Reasonable Layout of High Drainage Roadways for Jiaojiazhai Mine

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Research Article

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Abstract

To ensure that the gas concentration at the top corner does not exceed the limit, a reasonable level of the high drainage roadway layout in Jiaojiazhai Mine should be determined. In this work, based on the actual conditions of the working face, an SF₆ tracer gas was used to test the connectivity between the high drainage roadway and the working face. A discrete element analysis program was used to simulate the deformation law of the overlying strata in the goaf, and a corresponding caving control program for the surrounding rock was written based on the obtained parameters and “O” ring theory. A fluid simulation software was used to simulate and analyze five goaf models with different high drainage roadway layouts (10, 15, 20, 25, and 30 m). The gas drainage data for two layers (10 m and 20 m) of the high drainage roadway were measured. The results showed that the height of the caving zone in the goaf is approximately 20 m, and when the high drainage roadway is arranged along the roof (when the layout layer height is 10 m), the roadway will be directly connected to the working face, thus pumping fresh air to the working face. The gas extraction effect of the 20 m stratum was better than those of the other strata. The simulation results of the gas extraction were consistent with the measured data. The proposed scheme was practically applied, and its effect was found to be evident, thus solving the problem of high gas concentration at the top corner and increasing the mine output.

1 Introduction

Mine gas overrun is one of the main problems restricting the safe and efficient production of coal mines in China. In mines with a large amount of gas emission, the drainage technology for high drainage roadways is the main method to solve the gas overrun problem at the top corner [1–3]. Cheng [4] combined gas-related theories with engineering practice, summarized the classification methods of gas extraction suitable for coal mine gas extraction index assessment, and briefly summarized various extraction methods. Yuan [5] applied rock mechanics, rock movement, “O” ring, gas flow, and other theories to explore the theory of gas extraction by pressure relief mining, and established a technology system for gas extraction by pressure relief mining and coal and gas co-mining. Qian [6] described the distribution characteristics of “O”-shaped rings formed in the water and gas conduction zone by mining based on the theory of key strata. Zhu [7] analyzed the pumping effect of the high drainage roadway in Wuyang Coal Mine under different ventilation modes through Fluent simulation. Wang [8] determined a reasonable value of the negative pressure for a high drainage roadway through a numerical simulation. Among the many factors restricting the effect of high drainage roadways, a reasonable layer layout has a significant influence. Through numerical simulation software and field application analysis, Lin [9] obtained the optimal distance between the high drainage roadway, return air roadway, and roof of a coal seam. Most of the above studies concluded that the layout of the high drainage roadway (or pipeline) is related to “three vertical zones” of the goaf [10,11]. However, due to the different roof and floor structures and the lithology of overlying strata, the distribution characteristics of these zones in the goaf must be different; therefore, the height position of the high drainage roadway in the mine will also be different.

The height range of the “three vertical zones” of No. 2 coal seam in Xuangang mining area calculated using the empirical formula was found to be different from the actual situation. Therefore, a discrete element analysis program simulation software was used to simulate the height range of the three vertical zones of the caving formed after the overlying strata were destroyed during the mining of this coal seam. From the above data, a specific caving control program for the surrounding rock of the goaf was written and applied to the fluid simulation software. Based on the actual mining conditions, the gas extraction effect was simulated for goaf models with different layouts of the high drainage roadway (10, 15, 20, 25, and 30 m). Gas drainage data for two different layers (10 m and 20 m) and at the top corner of the working face were measured successively in the coal mine site, and the conductivity of the high drainage roadway in the different layers and working face was tested using an SF₆ tracer gas. By comparing the measured data with the simulated data, the difference in the pumping effect of the five layers was obtained, and a reasonable roadway layout was determined.

2 Research Background

Jiaojiazhai Mine is a high gas mine. The 22116 working face is located in the No. 2 coal seam with an average thickness of 5.54 m. The gas emission at the working face is 5.86 m³/min during mine production. To control the gas effectively, the gas control technology of “one side and four lanes” has been employed in the mine, including bottom and high drainage roadways. However, the coal seam floor has a large amount of gushing water, and the working face does not have the necessary conditions to arrange the bottom drainage roadway. Currently, the high drainage roadway is mainly used to control the gas. In the early stages of mining, the

high drainage roadway of the Jiaojiazhai 22116 working face is arranged 10 m away from the roof of coal seam and 20 m away from the return air roadway of the working face, with a net section of 9.00 m². The gas volume fraction at the top corner is always at a high value. Figure 1 shows the observed gas data at the top corner during the advancement of the working face.

Figure 1 shows that with the advancing of the working face, the gas volume fraction at the top corner presents an upward trend. Although it does not exceed the specified safety production value, it is in a high range, and the gas at the top corner will exceed the limit if no measures are taken. Generally, with the shortening of the high drainage roadway at the working face and the stability of the drainage system, the drainage capacity of the high drainage roadway should be relatively enhanced, and the gas volume fraction at the top corner has a small strain; however, the change trend in the measured data is opposite. When the layout layer of the high drainage roadway is low, the roadway may be directly connected to the working face through the caving zone so as to extract fresh air flow from the working face. Therefore, when the distance of the high drainage roadway becomes shorter, the time required for the fresh air to flow from the back slip position to the high drainage roadway will continue to decrease, and the gas extraction effect will become worse. To verify this prediction, the discrete element analysis program simulation and tracer gas method were used.

3 Analysis Of Reasons For High Gas Volume Fraction At Top Corner

3.1 Simulation of mining overburden caving distribution law

The range of the “three vertical zones” of the roof caving in the goaf significantly influences the gas distribution and gas control. The height of the caving and fracture zones in the goaf is mainly related to the mining thickness of the coal seam, coal seam dip angle, management method of the goaf roof, and the lithology of the overlying strata. The theory of “three vertical belts” has accumulated a great deal of practical experience and data in China’s coal mining system, and there have been many empirical formulae.

The height of the caving zone is closely related to factors such as the overlying rock fragmentation and the mining thickness of the coal seam. Generally, the height of the caving zone is 2–5 times the mining thickness of the coal seam. Based on the characteristics of the overlying lithology, dip angle of the coal seam, and management method of the goaf roof, the height of the falling zone is calculated on the basis of the hard rock layer:

$$H_m = \frac{100m}{2.1m + 16} \pm 2.5$$

1.

The thickness of the No. 2 coal seam is 5.6 m. From the above formula, the height range of the caving zone is found to be 17.67–22.67 m.

However, the geological conditions in the actual production process of the coal mine are complicated, and the height range of the “three vertical belts” calculated using the empirical formula is different from the actual value. Therefore, the range of the caving and fracture zones is simulated by combining the discrete element analysis program to judge the height range of the “three vertical belts.”

The discrete element analysis program was used to simulate the height range of the “three vertical zones” formed after the overlying strata of the goaf were destroyed when the 22116 working face advances 30, 70, 100, 300, and 600 m. The model strata were set up in 21 layers with a total thickness of 270 m, and the design size was X×Y = 800 m × 270 m. Figures 2 and 3 show the results of the surrounding rock deformation obtained by simulation. Due to space limitation, only the results corresponding to working face advancements of 30 m and 300 m are given.

From the overburden deformation shown in Figs. 2 and 3, it can be found that the deformation and failure range of the surrounding rock increases with the advancing of the working face. From the perspective of a quantitative analysis, based on the above simulation results, the variation in the height of the caving and fracture zones under different footages of the No. 2 coal seam working face are plotted, as shown in Fig. 4.

In the figure, when X > 300, the two curves are approximately parallel to the X axis, and the corresponding values are 20 m and 95 m, respectively, indicating that with the advancing of the working face, the heights of the caving and fracture zones are stabilized at approximately 20 m and 95 m, respectively. Combined with the empirical formula, the range of the caving zone in the goaf behind the

working face is set to 20 m. Therefore, when the layout height of the high drainage roadway is 10 m (along the roof of the coal seam), the large gap in the caving zone is likely to make the high drainage roadway to directly extract fresh air flow from the working face.

3.2 Tracer gas connectivity test

SF₆ is used as the tracer gas. Figure 5 shows the schematic of the gas release location. The 18 release points are located in the top-corner area, within 20 m of the leeward side of the high drainage roadway, within 20 m of the windward side of the high drainage roadway, and in the lower corner area. After the gas is released, the SF₆ gas detector is used to detect the gas in the high drainage roadway, and the measuring point is arranged near the opening of the high drainage roadway in the return airway.

Based on the locations of the above gas release points, gas release and detection experiments were conducted five times for 18 gas release points in the 10 m layer layout of the high drainage roadway in the 22116 working face of Jiaojiazhai mine. After a period of gas release, a continuous SF₆ gas detection was conducted for the gas in the pumping pipeline in the high pumping lane. Table 1 shows the gas release duration, release amount, and gas detection results at each release point of the working face.

The gas detection results show that at positions 12, 15, and 18, the SF₆ gas is released to reach a high detection value in the lane. This indicates that when the high drainage roadway in the 22116 working face is arranged along the roof of the coal seam (layer 10 m), the high drainage roadway will be directly connected to the working face, and the phenomenon of fresh air flow after drainage will occur; therefore, the volume fraction of the extracted gas in the high drainage roadway is relatively low.

Table 1
SF₆ gas detection results at working face

Layout layer	Test date	Release time /min	Detection concentration of SF ₆ gas in the roof gas drainage roadway /ppm																	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
10 m	4-12	5	0	0	0	0	0	0	0	0	0	0	0	1010	0	0	1005	0	0	1000
	4-21	5	0	0	0	0	0	0	0	0	0	0	0	1025	0	0	1010	0	0	998
	5-07	5	0	0	0	0	0	0	0	0	0	0	0	990	0	0	995	0	0	990
	5-14	5	0	0	0	0	0	0	0	0	0	0	0	1020	0	0	1015	0	0	1005
	5-22	5	0	0	0	0	0	0	0	0	0	0	0	1070	0	0	1025	0	0	1010

4. Reasonable Layout Of High Drainage Roadway

Limited by geological conditions, management and maintenance cost, and other factors, it is almost impossible to compare and analyze the effect of gas drainage by placing several high drainage tunnels in different strata at the same time. Therefore, fluid simulation software is used to simulate the effect of gas drainage on goaf models with the same size, boundary conditions, and different high drainage roadway layout layers.

4.1 Porosity setting in the simulation model

It is necessary to determine the caving condition of the surrounding rock in the goaf when simulating the drainage effect of roof drainage roadways in different layers. This requires writing a specific caving control program (UDF) for the surrounding rock, the most important aspect of which is to accurately depict the distribution of the fragmentation coefficient of the caving surrounding rock. The bursting coefficient of the caving surrounding rock is an important parameter reflecting the caving situation of the surrounding rock in goafs. It is typically related to the height of the caving zone in the goaf, coal seam thickness, and inclination angle of the coal seam. Equation (2) is generally used for estimating its value in field applications:

$$K_p = 1 + \frac{m}{h \cdot \cos \alpha}$$

2.

Here, K_p is the rock fragmentation coefficient; m is the mining height of the working face; h is the height of the falling zone; α is the coal seam dip angle.

The discrete element analysis program simulation results of the caving and fissure zones at different advancing positions of the No. 2 coal seam working face on the one hand show that when the 10 m layer is laid out, the extraction port of the top drainage roadway is just in the caving zone and has good connectivity with the working face, resulting in a good pumping effect. On the other hand, it also provides parameters for the size of the fluid simulation model and UDF of the surrounding rock caving. Using Equation (1) and from Fig. 4, the height of the caving zone in the No. 2 coal seam of Xuangang mining area is found to be $h = 20$ m. Therefore, the minimum value of the rock fragmentation coefficient $K_{p, \min}$ in the caving zone can be estimated using Equation (2). However, the fragmentation coefficient of the caved rock in the goaf exhibits a spatially nonequivalent distribution, making it necessary to determine the fragmentation coefficient at each point in the fluid simulation goaf model. Based on the observation law of the mine pressure, the K_p value between the caving and compaction on the goaf approximately shows a law of negative exponential attenuation^[12]. Based on this understanding, a mathematical model of the crushing coefficient of the goaf along the working face was established^[13]. For any shape of the goaf, specific to a certain boundary l , its unidirectional value can be expressed as:

$$K_{p, l} = K_p' + (K_p^{(0)} - K_p') \cdot e^{-a_l d}$$

3.

Here, l is the boundary distance; $K_p^{(0)}$ is the initial collapse fragmentation coefficient; K_p' is the compaction fragmentation coefficient; a_l is the decay rate, determined from the ore pressure observation; a_l is the distance from some boundary.

For a multidirectional heterogeneous goaf with an arbitrary boundary shape, based on the order of caving compaction, the caving fragmentation coefficient of the rock is a function of the position (coordinates) of the goaf. The K_p distribution function of the caving fragmentation coefficient is as follows:

$$K_p(x, y) = \max\{K_{p, j}\}$$

4.

The goaf compaction distribution in line with the "O" type circle law, based on the heterogeneity characteristic of the mined-out area and Equation (3), determine the gob caving medium in the x and y directions of the hulking coefficient distribution function, through the superposition and repeated parameters inversion function, obtained the hulking coefficient distribution in accordance with the "O"-type circle distribution calculation model, the distribution function is as follows:

$$K_p(x, y) = K_{p, \min} + (K_{p, \max} - K_{p, \min})e^{-a_1 d_1 (1 - e^{-\xi a_0 d_0})}, (\xi < 1). \quad (5)$$

Here, ξ is the adjustment coefficient; $K_{p, \max}$ is the initial collapse fragmentation coefficient; $K_{p, \min}$ is the real-time bursting coefficient of the caving rock; a_0, a_1 is the attenuation rate from the solid wall and working surface, $1/m; d_0, d_1$ is the distance between the point (x, y) and boundary of the solid wall and working face, m.

However, the fragmentation coefficient in front of the goaf also changes significantly in terms of the height (z-axis). Fig. 4 shows that the coefficient $K_{p, \max 1}$ in the lower part of the goaf is low, while the coefficient $K_{p, \max 2}$ in the upper part of the goaf should be large. The relationship is $K_{p, \min} < K_{p, \max 1} < K_{p, \max 2}$. Based on this relationship, the equation for the rock fragmentation coefficient in the goaf can be optimized as follows:

$$K_p(x, y, z) = K_{p, \min} + \left[K_{p, \max 1} + (K_{p, \max 2} - K_{p, \max 1})e^{-a_2 d_2} - K_{p, \min} \right] e^{-a_1 d_1 (1 - e^{-\xi a_0 d_0})}$$

6.

Here, a_2 is the attenuation rate from the top of the goaf, $1/m; d_2$ is the distance from the top of the goaf, m.

The simulation results of the caving and fracture zones obtained using the discrete element analysis program under different footages of the No. 2 coal seam working face show that, on the one hand, when a 10 m layer is laid out, the extraction port of the roof

gas drainage roadway is just in the caving zone with good connectivity to the working face, resulting in a poor pumping effect. On the other hand, it also provides parameters for the size of the fluid simulation model and UDF of the surrounding rock caving.

4.2 Simulation results of high drainage roadway

Based on the characteristics of the caving and fracture zones, the actual parameters of the mine roadway combined with the curve shown in Fig. 4 determine the simulation models with different layout heights (10, 15, 20, 25, and 30 m) of the high drainage roadway. The model size is $X \times Y \times Z = 300 \text{ m} \times 146 \text{ m} \times 33 \text{ m}$, the height of the inlet and return air roadway is 4 m and the width is 3 m, the height and width of the drainage roadway are set to 3 m, and the length of the three roadways is 50 m. Figure 6 shows the simulation model. During the simulation, all the boundary conditions (such as the air intake and gas emission) in the software are ensured to be consistent.

The purpose of the simulation is to obtain the high drainage roadway layout with the best drainage effect; therefore, the related boundary conditions and simulation results, such as the pressure in the drainage roadway, drainage flow rate, and gas flow field distribution in the goaf, need not be consistent with the actual situation of the mine. Through simulation, the slice cloud diagram of the gas extraction results in the plane where the center point of the drainage roadway is located in the five layers with different layouts is obtained, as shown in Fig. 7. As shown, with the increase in the section height of the goaf, the gas distribution range of the high volume fraction shows a change trend of first increasing and then decreasing. The gas distribution range is the highest at the 20 m layer. From the analysis of the general law, because the gas is lighter than air, it easily floats up and accumulates in the upper part of the caving zone in the goaf of the working face, namely in the 20 m layer. With the increase in the height, the gas continues to float up after entering the range of the fracture zone; however, the total gas distribution is less than that at 20 m because the fracture development in the fracture zone is worse than that in the caving zone, consistent with the law presented by the simulation results.

To more intuitive and from the angle of quantitative judgment about five different layout layer gas extraction effect, from the fluid simulation software to extract the corresponding high drainage along the center point of the gas volume fraction value and map as shown in Fig. 8a curves, and calculate the average value of drawing as shown in Fig. 8(b) high extraction gas volume fraction in the lane changing with decorate a horizon of the curve.

The simulated curve in Fig. 8 shows that the volume fraction of the gas extracted from the high drainage roadway is the highest when the layout layer height is 20 m. It can be concluded that the gas extraction effect of the high drainage roadway should be the best under the premise that the gas emission quantity is consistent. Based on the above research, a scheme of the high drainage roadway layout has been proposed for the 22116 working face; it is changed from 10 m to 20 m and has been applied in the mine in early 2021.

5. Field Data After Re-arrangement Of High Drainage Roadway

After the high drainage roadway layout layer of the Jiaojiazhai 22116 working face was changed to 20 m, the connectivity between the high drainage roadway and the working face was tested by referring to the tracer gas detection point layout and test method shown in Fig. 5. Table 2 shows the SF₆ gas detection results of the working face. The five gas detection results listed in the table are the same and all are 0, that is, the SF₆ gas is not detected in the pumping pipeline of the high drainage roadway when the SF₆ gas is continuously released at points 1–18 for 15 min. This means that when the high drainage roadway layer at 20 m is laid out on the 22116 working face, the high drainage roadway will not be directly connected to the working face and result in fresh air flow to the pumping working face.

Table 2
SF₆ gas detection results of the working face

Layout layer	Test date	Release time /min	Detection concentration of SF ₆ gas in roof gas drainage roadway /ppm																	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
20 m	3-12	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3-15	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3-17	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3-18	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3-20	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

During the period from January to August in 2020 and 2021, the total amount of drainage and the pure amount of drainage gas in the high drainage roadway with two different strata layouts are recorded and calculated, and the data line graph shown in Fig. 9 is drawn. In the figure, the black lines represent the total amount of gas extracted from the top suction roadway, and the red lines represent the pure amount of gas extracted from the roadway. Due to the limited connectivity between the high drainage roadway and the working face, the total pumping flow in the high drainage roadway at the 10 m level is less than that at the 20 m level. To quantitatively analyze the advantages and disadvantages of the drainage effect of the high drainage roadway in the two different layers, the average pure amount of the gas drainage in the high drainage roadway is 2.06 m³/min, and the average total amount of the gas drainage is 64.07 m³/min, accounting for 3.2% of the total amount of gas. When the layer is at 10 m, the average pure gas extraction volume of the high drainage roadway is 0.41 m³/min, and the average total gas extraction volume is 15.35 m³/min, accounting for 2.7% of the total gas. Therefore, it can be concluded that the drainage effect of the rearranged high drainage roadway is indeed better than that of the layer at 10 m.

In addition to the recording and comparative analysis of the gas data in the high drainage roadway in the two different strata, the data of the gas volume fraction at the top corner of the working face before and after the rearrangement of the high drainage roadway were also observed. Figure 10 shows the recorded value of the gas volume fraction at the upper corner after the rearrangement of the high drainage roadway. The gas volume fraction at the top corner is lower than 0.5% after the rearrangement of the high drainage roadway, and this value decreases with the shortening of the high drainage roadway advancing in the working face.

In Fig. 10, the gas volume fraction at the top corner increases with the advancing of the working face when the high drainage roadway layer is arranged at 10 m. If no measures are taken, the gas at the upper corner would inevitably exceed the limit and cause the mine to stop production. However, the method of increasing the negative pressure of the drainage to increase the drainage flow was ineffective, as shown in Fig. 9. In the field application, the proposed scheme with the 20 m layer layout of the high drainage roadway is effective, and the problem of high volume fraction of the top corner tile is solved. Compared with the previous, the average daily output of the 22116 working face in the Jiaojiazhai mine is increased from 2600 t to 3500 t. With 400 yuan per ton as the coal price, the annual output value of the production increase is 330×900×400 = 119 million yuan, yielding evident economic and social benefits.

6 Conclusions

- (1) Based on the simulation results of the caving situation of the overlying strata of the No. 2 coal seam obtained using the discrete element analysis program, combined with the empirical formula, the height of the caving zone in the goaf of the 22116 working face of the Jiaojiazhai mine was determined to be 20 m. The tracer gas test results showed that the high drainage roadway is directly connected to the working face when the layer is 10 m; however, this situation will not occur when the layer is 20 m.
- (2) The law of the gas extraction results obtained using the fluid simulation software is consistent with the law obtained by the theoretical analysis for five groups of strata with different layouts of the high drainage roadway. The measured data showed that the total amount of extracted gas and pure amount of the extracted gas in the high drainage roadway are greater, and the volume fraction of the gas at the top corner was evidently reduced compared with that in the 10 m layer.

(3) The actual underground verification showed that the proposed scheme with the 20 m layer layout of the high drainage roadway can not only solve the problem of high gas volume fraction at the corner of the working face, but also help increase the daily output of the mine, resulting in evident economic and social benefits.

Declarations

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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Figures

Figure 1

Observed gas volume fraction at the top corner

a. overlying rock span fall condition

b. overburden plastic zone

c. vertical stress in overburden

d. horizontal stress in overburden

Figure 2

Deformation of surrounding rock when working face advances 30 m

a. overlying rock span fall condition

b. overburden plastic zone

c. vertical stress in overburden

d. horizontal stress in overburden

Figure 3

Deformation of surrounding rock when working face advances 300 m

Figure 4

Height variation curves for “two zones” with the advancing distance of the working face

Figure 5

Schematic of SF₆ gas release position

Figure 6

Figure 7

Simulation results of gas extraction in different layers of a high drainage roadway

Figure 8

Gas volume fraction of high drainage roadway in different layers

a. Layout layer 20 m

b. Layout layer 10 m

Figure 9

Data curve diagram of gas drainage in the high drainage roadway

Figure 10

Gas detection data from the upper corner of the 20 m high drainage roadway