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Research Article

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Study on the Distribution Law of Gas Concentration in the Goaf under the Action of High Pumping Alley in the Underlying Coal Seam Mining

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Abstract The large amount of gas emission from goaf is an important reason for exceeding the limit of gas concentration in the upper corner of the working face. High pumping alley can not only extract disaster gas from adjacent layers, but also take into account the extraction and treatment of gas in the goaf of the coal seam. To study the effectiveness of low level high pumping alley in controlling gas in the goaf of this coal seam, the 8714 working face in the 307 panel of the 12^{-2} coal seam in Jinhuagong Mine was taken as the research object. Through a combination of theoretical calculation and numerical simulation, the reasonable arrangement of high pumping alley layers was studied; On this basis, further simulation research was conducted on the distribution characteristics of gas concentration in the experimental working face, upper corner, and goaf under the action of high pumping alley, and the gas extraction effect of high pumping alley was analyzed. The results showed that after using high pumping alley to extract gas from the goaf in the 8714 working face, the gas concentration in the return airway of the working face remained below 0.18%, and the gas concentration in the upper corner also decreased to below 0.20%. This effectively prevented gas accumulation, prevented gas exceeding limit accidents in the working face, and ensured the safety of the working face.

Keywords Goaf; High pumping alley; Gas extraction; Upper corner;

1. Introduction

During the coal mining process, gas accidents are one of the frequent accidents in coal mines. Once the gas concentration in the working face exceeds the limit, there is a risk of gas explosion, which seriously threatens the safety of personnel and equipment [1]. During the mining process of the overlying coal seam in the goaf, due to the influence of mining, the coal mining face will form connecting cracks with the overlying old goaf space [2], leading to the influx of hazardous gases from adjacent layers into the goaf of the mining face, resulting in the accumulation of hazardous gases in the goaf. Under the negative pressure ventilation of the working face, disaster gases such as gas and CO_2 in the goaf are prone to flow into the working face, causing the concentration of disaster gases in the upper corner and return air flow of the working face to exceed the limit.

One of the effective measures to solve this problem is to use high pumping alley for gas extraction in goaf [3]. High pumping alley can quickly and efficiently intercept and extract disaster gases from adjacent layers, effectively avoiding the influx of disaster gases into the goaf of the mining face, and controlling the concentration of disaster gases in the upper corner of the working face and the return air flow exceeding the limit. In 1992, the High Pumping Alley was first used in the 15th coal seam of Yangquan Fifth Mine [4]. Its construction site was located in the return air roadway of the mining area, where a section of a flat roadway was first drilled along the coal pillars between the main roadway of the mining area. Then, a slope was raised to the adjacent layer, and the entire mining area was opened along the direction of the mining area. After the construction was completed, a closed wall was built at the bottom of the slope for pipe passing extraction, with a extraction rate between 80% and 90%. Afterwards, Yangquan No.3 Mine also adopted a high pumping alley approach to successfully solve the problem of gas exceeding the limit in the K8206 working face [5]. Wang Cheng used the K8206 fully mechanized caving face of Yangmei No.3 Mine as the engineering background to analyze the relationship between the negative pressure of gas extraction and the amount and concentration of gas extraction when using high pumping alley for gas extraction in the fully mechanized caving face. He conducted numerical simulation on the extraction effect under different extraction negative pressures and obtained the optimal extraction negative pressure [6]; Li Yibo, Yang Hongmin [7][8], and others have conducted research on key parameters such as the layout layer of the high pumping alley, and determined the layout parameters of the roof's high pumping alley. Wang Zhengang [9] and others proposed using the high pumping alley drainage method to treat the problem of gas exceeding the limit in the fully mechanized caving face, and determined the optimal drainage negative pressure through numerical simulation and on-site experiments; Yang Feng et al [10]. compared the effectiveness of three methods for preventing and controlling gas exceeding limits in fractured zone high-level pumping boreholes, high pumping alleys, and goaf pumping boreholes on site, and proved that the reasonable arrangement of high pumping alleys can effectively solve the problem of gas exceeding limits in close range coal seam mining.

The overlying area of the 8714 working face in the 307 panel of the 12^{-2} coal seam in Jinhua Palace Mine is the old goaf of the 11th coal seam. During the mining process, due to the gas outburst of the coal seam and the large amount of gas leakage from the overlying old goaf, a large amount of mixed disaster gas inside the goaf flowed into the working face, causing frequent high gas and high CO_2 phenomena in the upper corner of the working face and the return air flow, seriously affecting the safety production of the mine. Therefore, the Jinhua Palace Mine adopts high pumping alley extraction measures to simultaneously extract gas from the coal seam and overlying goaf, in order to achieve good governance effects. This article uses COMSOL software to simulate the distribution of gas concentration in the 8714 working face under high pumping alley extraction. It analyzes the changes and distribution characteristics of gas concentration in the 8714 working face and goaf under the action of high pumping alley, and combines with on-site measured data for simulation verification. It provides a reference for the treatment of gas in the goaf of this coal seam by low level high pumping alley extraction.

2. High Pumping Alley Principle for Controlling Gas in Goaf

High pumping alley is generally used to control the large influx of unloading gas from adjacent layers into the goaf of this coal seam, to avoid exceeding the limit of gas concentration in the upper corner of the working face. During the backfilling of the working face, in addition to the gas gushing out of the coal seam, the collapse of the roof has a depressurization effect on the adjacent layers, causing the fissure channels between the backfilling area and the adjacent layers to connect, causing the gas from the adjacent layers to rush into the goaf of the backfilling working face, resulting in the accumulation of gas in the goaf [11][12]. For the U-shaped ventilation system, the fresh air entering the mining face is divided into two parts, with one part flowing towards the working face to provide normal air supply to the coal mining face and bring the gas from the working face to the return air flow. The other part enters the goaf through the ventilation outlet of the working face, carrying out some of the gas inside the goaf and converging with the airflow of the working face at the upper corner (return air corner) of the working face. In addition, the roof near the upper corner is often suspended, and a large amount of gas gushes out from the goaf and adjacent layers, causing the gas in the working face and upper corner to exceed the limit [13]. High pumping alley gas extraction technology is based on the development and distribution law of mining fractures. It concentrates gas extraction in the roof fracture zone through construction specific gas extraction tunnels along the direction or inclination of the working face. It has the advantages of wide pressure relief range and large gas extraction flow rate [14][15].

3. Engineering Background

The 8714 working face of Jinhua Palace Mine is the first mining face in the 307 panel of the 12^{-2} coal seam, with a strike length of 1560m and a dip length of 196m. The average coal thickness is 4.17m, and the average mining height of the working face is 4.5m. It belongs to the high mining height coal mining technology. The working face adopts a dual roadway layout, with Lane 2714 serving as the intake and coal transportation channel, and Lane 5714 serving as the return air and material transportation channel. The layout diagram of the 8714 working face is shown in Figure 1. The main mining seam on this face is the No. 12 coal seam, with an average distance of 25m from the overlying No. 11 coal seam.

The gas content in the 12^{-2} coal seam is $3.54m^3/t$. The original gas content of the 8714 working face in the 307 panel is $1.95\text{-}2.54m^3/t$, with an average of $2.25m^3/t$. The minimum residual gas content is $0.28m^3/t$, and the range of desorbable gas is $1.49\text{-}2.26m^3/t$, with an average of $1.89m^3/t$. The absolute gas emission during the mining period is about $8m^3/min$.

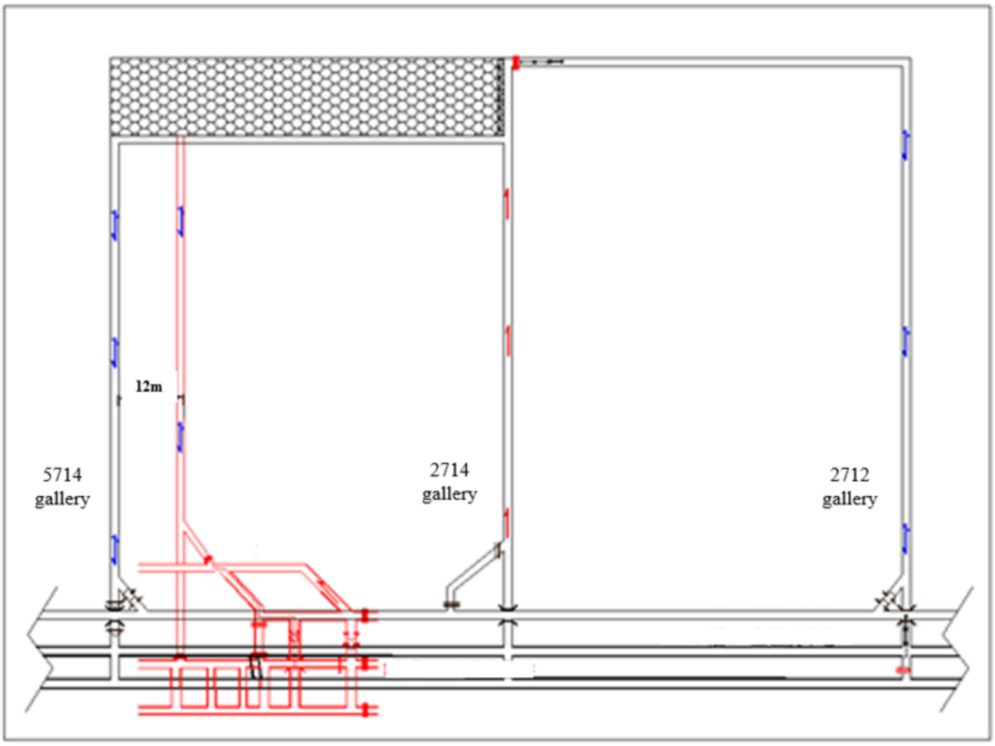


Figure 1: Schematic diagram of 8714 working face layout

During the mining process of the 8714 working face in the 307 panel of the 12^{-2} coal seam in Jinhua Palace Mine, high gas and high CO_2 phenomena frequently occurred in the upper corner of the 8714 working face and in the return air flow due to gas leakage from the overlying goaf and gas outburst from the coal seam. In order to solve the problem of high CO_2 and gas exceeding the limit, Jinhuagong Coal Mine adopts high pumping alley extraction measures to simultaneously extract CO_2 gas from the coal seam and the overlying goaf of the test working face, in order to achieve good governance effects.

4. Reasonable Layer Determination for High Pumping Alley

4.1 Theoretical Calculation

With the gradual progress of underground coal seam mining activities, the roof behind the goaf loses the support of the coal seam, causing the stress balance of the overlying rock layer to be disrupted. The roof moves, deforms, and fails under the combined action of its own gravity and overlying rock pressure. The roof located in the middle of the goaf first reaches its tensile strength limit and undergoes tensile failure, while the roof near the coal wall support area undergoes shear failure under the action of shear stress. As the distance from the goaf continues to increase, the overlying rock layers exhibit overall movement and deformation from bottom to top. At the same time, the deformation and failure of the overlying rock also show zonal differences, gradually forming falling zones, fracture zones, and curved subsidence zones from bottom to top, as shown in Figure 2. The fracture zone provides a transportation channel and storage space for the depressurized gas in the coal rock mass, and is the main place for gas accumulation in goaf. Whether the High pumping alley can be accurately arranged in this area is of great significance for gas extraction in goaf. If the High pumping alley is placed within the caving zone, it will be destroyed with the collapse of the roof rock layer in the goaf, resulting in poor gas extraction efficiency in the goaf; If the High pumping alley is arranged in a curved subsidence zone, the vertical distance from the coal seam and goaf is too large, and the integrity of the rock layers in the zone is good and the permeability is poor, making it easy to not extract gas. Therefore, the High pumping alley should be arranged within the overlying rock fracture zone. The development height of fracture zones is generally achieved through a combination of theoretical calculations and numerical simulations.

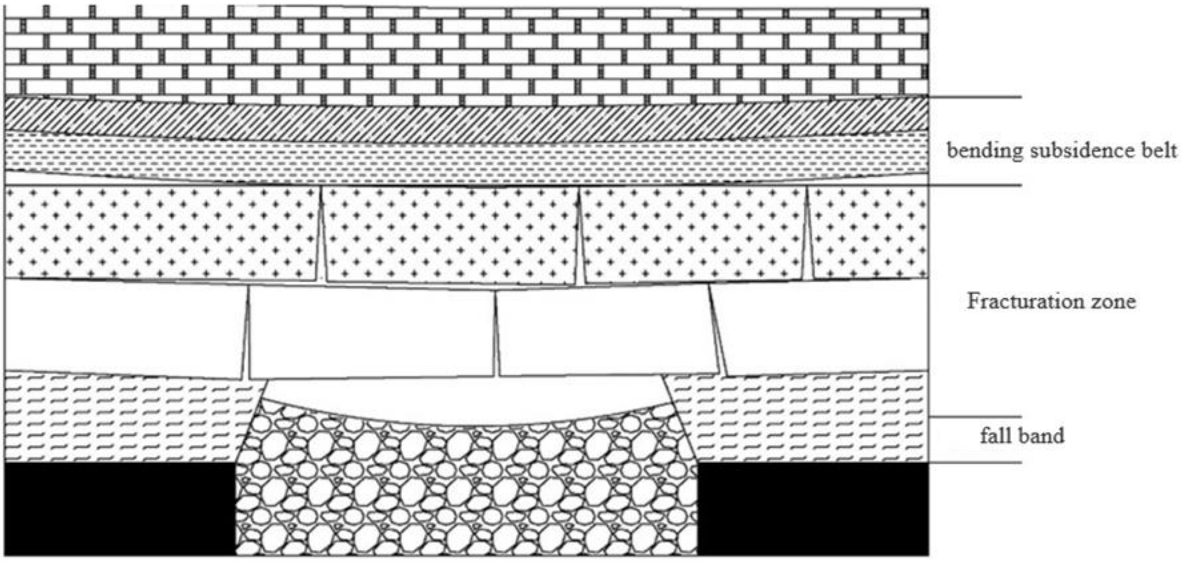


Figure 2: Division of three zones of overlying rock in goaf

The development height of fracture zones in coal mining faces can be estimated using empirical formulas. According to the "Three Down" coal mining regulations, the roof of the 8714 working face of the 12^{-2} # coal seam is mainly composed of quartz and mudstone, with a compressive strength generally above 70MPa, which belongs to a hard coal seam. Formulas (1) and (2) [16] are selected as empirical formulas for calculating the heights of collapse zones and fracture zones.

$$H_m = \frac{100\sum M}{2.1\sum M+16} \pm 2.5 \qquad (1)$$

$$H_f = \frac{100\sum M}{1.2\sum M+2.0} \pm 8.9 \qquad (2)$$

In the formula: H_m is the height of the falling zone, m;H_f is the height of the falling zone, m; M is the thickness of the coal seam being mined, m;

By substituting the coal seam mining height of 4.5m into formulas (1) and (2), it can be calculated that the range of values for the height of the caving zone is 15.18-20.18m, with an intermediate value of 17.68m. The height of the fracture zone is 51.91~69.71m, with a median value of 60.81m.

4.2 Numerical Simulation Research

Based on the actual geological conditions of the 8714 working face in Jinhuagong Coal Mine, 3DEC numerical simulation software was used to establish a three-dimensional numerical calculation model as shown in Figure 4-2, with the mining layout and rock occurrence conditions of the 8712 working face, 8714 working face, and 307 working face in the 11th coal seam of Jinhuagong Coal Mine as the background. The X-axis in the model represents the direction of the working face, the Y-axis represents the direction of the working face inclination, and the Z-axis represents the relative height of the reference layer to the bottom plate. The calculated model size is 400m (length)×370m (width) ×100m (height), and the distance between the 11th coal seam and the 12^{-2} coal seam is 25m.

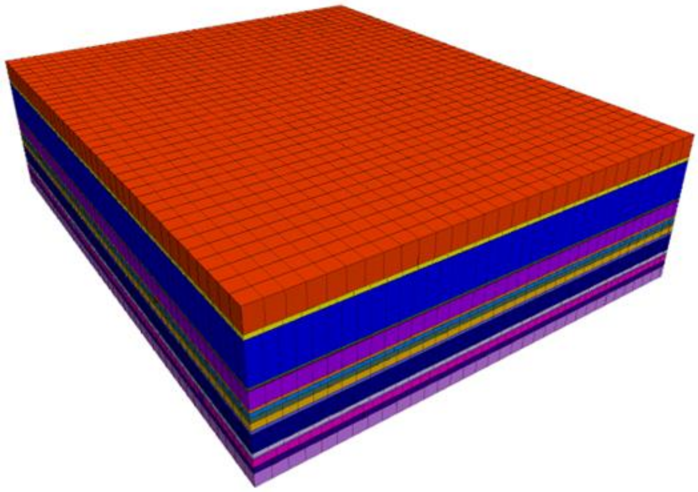
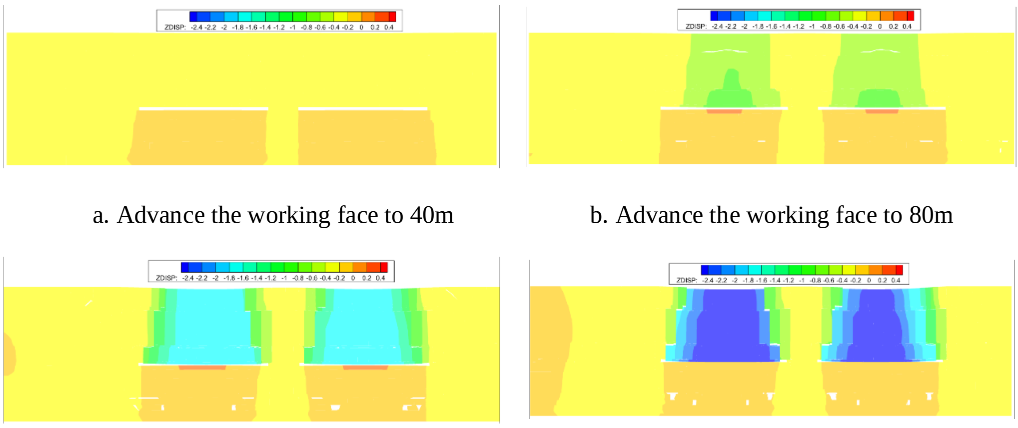


Figure 3: Numerical Model of Working Face

To study the movement and deformation of the overlying strata after coal mining in the 8714 working face, this study is based on the analysis of the vertical displacement of the overlying strata in the mining area, indirectly reflecting the evolution process of the fracture zone. With the mining of coal seams, the stress balance of the overlying rock in the goaf is disrupted. Under the combined action of self weight and upper load, the overlying rock fractures, collapses, bends and sinks until it contacts and compacts with the bottom plate of the goaf to reach a new equilibrium state. When the advancing working face reaches 40m, 80m, 120m, and 160m, the vertical displacement changes of the mining area are shown in Figure 3. The displacement changes of the overlying strata directly above the goaf when the advancing working face reaches 40m, 80m, 120m, and 160m are shown in Figure 4.

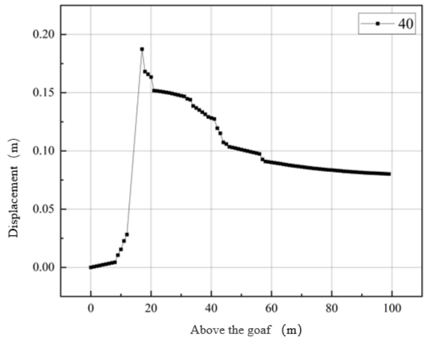


a. Advance the working face to 40m b. Advance the working face to 80m

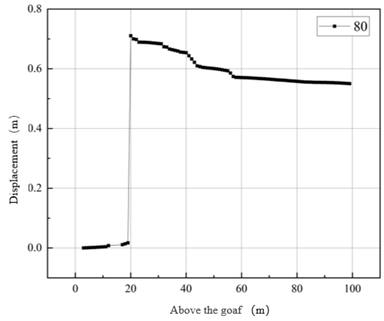
c. Advance the working face to 120m d. Advance the working face to 160m

Figure 4: Vertical displacement cloud map of the top plate

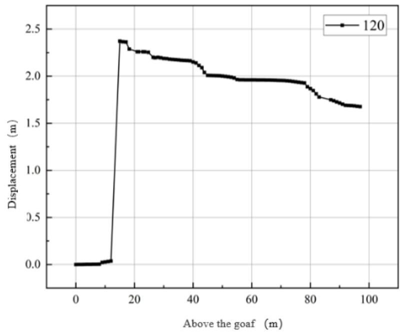
From Figures 3 and 4, it can be seen that as the working face advances, the subsidence value of the overlying rock in the goaf gradually increases. When the working face is pushed to 120m, the subsidence value of the overlying rock in the goaf gradually increases, with a maximum subsidence value of about 2.37m. When the working face is pushed to 160m, the subsidence value of the overlying rock in the goaf continues to increase. At this time, the maximum subsidence value is about 4.43m, which is close to the mining height of 4.5m, indicating that mining has been basically enriched at this time. The subsidence and collapse of the overlying rock will compact the goaf, and the development of water conducting fracture zones is basically stable. At this point, the goaf can be divided into three areas, with 0-1.89m located in the area with the maximum subsidence value, which is the range of the caving zone; 18.89-63.64m is located in the area with relatively large subsidence values, within the range of fracture zones; 63.64m and above are located in the normal subsidence area, which is a curved subsidence zone. Therefore, the maximum height of the roof caving zone is about 18.89m, and the maximum height of the fracture zone is about 63.64m



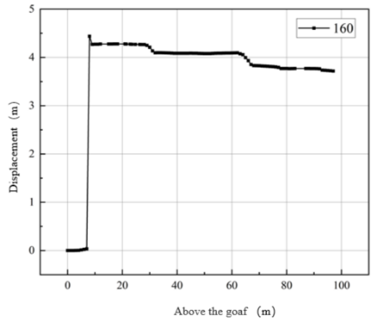
a. Advance the working face to 40m



b. Advance the working face to 80m



c. Advance the working face to 120m



d. Advance the working face to 160m

Figure 5: Vertical displacement diagram of the top plate

Based on comprehensive theoretical calculations, numerical simulation analysis, and on-site measurement data, the height range of the "three zones" of the overlying strata in the goaf of the 8714 working face of the 12^{-2} coal seam in Jinhuagong Mine can be divided into: the caving zone is 0-18.89m above the coal seam roof, the fracture zone is 18.89-63.64m above the coal seam roof, and the roof above 63.64m is a curved subsidence zone. The reasonable level of the high extraction roadway layout is within the range of 18.89~63.64m from the coal seam roof of the working face.

5. Study on the Distribution Law of Gas Concentration in Mining Areas

Based on the research and analysis of reasonable layers in the High pumping alley, and combined with the actual mining situation of the 8714 working face, a COMSOL numerical model is established, as shown in Figure 6. The length, width, and height (X direction, Y direction, Z direction) of the model are 257m, 196m, and 50m, respectively. The length, width, and height of the goaf are 200m, 196m, and 50m, respectively; The length, width (strike length), and height of the working face are 7m, 196m, and 4m, respectively; The length, width, and height of the tunnel are 50m, 5.6m, and 4m respectively; The size of the High pumping alley section is 3×2.5m.

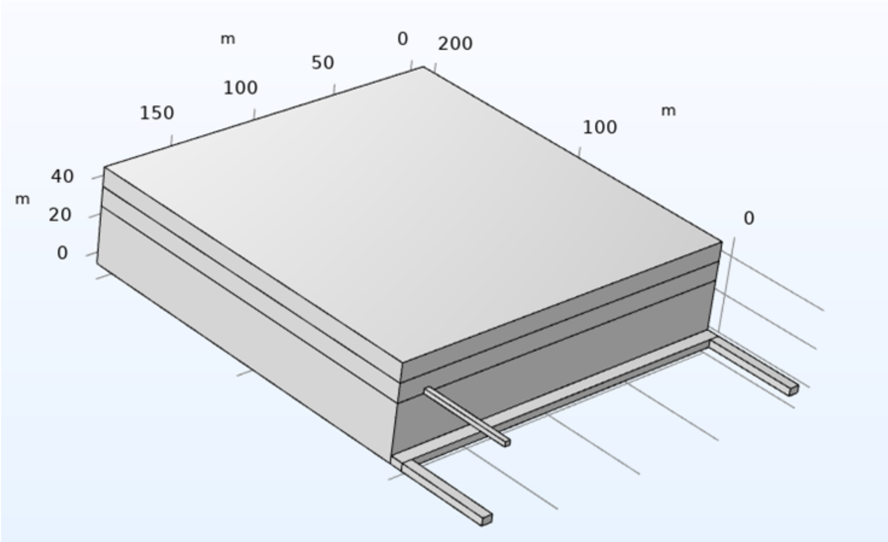


Figure 6: Numerical Model of High Extraction Roadway Extraction

5.1 Research on Gas Concentration Distribution in Working Faces

The changes in gas concentration in the upper corner, return air flow, and high pumping alley of the 8714 working face under high pumping alley extraction conditions obtained through numerical simulation using COMSOL software are shown in Figure 7. After the implementation of high pumping alley extraction measures, the gas concentration in the mixed gas extracted from high pumping alley rapidly increased to around 2.2%. As the extraction effect gradually expands and stabilizes, a large amount of gas inside the goaf is extracted, the air pressure inside the goaf decreases, and the airflow will flow towards the low-pressure area. Therefore, the leakage air volume of the working face increases, and the airflow entering the goaf increases, which is continuously extracted by the high pumping alley. Most of the fresh airflow entering the goaf through the leakage port is stably extracted into the high pumping alley, The gas concentration in the mixed gas extracted from the high pumping alley gradually decreases and eventually stabilizes at around 1.9%. At the same time, the entire process contains gas in the airflow, causing a large amount of gas to be carried away and greatly reducing the amount of gas entering the working face, avoiding the accumulation of excessive gas in the return airflow and upper corner. At this time, under the action of high pumping alley, the gas concentration in the upper corner and return air flow of the 8714 working face rapidly decreases. After reaching stability, the gas concentration at the upper corner is 0.20%, and the gas concentration in the return air flow is 0.19%. Can effectively meet the safety production needs of the working face.

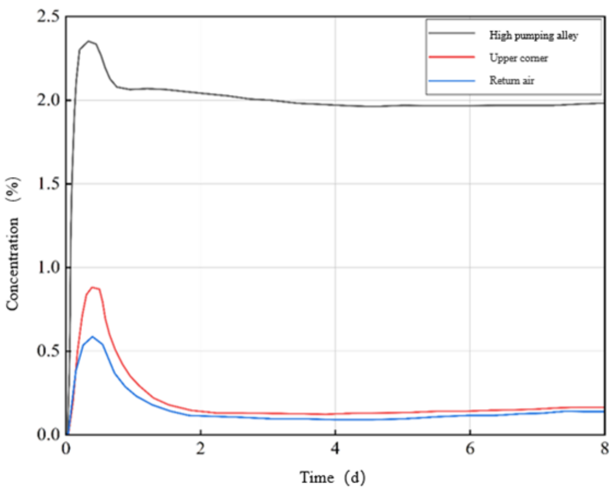


Figure 7: Changes in gas concentration at various locations on the working face

Figure 7 shows the simulation results of CH_4 concentration along the working face under high pumping alley extraction conditions. It can be seen that the CH_4 concentration shows an overall upward trend from the head to the middle to the tail of the experimental working face, and the closer it is to the tail of the working face, the more obvious the increasing trend. Affected by the High pumping alley extraction, the CH_4 concentration is close to 0% at a distance of 0-100 from the transport channel; At a distance of 100m from the transportation trough, the CH_4 concentration begins to rise. At the end of the working face, the CH_4 concentration rises to 0.19%, and there is still an upward trend near the upper corner.

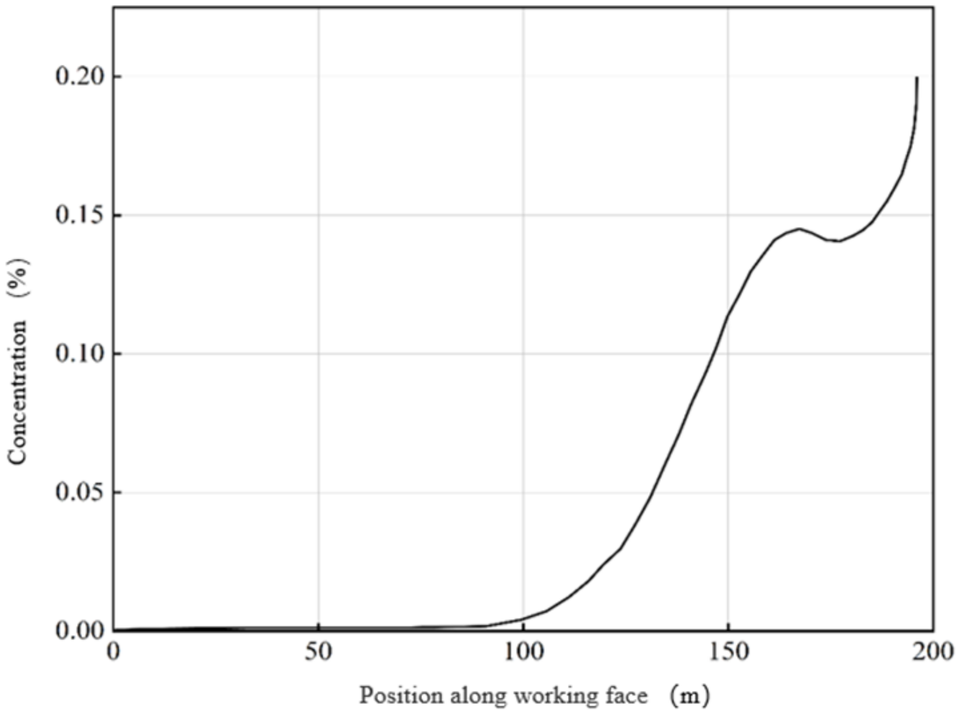
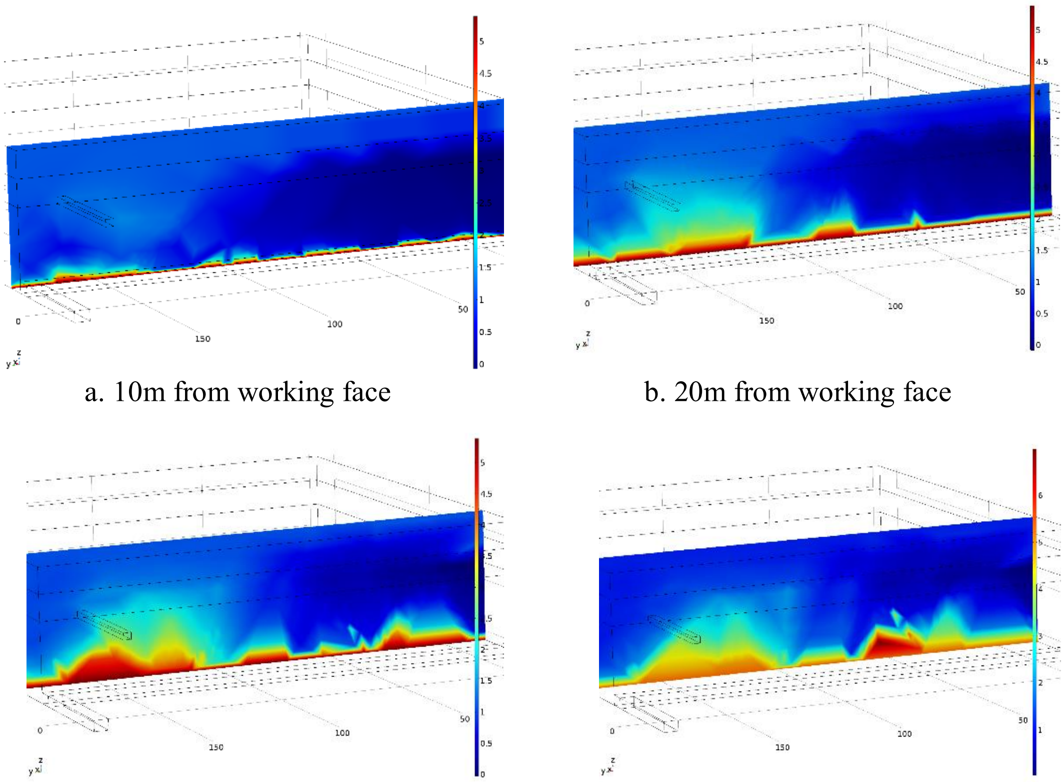


Figure 8: Gas concentration variation along the working face inclination

5.2 Research on the Distribution Characteristics of Gas in Goaf

The variation of gas concentration distribution in goaf under high pumping alley extraction conditions is shown in Figure 8. The gas concentration in the goaf gradually decreases vertically from the bottom to the top. This is because after the mining of the 8714 working face, a portion of the fallen coal was buried in the goaf. This residual coal, under the pressure relief and crushing effects, continuously releases gas, forming a gas release source on the floor of the goaf. Under the action of air leakage in the working face, the gas released in the goaf is diluted. In the direction of direction, in the goaf 10 meters deep from the working face, as shown in Figure 9a. Under the extraction effect of the high extraction roadway, the air leakage volume of the working face also increases, playing a certain dilution role. Under the dual effect, the average gas concentration in the goaf is less than 1%, especially in the goaf on the inlet side, where the gas concentration is close to 0, and there is a relatively high gas concentration (5%) only at the bottom coal seam. At this point, the gas concentration in the High pumping alley is still relatively low. In the goaf 20 meters deep from the working face, as shown in Figure 9b. At this time, the dilution effect of the air leakage in the goaf is weakened, and under the dilution effect of the air leakage in the goaf on the inlet side, the gas concentration still fluctuates at 0%. Due to the weakening of the dilution airflow effect, the range of action of High pumping alley is still significant. Under the extraction of High pumping alley, the gas concentration in the goaf on the return air side gradually increases to about 3%, and a significant gas upward phenomenon appears from 110 meters away from the intake side. This is mainly caused by the negative pressure extraction effect of High pumping alley.



a. 10m from working face

b. 20m from working face

c. 30m from working face

d. 35m from working face

Figure 9: Gas concentration distribution in goaf

In the goaf 30 meters away from the working face, as shown in Figure 9c. It can be clearly observed that there is a hill shaped gas accumulation area near the return air side of the goaf. In the environment where the dilution effect of air leakage is further weakened, there is a general phenomenon of gas concentration increase at 30 meters in the goaf, especially when the gas concentration in the bottom plate reaches about 5%. At a distance of 110 to 180 meters from the intake side of the goaf, the accumulation of gas in the "hill" is more pronounced, with a concentration of about 2% -5%. Compared to the distance of 110 meters from the intake side of the goaf, the negative pressure pumping distance of about 30 meters from the High pumping alley has obvious distance advantages and negative pressure concentration advantages. Therefore, under the action of High pumping alley, gas migration and accumulation phenomenon occurred at a distance of 110 meters to 180 meters from the intake side of the goaf. At a distance of 35 meters from the working face, the goaf is shown in Figure 5-4d. The phenomenon of gas accumulation "hill" gradually weakens, which may be due to the fact that as the pumping distance increases, it exceeds the range of action of High pumping alley, and the pumping effect of High pumping alley weakens. At the same time, the dilution effect of air leakage in the goaf is further weakened, resulting in a more uniform distribution of gas concentration in the goaf.

From the simulation results, it can be seen that under the High pumping alley extraction conditions, the gas concentration inside the goaf shows a pattern of first increasing, then decreasing, and finally stabilizing. Within the scope of action of High pumping alley, the closer to the working face, the more obvious the pumping effect of High pumping alley, and the lower the gas concentration inside the goaf. When approaching the working face, the average gas concentration in the goaf is less than 1%, which effectively solves the problem of gas emission in the goaf, significantly reduces the gas concentration in the return air flow and upper corner, and meets the safety production standards.

6. Conclusion

1) High pumping alley effectively controls gas in the coal seam. The numerical simulation results and on-site monitoring data show that high pumping alley extraction significantly reduces gas concentrations in the return air flow and upper corner of the 8714 test working face. The gas concentration in the

return air alley remained below 0.18%, while the gas concentration in the upper corner fell to less than 0.20%. The problem of gas exceeding the limit was successfully resolved, demonstrating the efficacy of high pumping alley extraction in treating gas in the goaf of this coal seam.

2) The distribution pattern of gas concentration in the goaf of the 8714 experimental working face was obtained using high pumping alley action. Because of the high pumping alley extraction, the gas concentration in the goaf near the working face is significantly reduced. As the distance from the working face increases, so does the gas concentration; however, the gas concentration in the deep goaf remains relatively stable. In the vertical direction, the gas concentration in the goaf generally decreases from bottom to top due to the continuous release of gas from high pumping alley and residual coal within the goaf.

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