the gas concentration in the upper corner.

4.3. DETERMINATION OF PUMPING NEGATIVE PRESSURE

In the simulation, the horizontal spacing of 20 m and vertical spacing of 7.5 m are set. The negative pressure of pumping and discharging is, respectively, 2.0, 3.5 and 5.0 kPa. The upper corner gas change curve is shown in Fig. 7.

When the negative pressure in the inner interlocked tail road is 2 or 3.5 kPa, the gas concentration in the upper corner is almost the same since the two curves in Fig. 7 are basically the same. This indicates that seepage resistance of gas due to the falling rock mass in the goaf is still difficult to overcome even in the negative pressure circumstance. Thus the inner interlocked tail road does not play any role in reducing the gas concentration in the upper concern.

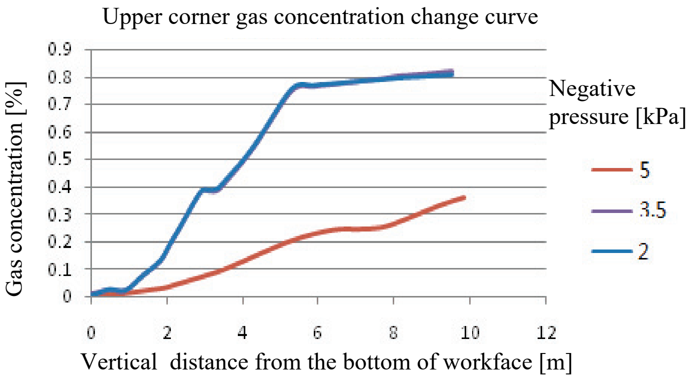

Fig. 7. The upper corner gas concentration change curve under different pressure

When the negative pressure in the inner interlocked tail road is 5.0 kPa, the change of gas concentration in the upper corner is obvious. This indicates that the negative pressure overcomes the influence of the resistance of the caving rock mass, and makes the eddy current in the upper corner take away the gas. Thus, the gas concentration in the upper corner is reduced.

Due to the different heights of the immediate roof collapsed rock mass, the seepage resistance is also different. Thus, the pumping negative pressure should be determined according to the actual situation. Under normal circumstances, when the negative pressure is 5.0 kPa, the inner tail road can affect the upper corner, which can effectively reduce the gas concentration.

5. FIELD APPLICATION OF THE OBTAINED THEORIES OF INNER INTERLOCKED TAIL ROAD

The inner interlocked tail road in this research is 7 m in height and 15 m far from the return airway. The gas concentration change curve is show in Fig. 8 while the gas concentration curve of the upper corner is shown in Fig. 9 The statistics of the return airway, gas lane and upper corner gas are shown in Table 3.

Table 3.1. Statistics of coal face gas parameters

Return airway		
Air [m^3/min]	CH_4 maximum concentration [%]	CH_4 average concentration [%]
1120	0.53	0.39

Table 3.2. Statistics of coal face gas parameters

Gas lane		
Air [m^3/min]	CH_4 maximum concentration [%]	CH_4 average concentration [%]
310	0.77	0.54

Table 3.3. Statistics of coal face gas parameters

Gas concentration of upper corner	
CH_4 maximum concentration [%]	CH_4 average concentration [%]
0.72	0.45

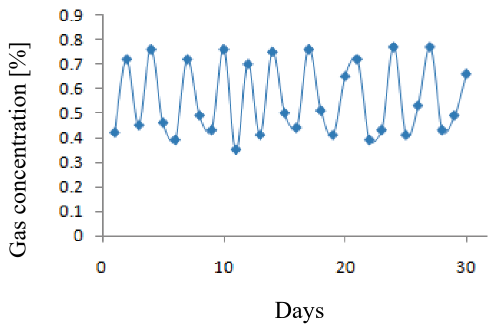

Fig. 8. Gas concentration change curve in the inner interlocked tail road

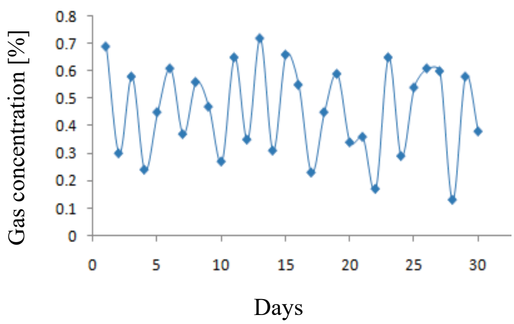

Fig. 9. Upper corner gas concentration change curve

It can be seen from Figs. 8 and 9 that the concentration of gas in the inner and rear corners changes periodically, mainly due to the cyclical changes of the old roof.

When the main roof is not fallen, the goaf is not collapsed. Thus, the inner interlocked tail road is connected with the unfilled space. In addition, the seepage resistance for gas at the upper corner is the smallest. Thus, the gas concentration in the inner interlocked tail road is higher, and the gas concentration in the upper corner is lower; when the main roof collapses, the fallen rock blocks the port of the inner interlocked tail road, the resistance between the inner interlocked tail road and the goaf increases. Meanwhile, the gas concentration in the inner interlocked tail road decreases, and the gas concentration in the upper corner increases.

It can be seen from Table 1 that the main fall step is about 6 m, and the working surface advance speed is about 5 m/d. The periodical change of gas concentration in the inner interlocked tail road and the upper corner is also about one day. Since the gas in the working face is pumping, the number of gas overruns in the upper corner has been significantly reduced, and the gas drainage effect is very obvious. This indicates that the simulation results reflect the gas in the goaf area. In addition, the proposed method can be used to design more reasonable relevant parameters, such as pumping negative pressure, the horizontal distance between the inner interlocked tail roadway and the return airway, the height of the top floor of the inner interlocked tail roadway, which provide a basis and reference for the use of the inner interlocked tail road to control gas disasters in high gas coal seam working face.

6. CONCLUSION

Based on the theory of fracture mechanics, the mathematical model for the main roof and the immediate roof has been established in the fully mechanized coal caving mining. According to the delay of the coal seam immediate roof and the main roof collapse, the gas seepage process in the fallen coal rock in the empty area is simulated, and the vector relationship of the inner gas migration in the upper corner is obtained.

The reasonable layout parameters of the inner interlocked tail road are proposed. The roadway should be arranged within the range of 15~20 m from the return air side, and the top surface should be higher than the immediate top collapse coal rock deposit by more than 0.5 m.

For the occurrence conditions of different coal seam roofs, the negative pressure of the inner interlocked tail road should be different, and its size should not be less than the seepage resistance of the fallen rock mass. For general mines, the negative pressure should not be lower than 5 kPa.

Finally, the numerical model and the appropriate parameters obtained by simulation analysis are applied to simulate the gas distribution in a real coal mine. The model results agree well with the current situation in the coal mine. Thus, the actual application of the model on a coal mine verifies the accuracy and reliability of the parameters determined by numerical simulation. The simulation method can provide a reference for the design of high gas coal mine with thick coal seam.

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