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Study on Nitrogen Injection Fire Prevention and Extinguishing Technology in Spontaneous Combustion Gob Based on Gob-Side Entry Retaining

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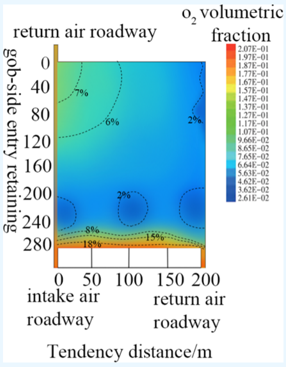
ABSTRACT: Under the gob-side entry retaining mining mode with roof cutting and pressure relief (GERRC), the gob and retained roadway section are interconnected to create an open area. Owing to the increased airflow, the coal remnants in the gob are more prone to spontaneous combustion. This study aimed to investigate the distribution of oxygen concentration within a gob and identify optimal parameters for nitrogen injection. The engineering context was the "110 method" introduced in the 1201 working face of the South Five mining area at Daxing. Computational fluid dynamics simulation software was used to analyze the effects of various nitrogen injection treatment parameters on the overall performance of the gob, including their impact on oxygen distribution. The simulation results showed that air leakage within the gob primarily originates from the working face adjacent to the intake roadway, as well as gaps within the retained roadway. The increased air leakage causes the high O_2 concentration range in the gob to expand, and the retained roadway section is connected to an area with a high concentration of oxygen near the working face, which increases the risk of residual coal spontaneous combustion. The results show that the optimal nitrogen injection conditions for inerting and reducing the risk of spontaneous combustion within the gob require an injection quantity of 500 m^3/h, with the injection point located at a depth of 60 m. With these parameters, the range of the oxidation zone was significantly reduced. To monitor the O_2 concentration and temperature change curves in the gob during the project implementation, a bundle tube monitoring system was used, considering the actual mining situation. By varying the nitrogen injection spacing and quantity, we found that injecting nitrogen at a spacing of 30 m and at a quantity of 500 m^3/h effectively placed most areas of the gob in the suffocation zone, reducing the risk of spontaneous combustion of residual coal. The accuracy of the simulation was verified. The study offers valuable insights into improving safety in coal mines and reducing spontaneous combustion incidents, providing important reference significance for fire prevention and control.



1. INTRODUCTION

GERRC is regarded as the third technological revolution in longwall mining in China.[1−4] By breaking the pressure transmission of the roof through directional pre-splitting and roof cutting, automatic roadway formation and coal pillar-free mining are achieved, aided by the mine pressure.[5−7] This phenomenon changes gas migration, causing fresh air to leak continuously into the gob from the working face.[8−10] The increased likelihood of spontaneous combustion in residual coal[11−14] not only decreases the economic viability of coal mining but also poses significant threats to the safety of underground workers.[15−17] Many scholars have conducted extensive research in this area. Wang et al.[18] analyzed and calculated the expansion coefficient of collapsed gangue over time and space, and they examined the effect of roof movement on the flow field in a mining scenario where the gangue is retained in the entryway via a cutting method. Lin et al.[19] analyzed the coal seam stress and obtained the dynamic response of coal permeability to coal seam stress, which indicated that permeability and porosity are negatively correlated with stress. Ma et al.[20] developed a mechanical analysis and numerical simulation-based approach for investigating the cutting top connectivity and its design methodology. Wang[21] effectively addressed spontaneous combustion and fire hazard problems within the gob-side entry retaining by applying comprehensive fire prevention measures such as air control and nitrogen injection. Qi et al.[22] used COMSOL simulation to study the difference in fire prevention and control effect with nitrogen injection in different locations in the gob, concluding that the location of nitrogen injection has a notable effect on the minimum threshold of the oxidation spontaneous combustion zone. However, the impact on the maximum threshold was relatively insignificant. Sun et al.[23]

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used three-dimensional CT reconstruction technology to extract the pore network structure of a coal sample and found that the injectivity and permeability of the heated coal samples were poor after nitrogen injection. Chai[24] conducted a temperature-programmed experiment on coal and improved the prediction index gas system of SC, suggesting that CO and C_2H_4 can be used as warning indicators for suspended solids in the gob. The scope of the "three zones" of spontaneous combustion can be comprehensively determined by the oxygen concentration, air leakage velocity, and temperature in the gob.[25,26] Through the coal spontaneous combustion experiment, Gui et al.[27] developed a method to determine the "three zones" of a gob using O_2 concentration through regression analysis. Dai[28] prevented residual coal spontaneous combustion accidents using a fire prevention system comprising pressure equalization, gas monitoring, and nitrogen injection. Xue[29] proposed a gob fire prevention technology that combines inertization and reduction in oxygen concentration, considering the practical characteristics of fire hazards in mining operations. The technology includes measures such as heat absorption and cooling. Zhang et al.[30] conducted pressure tests to investigate how different nitrogen injection pressures affect the O_2 concentration in a gob. Wang[31] implemented an engineering project on fire prevention by nitrogen injection and concluded that the diffusion radius of nitrogen gas decreases and fluctuates with increasing nitrogen injection intensity. Nikodem[32] replaced the O_2 in the gob of a coal mine with inert gas and demonstrated that inertization effectively mitigates the danger of spontaneous combustion. Tao et al.[33] developed a closed mining face to improve the purity of extracted gas and studied the effect of micropores in coal on residual coal spontaneous combustion using low-temperature nitrogen adsorption. However, after implementing the "Y"-type ventilation system with GERRC, the airflow pattern within the gob changed. Changes in the O_2 concentration in the gob and the optimal nitrogen injection parameters under the GERRC mode still lack in-depth research.[34−37] To address safety concerns related to fire prevention and inertization in a gob, we used CFD simulation in this study to investigate how the O_2 concentration in a gob is influenced by node pressure energy change in the ventilation system during the working face advancement. The "Y"-type ventilation in the GERRC mode were studied in-depth to address safety problems related to fire prevention and inertization in the gob.

2. ENGINEERING BACKGROUND

2.1. Working Face Overview. The working face considered in this study is in the mining area of Daxing Coal Mine in the southern region. The working face has a dip width of 195 m and a length of 1221 m along the strike, with a total area covering 238,095 m^2. The coal seam under the working face is characterized by noncohesive properties, and the thickness of the coal seam varies between 1.42 and 2.35 m, with an average thickness of 1.84 m. The coal seam in the southern part is thinner than that in the northern part, and the mining boundary is located near the lowest mining line. The coal seam structure in the southern part of the working face is complex. One to five layers of interlayered rock are in the coal seam, which is mainly composed of medium sandstone, mudstone, and carbonaceous mudstone, with a thickness of 0.08 to 0.81 m. During the tunneling phase of the excavation, the coal seam encountered local metamorphosis and sporadic, irregular igneous rock formations, which had no effect on the coal seam. The classification of coal seams prone to spontaneous combustion falls under level I in terms of the tendency for spontaneous combustion.

2.2. Cause Analysis of Spontaneous Combustion. Initially, the South Five 1201 working face had a "U"-type ventilation. However, the upper corner of the working face was frequently affected by the dynamic changes in the gas flow in the gob, leading to the gas exceeding the limit. To improve economic efficiency and prevent the gas from exceeding the limit in the upper corner, a gob-side roadway was constructed when the working face reached the cutting eye of the 14-1 working face. The transport roadway was used as the return airway for subsequent working faces, as shown in Figure 1. As production progressed, the length of the retaining roadway increased. Currently, the gob is directly connected to the retaining roadway, causing leakage airflow through the gob from the retaining roadway. Consequently, the working face ventilation network, gas transport laws in the gob, and the gob flow field undergo changes. Taking into account the air leakage in the gob, the ventilation network can be considered as a corner-connected structure from branches and nodes. As the working face is mined, the sealing walls along the retaining roadway may be inadequately sealed or deformed by pressure, forming a leakage channel between the retaining roadway and the gob. This phenomenon results in long-term O_2 supply to the gob, altering the spontaneous combustion risk zone and increasing the range and risk of natural combustion.

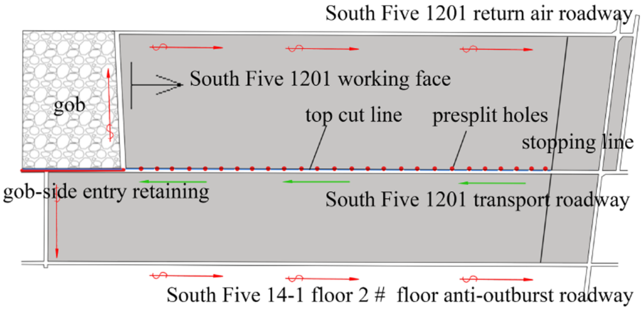


Figure 1. Layout of South Five 1201 working face.

3. MODEL CONSTRUCTION

Based on practical work, a homogeneous porous media gob model with 280 m length, 200 m width, and 50 m height was established. The intake and return air roadways were set at 4.2 m × 3.1 m, with a working face width of 200 m and a height of 10 m, as shown in Figure 2. The formula used to calculate the porosity of the gob is $n = 1 - \frac{1}{K}$,

where K is the bulking coefficient of the gob.

The formula for calculating bulking coefficient is $K = \frac{V}{V_0}$,

where V is the volume change of the rock under external forces and V_0 is the initial volume of the rock before the external forces were applied.

The formula for calculating permeability is $K_p = \frac{d^2 n^3}{150(1-n)^2}$,

where K_p is the permeability, m^2; n is the porosity of the porous medium; and d is the particle diameter, m.

The pressure relief zone was designed as a retaining roadway, and the boundary surface between the retaining roadway and gob was set as an interface. Because of the

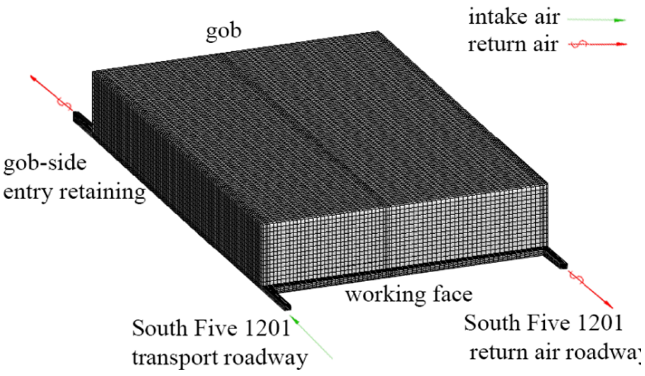


Figure 2. Gob model of the South Five 1201.

unknown flow velocity and pressure of the return air roadways, the velocity and pressure were modeled as a free flow. The gob filling rate was obtained through PFC discrete element numerical simulations with real mine data and written into UDF files, which were imported into Fluent to call the DEFINE_INIT macro function. The basic parameters are presented in Table 1.

Table 1. Basic Parameters

project	parameters
air distribution volume	1891.2 m^3/min
transport roadway air velocity	1.35 m/s
floor anti-outburst roadway air velocity	free flow
return air roadway air velocity	free flow
permeability	2.31×10^{-15} m^2
porosity	0.26
gob filling rate	86.4%
bulking coefficient	1.38

4. RESULTS AND DISCUSSION

4.1. Analysis of Air Flow Field in the Gob.

Figure 3 depicts the wind pressure cloud diagram of a nonuniform gob with a longitudinal length of 280 m. The simulation parameters were an air flow rate of 25 m^3/s for the intake air roadway and an air flow rate of 11.52 m^3/s for the returning air roadway. The air flow rate of the working face was 1500 m^3/min and that of the floor anti-outburst roadway was 360 m^3/min. Fresh air moved into the return air roadway and the floor anti-outburst roadway after passing through the working face. At the initial air velocity, the maximum pressure was 32.53 Pa in the intake air roadway; the pressure was lower in the deeper section of the gob closer to the return air roadway. The pressure decreased gradually along the intake airway route in the direction, and the lowest pressure point (1.12 Pa) was at the upper corner. The implementation of the GERRC technique in mining areas increased the pressure of the surrounding rock and amplified airflow leakages. The gob flow field caused a decrease in pressure potential from the retaining roadway and return air roadway to the interior of the gob. This phenomenon resulted in a pressure difference of up to 31.41 Pa between the intake air roadway and return air roadway in the simulation. Leaked air mainly flowed out through the cracks in the roadway walls. The retaining roadway was directly connected to the gob, raising the pressure levels across the retaining roadway segment because of the void space within the gob.

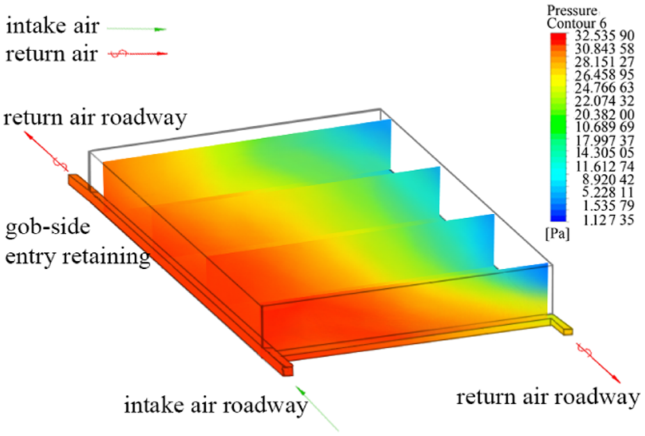


Figure 3. Wind pressure simulation cloud diagram of the gob.

An analysis of the simulation results shows the air leakage for different lengths of the retaining roadway, as illustrated in Figure 4. During the initial phase of mining, as the working face advanced within the range of 0−500 m, the airflow moved from the retaining roadway toward the gob. When the length of the retaining roadway increased, the air leakage rate increased accordingly. When the working face advanced to 500 m, the air leakage rate reached its maximum value of 247 m^3/min. Subsequently, within the range of 500−1300 m, the air leakage rate gradually decreased. As the working face advanced to 1300 m, the air flow moved from the retaining roadway to the gob, resulting in an air leakage rate of 175 m^3/min. During mining, the mining pressure caused a deformation to the roadway, which altered the cross-sectional area, shape, and smoothness of the roadway. When mining near the boundary, the roadway underwent a certain deformation, increasing the friction coefficient 1.5 times and decreasing the cross-sectional area to 85% of the original size, which obstructed the air flow and decreased the air leakage.

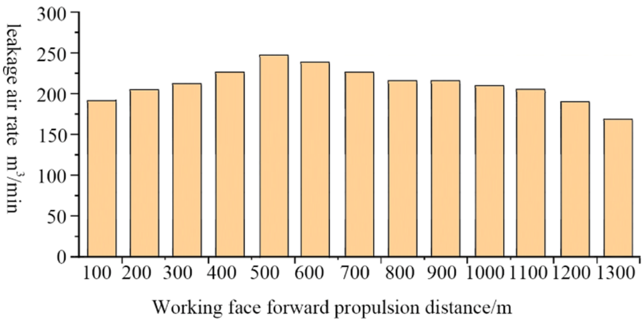


Figure 4. Air leakage rate under different lengths of entry retaining.

4.2. Distribution Characteristics of O_2 Concentration in the Gob.

On-site measurements, laboratory analysis, and gas chromatography were used to assess the characteristic parameters of coal spontaneous combustion and gas composition in the South Five 1201 working face of Daxing Coal Mine. Numerical simulation analysis was used to uncover spatial distribution profiles of O_2 concentration and temperature variations in the gob. The findings provide comprehensive insights into the laws governing spontaneous combustion of residual coal in the gob.

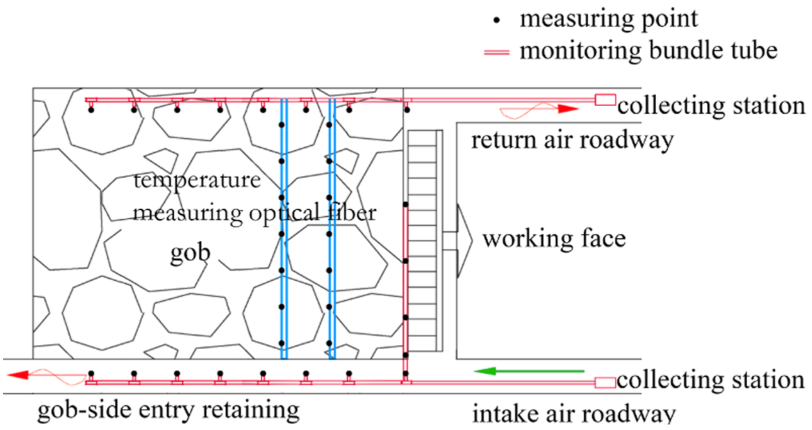


Figure 5. O_2 concentration and temperature measuring point location in the gob.

The layout of the gob O_2 concentration observation pipeline in the South Five 1201 working face is shown in Figure 5. Two fire monitoring bundle tubes were laid from the return air roadway to the gob direction, spanning a length of 40−80 m. Monitoring points were arranged in the retaining roadway to monitor fire in the gob. After every 15 m of advancing the working face and installing the first set of support on the transportation roadway side, one 4-way pipe was pre-embedded for pressure difference observation and sampling, and the end was pre-embedded in the upper part of the gob to a depth of 12 m. To prevent water accumulation from blocking the bundle tube, the monitoring points were raised beyond 1.2 m, and an iron box with holes was used to cover the probe outside to prevent squeezing. A tee was used to connect the two monitoring points, one end of which penetrated the sealed wall to the glue transportation roadway as a gas extraction point and temperature observation point. A specification bundle tube ($\varphi 8$) was used for gas extraction, and a DN40 steel pipe was penetrated as a protective casing.

Sampling was performed once in the morning every day. The measured components were O_2 concentration and temperature. Figure 6 depicts the cloud map of O_2 concentration distribution within the gob. The figure indicates that the main cause of high O_2 concentration was the significant air leakage on the intake air roadway side. In most intervals, the gas sampling analysis results of the observation bundle tube in the retaining roadway section show that the edge flow closer to the retaining roadway had better mobility. This phenomenon occurred because of the formation of an open space between the retaining roadway and the gob. The distribution of O_2 concentration was affected by the flow field, decreasing from the retaining roadway to the interior of the gob. As the air leakage flow was primarily from the side closer to the intake air roadway, the O_2 concentration was higher on the intake air roadway side because of a smaller change in O_2 concentration compared to that of the return air roadway side. Moreover, the width and depth of the higher concentration region were larger on the intake air roadway side. The gas composition was relatively stable and mainly consisted of air. Within a distance of 80 m from the working face on the intake air roadway side, the O_2 concentration remained consistently at or above 18%. Additionally, the high O_2 concentration range area of the retaining roadway segment was connected to the working face and diffused deeper into the gob because of air leakage. This area demands priority attention as it is more susceptible to natural combustion. In the deeper regions of the gob closer to the return air roadway, the degree of compaction increased because of caving pressure, resulting in reduced air leakage and increased O_2 consumption of residual coal, mainly in the form of heat dissipation zone.

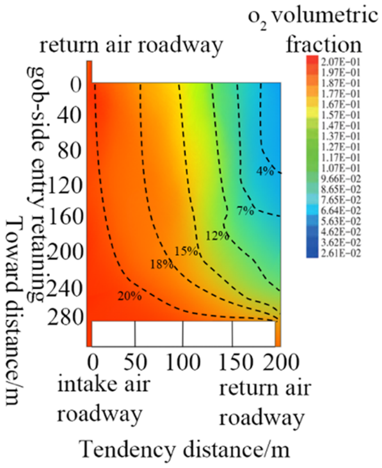


Figure 6. Distribution cloud map of O_2 concentration in the gob.

Temperature index is an empirical indicator for dividing the “three zones” of spontaneous combustion in the gob. An analysis of the fire monitoring data is illustrated in Figure 7. The average temperature of the monitoring fiber at the gob has remained stable between 24 and 26 °C since mining began, indicating that the optical fiber is located in a stable position without any abnormal temperature increase. The average temperature in the return air roadway fluctuated between 34 and 38 °C, with large fluctuations occurring at a distance of 220 m from the working face. The temperature was the highest (43.94 °C) at a distance of 252 m from the return air roadway. The other high-temperature points were mainly located near the starting point of the working face, with only two high-temperature points occurring at distances of 228 and 269 m from the working face. Although there were five relatively high-temperature points, they rapidly decreased to normal levels. Therefore, the areas where high-temperature changes occurred should be focused on, which are the range of 140−178 m in the return air roadway, the 228 m point, the 252 m point, and the 269 m point in the return air roadway.

4.3. Analysis of Fire Prevention and Extinguishing under Different Nitrogen Injection Parameters. The fire

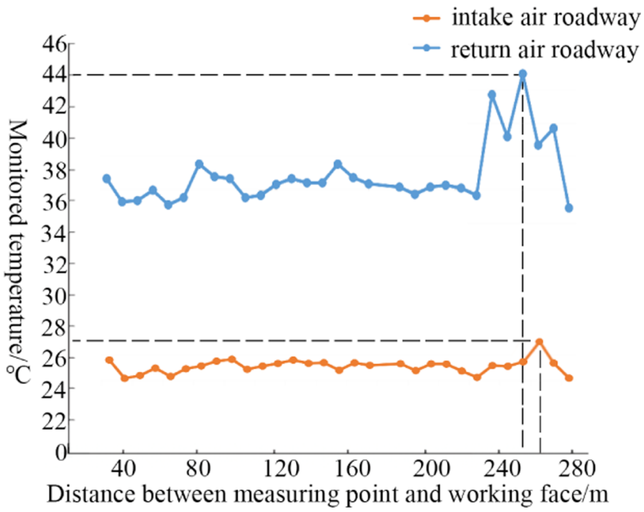


Figure 7. Temperature change curve of intake air roadway and return air roadway.

prevention and extinguishing effects differ under different nitrogen injection processes. We integrated the measured data of the mining process and the actual mine conditions to establish a relevant mathematical model, which was then used for numerical simulation. The O_2 concentration index was taken as the basis for dividing the "three zones" of spontaneous combustion in the gob: heat dissipation zone, O_2 concentration >18.0%; oxidation temperature rising zone, $18.0\% \geq O_2$ concentration ≥8.0%; and suffocation zone, O_2 concentration <8.0%. The primary objective of this study was to explore the efficacy of different nitrogen injection positions and volumes, which will help determine the optimal parameters for nitrogen injection. These findings can then be utilized as a guide for fire prevention and extinguishing measures in the gob under the GERRC mining mode.

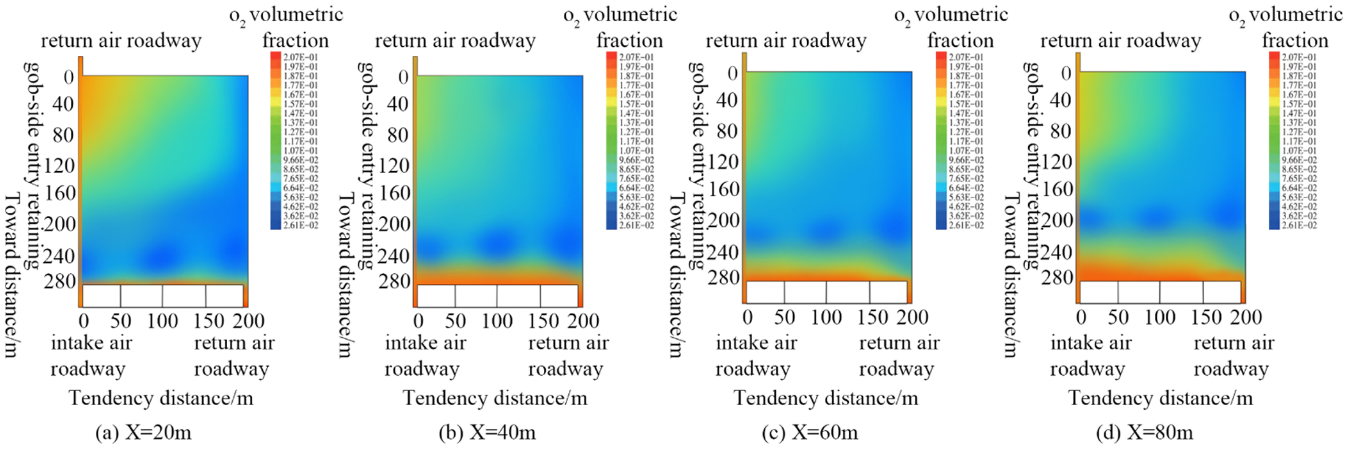
4.3.1. Analysis of Simulation Results of Different Nitrogen Injection Positions. In the design of nitrogen injection schemes for preventing spontaneous combustion of residual coal in a gob, the injection port location is a crucial parameter. A correct and reasonable injection port location enables the nitrogen gas to be released quickly from the gob. To investigate the influence of different injection locations on the distribution of O_2 concentration within the gob, we installed a nitrogen injection pipeline along the retaining roadway section. The O_2 concentration distribution cloud maps were then simulated at distances of 20, 40, 60, and 80 m away from the working face. Here, X denotes the distance from the injection point to the working face. According to the data presented in Figure 8, when the nitrogen injection quantity is 500 m^3/h, as the injection location deepens, the position of the oxidation zone shifts backward, and the O_2 concentration at the injection location drops significantly. When the injection location is X = 20 m, the change in O_2 concentration is not significant, and most of the injected nitrogen gas returns to the working face with the leakage airflow, resulting in limited inerting effect. At the X = 40 m injection location, the injected nitrogen gas effectively enters the gob, resulting in a significant inerting effect and a considerable reduction in O_2 concentration on the intake air side. The oxidation zone extends from a range of 22−35 m away on the intake air side and 17−33 m on the return air side. The optimal effect is achieved when the injection location is X = 60 m, with the range of the oxidation zone being 20−33 m on the intake air side and 15−28 m on the return side, and with the width of the oxidation zone reaching the minimum. When the injection location is X = 80 m, the range of the oxidation zone is not significantly affected by the leakage airflow, resulting in poor control effect.

4.3.2. Analysis of Simulation Results of Different Nitrogen Injection Quantities. The quantity of nitrogen injection flow for fire prevention is mainly influenced by actual mining and geological conditions. The design of nitrogen injection quantities should meet fire prevention requirements while reflecting economic and technical rationality. In accordance with the fire inertization index, which involves decreasing the O_2 concentration in the oxidation zone following nitrogen injection, the O_2 content within the gob oxidation zone should be less than 8%. This requirement is based on the "Technical Specification for Nitrogen Fire Prevention in Coal Mines" (MT/T701-1997). The formula for calculating the nitrogen injection quantity, which is based on the leakage of the oxidation zone airflow, is as follows:

$$Q_n = 60Q_0\frac{C_1 - C_2}{C_n + C_2 - 1}$$

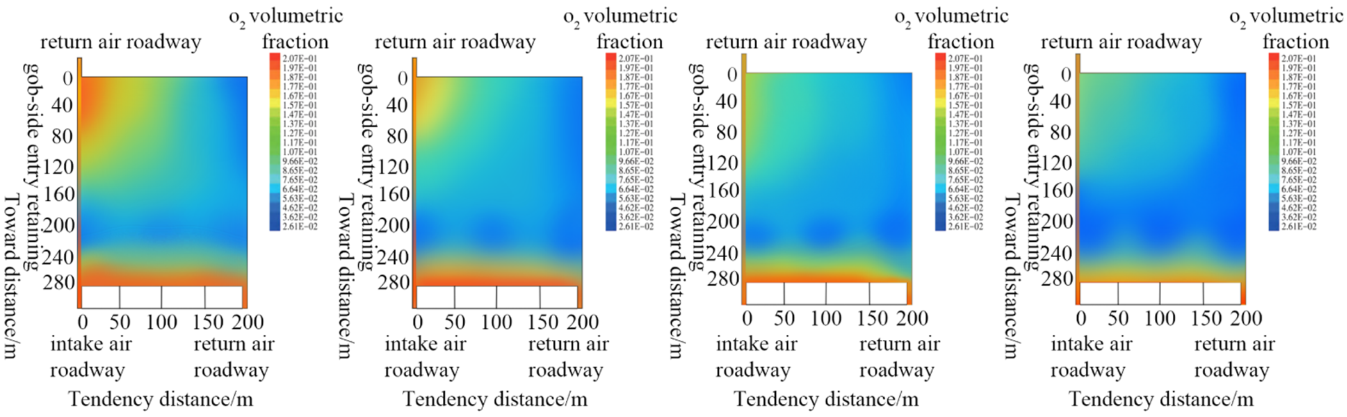
where

Q_n— nitrogen injection quantity, m^3/h;



(a) X=20m (b) X=40m (c) X=60m (d) X=80m

Figure 8. O_2 distribution cloud diagram under different nitrogen injection positions.



(a) Q=300m³/h (b) Q=400m³/h (c) Q=500m³/h (d) Q=600m³/h

Figure 9. O_2 distribution cloud diagram under different nitrogen injection quantities.

Q_0— leakage of the oxidation zone airflow within the gob, with a value of 7 m^3/min;

C_1— average oxygen content within the oxidation zone of the gob, with a value of 13%;

C_2— fire inertization index of the oxidation zone within the gob, with a value of 8%; and

C_n— nitrogen purity during fire prevention, with a value of 97%.

Considering the actual mining conditions of the mine, we utilized the aforementioned equation to simulate the O_2 concentration distribution within the gob while varying the nitrogen injection quantity at 300, 400, 500, and 600 m^3/h. The nitrogen injection point was located at a distance of 60 m from the working face on the air intake side, and a nitrogen injection pipeline was installed along the retaining roadway section. The O_2 concentration distribution cloud map in the gob for varying nitrogen injection quantities is shown in Figure 9. The results indicate that as the flow quantity of nitrogen injection increased, a noticeable decrease occurred in the overall O_2 concentration within the gob, and the oxidation zone gradually shrank. A nitrogen injection quantity of 300 m^3/h resulted in the oxidation zone being closer to the working face and with a width of 35 m. However, the reduction in O_2 concentration was insignificant in the retaining roadway. At the edge of the retaining roadway section in the deeper parts of the gob, the O_2 concentration was approximately 17%. At a nitrogen injection rate of 600 m^3/h, a significant decrease in O_2 concentration occurred in the gob within a range of approximately 280 m ahead of the working face. Likewise, the oxidation zone width on the intake side reduced significantly, measuring only 12 m, and the overall O_2 concentration in the gob remained below 8%. At a nitrogen injection quantity of 600 m^3/h, the O_2 concentration decreased more rapidly on the intake side, and the oxidation zone was located nearer to the working face, with a minimum distance of 10 m. The results are illustrated in Figure 10, depicting the variation of O_2 concentration with distance along the intake and return air roadways. The decrease in O_2 concentration on the return airway side was comparatively gradual, and an increase in the quantity of nitrogen injected moved the oxidation zone nearer to the working face, thereby endangering safe production at the working face. Therefore, a nitrogen injection quantity of 500 m^3/h can effectively reduce the size of the oxidation zone while ensuring an adequate safe distance from the working face.

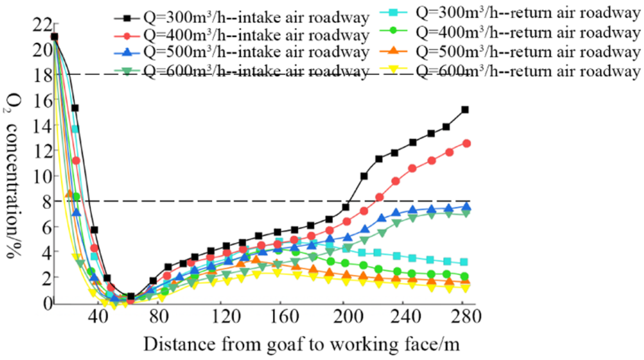


Figure 10. Variation curve of O_2 concentration in intake and return air roadways under different nitrogen injection quantities.

5. APPLICATION

In the practical application, continuous nitrogen injection was used to fill the gob. Prior to mining, a pipe with a diameter of 108 mm was installed in the first set of supports and thereafter every 15 m along the gob in the transport roadway. The end of the buried pipe was at a depth of no less than 10 m below the gob floor. At the first pressure bump after mining, nitrogen was immediately injected into the gob from the pre-buried pipe along the transport roadway to increase the inert gas content in the gob. Subsequently, a pipe was installed every 15 m along the bottom of the transport roadway. After 30 m of mining, nitrogen was injected into the pre-buried pipe in the transport roadway along the gob at 30−60 m from the working face, as illustrated in Figure 11. The nitrogen injection rate during mining was maintained at 500 m^3/h or above, and the nitrogen concentration was kept at a minimum of 97%. An increase in the concentration of carbon monoxide and temperature required a corresponding increase in the nitrogen injection frequency. The number of nitrogen injection points was also increased according to abnormal changes in the indicative gases of the gob.

Figure 12 shows the variations in O_2 concentration at different locations in the gob after continuous injection of nitrogen. At a distance of 50 m from the working face, which is in close proximity to the injection port, the O_2 concentration reduced significantly, indicating a considerable impact of nitrogen injection at this point. The O_2 concentration was nearly negligible, and the O_2 concentration distribution along the return airway reduced considerably at distances of 180 and

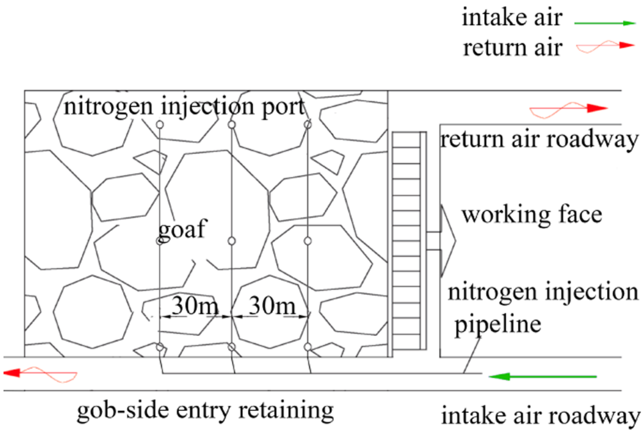


Figure 11. Nitrogen injection pipeline and release port location.

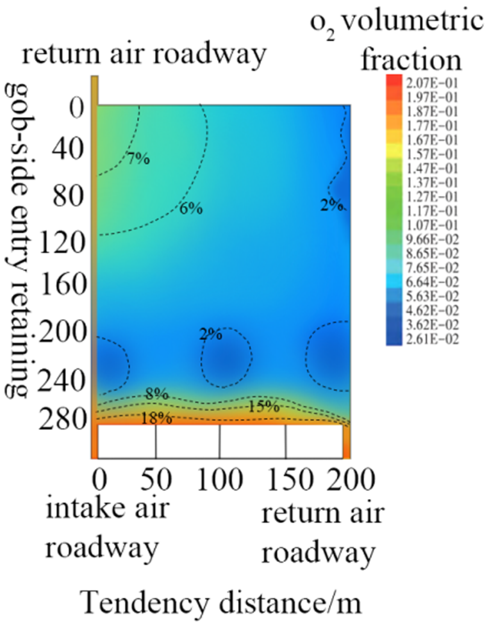


Figure 12. O_2 distribution cloud diagram in the gob during nitrogen injection.

240 m. This phenomenon implies that the effects of nitrogen injection extended to the section where the pipe was located on the return air roadway. As the roof collapsed and compacted during mining, the gas in the gob was influenced by nitrogen injection, which quickly responded to alterations in pressure energy. Most areas of the gob had O_2 concentrations lower than 8%, and the suffocation zone dominated the gob.

6. CONCLUSIONS

To scientifically and effectively prevent and control spontaneous combustion during mining at the South Five 1201 fully mechanized mining face, we numerically simulated nitrogen injection fire prevention parameters. The O_2 concentration and temperature monitoring data were used to implement nitrogen injection fire prevention and control engineering in the gob. The following conclusions were drawn:

(1) In the GERRC mode, the pressure reached its maximum value of 31.41 Pa near the intake air roadway because of the high air velocity. The leakage air mainly flowed from the gob along the retaining roadway, and the gob formed an open space because of the retaining roadway. The airway was connected, and the leakage airflow increased with the length of the retaining roadway. When the working face advanced 500 m, the maximum leakage airflow was 247 m^3/min. Under the influence of mining pressure, the roadway deformed as the working face advanced 1300 m. The observed minimum airflow leakage was 175 m^3/min.

(2) Numerical simulation studies on various nitrogen injection conditions at the working face indicate that an increase in the quantity of nitrogen injected gradually reduced the oxidation zone range and moved it closer to the working face. The position of the oxidation zone shifted backward as the nitrogen injection position deepened. The reduction in O_2 concentration was more rapid in the intake air roadway side and gradual in the return air roadway side. The optimal effect was achieved with a nitrogen injection rate of 500 m^3/h and an injection depth of 60 m. At this time, the size of the oxidation zone was effectively reduced while maintaining a safe distance from the working face.

(3) After technical considerations, a plan was adopted for fire prevention and control in the 1201 transportation roadway of the Daxing Coal Mine. The plan involved using buried piping for injecting nitrogen. According to the actual mining situation and economic benefits, a nitrogen injection quantity of 500 m^3/h and a nitrogen injection pipe spacing of 30 m were found to reduce the width of the oxidation zone effectively. The long-term monitoring results of the on-site application demonstrated that continuous nitrogen injection measures caused the suffocation zone to dominate the gob, thus mitigating the risk of spontaneous combustion and fire, and ensuring safe production at the mine.

■ ASSOCIATED CONTENT

Data Availability Statement

All data generated or analyzed during this study are included in this article.

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Author Contributions

X.Z. and Y.L. were responsible for checking the rationality of the content of the paper, and Z.J. was mainly responsible for the writing and conception of the paper. All authors reviewed the manuscript.

Notes

The authors declare no competing financial interest.

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