ABSTRACT: Coal spontaneous combustion in gob often induces gas explosion accidents. To solve the frequent occurrence of gas and coal spontaneous combustion (GCSC) symbiotic disaster of highly gassy and spontaneous combustion-prone short-distance coal seams, the stope space of a complex working face formed by the old gob above and the coal seam mined below in Hengda Mine is divided into three zones, a completely connected zone, a partially connected zone, and an unconnected zone, according to the connectivity degree of fractures. A numerical model is established to study the relationship between gas drainage and coal spontaneous combustion. The effects of ventilation flux in the working face, gas drainage flow in the upper corner, gas drainage flow in the high-drainage roadway, fracture grout sealing, and nitrogen injection flow on the airflow field, gas concentration field, oxygen concentration field, and the temperature field in the completely connected and partially connected zones are analyzed. A multifactor interaction relationship under the conditions of ventilation, gas drainage, and nitrogen injection is revealed, and a multipoint and zoning coordinated prevention method for the GCSC symbiotic disaster is proposed. On the basis of the proposed method, the gas drainage flow in the high-drainage roadway and corner pipe of 5333(B) working face are determined to be 45.4 and 112.1 m³/min, respectively, and the total nitrogen injection flow in the upper gob and the lower gob are 350 and 640 m³/h, respectively. The upper corner gas concentration and the return roadway maximum gas concentration are lower than 0.8% during the stoping process, and there is no spontaneous combustion risk of the gob residual coal, thus reducing the greenhouse gas emission and realizing safety mining. This study is conducive to facilitate the realization of the goal of carbon neutrality and peak carbon dioxide emissions.

1. INTRODUCTION

Against the energy background of “rich coal, less gas, and poor oil” of China, coal is crucial for the steady development of national industry and economy, accounting for more than 57% of the total energy consumption of China. Among the key coal mines in China, the number of highly gassy mines accounts for more than 70%, the number of severe spontaneous combustion-prone mines accounts for over 56%, and the number of mines affected by the above-mentioned symbiotic disaster accounts for up to 49%.1,2 As the underground mining continuously moves from shallow to deep, the gas and coal spontaneous combustion (GCSC) symbiotic disaster is becoming increasingly severe. There are some challenges in the prevention of the above-mentioned symbiotic disaster. On one hand, coal looseness and fracture caused by gas drainage aggravate gob air leakage, while gob air leakage may further aggravate the spontaneous combustion and lead to gas explosion accidents. On the other side, the grout sealing used to reduce gob air leakage and the nitrogen injection fire

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prevention and extinguishing measures can effectively solve the hazard of coal spontaneous combustion but also reduce the gas drainage efficiency. Therefore, in order to ensure safe and efficient mining and address the contradictoriness between gas and coal spontaneous combustion cogovernance, it is necessary for us to figure out the mechanism of GCSC symbiotic disaster and meanwhile to study its coordinated prevention technology.

At present, extensive study on occurrence mechanism, influencing factors, and the cogovernance technology of GCSC symbiotic disaster has been conducted by many researchers based on different theoretical methods. Numerous coal mine gas accidents and experiments indicated that pressure relief gas drainage can significantly increase the permeability of coal seam and reduce the risk of gas accidents; meanwhile, the pressure-relief paths and pressure-relief process have a vital impact on the gas flow characteristics and coal permeability. The application of numerical simulation also promotes the study on the optimization of gas drainage parameters. Yang et al. used FLAC 3D to research and divide the stress distribution characteristic areas of coal seam in the horizontal and vertical directions and revealed the flow law of gas under its own pressure gradient. Liu et al. studied the deformation process of the overlying coal seam during the gas drainage of double coal seams in the Wulan coal mine by numerical simulation methods, and they figured out the reasonable layout of ground boreholes. Ding et al. optimized a gas drainage borehole parameter in a pressure-relief gas-rich area by using a CFD model that improved the gas drainage efficiency and realized accurate gas drainage.

According to the coal spontaneous combustion experiment in Beamish and Jabouri, it is found that the contact area between O₂ and coal increases after gas drainage, thus enhancing the rate of oxidation exotherm and leading to spontaneous combustion. Shi et al. studied the variation law of the oxygen consumption rate in each stage of the coal oxidation process and found that a higher temperature will aggravate the complexity of coal spontaneous combustion. Zhang et al. reduced the gob air leakage by the relative positive pressure in the nitrogen injection chamber and analyzed the gob fire prevention effect of the combined sealing of the nitrogen injection chamber and sand column. Zhuo et al. found through FLUENT that various working face air leakage conditions determine differences in the scope of the spontaneous combustion hazard areas. Zhang et al. proposed a novel dynamic calculated way of fracture evolution–pore distribution in gob by combining PFC and Fluent, studied the influence of dynamic porosity on the flow field in gob, and verified the accuracy of the model in identifying the spontaneous combustion-prone zones of residual coal based on engineering samples.

Zhou investigated the main coal and gas spontaneous combustion mines in China and found that the main causes for the frequent occurrence of GCSC symbiotic disasters are interaction of the underground mixed gas concentration field, temperature field, and fracture field. Zhu et al. studied the temperature distribution characteristics of the surrounding rock of roadway in the deep coal mine. Li et al. proposed an index of air volume safety regulation range and the judgment condition of composite disaster imbalance and extensively discussed the mutual restriction relationship under the condition of implementing disaster-prevention technical measures. Xia et al. found that increasing the ventilation flux diluted the methane concentration in the return air roadway or working face but increased the area of oxidation zone in gob. After studying the gob experiment, Ma et al. found that the migration process and distribution of methane concentration were mainly affected by the spontaneous combustion area of coal and temperature change. Through numerical simulation, Li et al. determined that the highest-risk area of a GCSC symbiotic disaster was located in the return roadway close to the working face. Yang et al. found that the range of GCSC symbiotic disaster was positively correlated with the intake ventilation flux, and the gas concentration field moved to the deep part of the gob after the ventilation flux increased gradually. Wang et al. analyzed the distribution of methane and oxygen concentration fields under different drainage modes based on the CFD model and found that gas drainage caused the GCSC symbiotic disaster risk zone to move to the deep zone of the gob.

On the basis of the above discussion, it is clear that studies on the optimization of gas drainage parameters, coal spontaneous combustion process, fire prevention measures in the gob, affected zones, and mechanisms of GCSC symbiotic disaster have already been conducted. However, only few studies have been conducted on the balance point of coordinated prevention and under the condition of mutual influence and restriction between gas drainage and measure for fire prevention and extinguishing. Moreover, when combined drainage is adopted, the distribution rule of stereoscopic air leakage field, gas concentration field, and oxygen concentration field are of immense significance for the subsequent optimization of combined drainage mode and the determination of fire prevention and extinguishing measures. Nonetheless, these aforementioned topics still remain to be studied.

Therefore, considering the contradictions and complexities in the prevention of GCSC symbiotic disaster as well as the effects of gas drainage and fire prevention and extinguishing, it is of essence that research on the coordinated prevention technology of GCSC symbiotic disaster for realizing safe and efficient production. In this study, 5331(A) and 5333(B) working faces in No. 153 mining area with high gas emission and short spontaneous combustion period in Hengda mine were considered as the study objects. According to the different degrees of connectivity between the upper gob and the lower 5333(B) coal seam being mined, in order to facilitate the study of interaction relationship between gas and coal spontaneous combustion the complex working face is divided into three zones: completely, partially, and unconnected, and physical and numerical models of GCSC symbiotic disaster are established. The effect and variation law of the airflow field, gas concentration field, temperature field of gob residual coal, and oxygen concentration field in the completely connected zone and partially connected zone under the changes of ventilation flux, the drainage flow of buried pipe in the corner and high-drainage roadway, grout sealing, and nitrogen injection flow are analyzed. The multifactor interaction effect of ventilation-nitrogen injection-gas drainage combined prevention measures is studied. On the basis of the above analysis, a multipoint and zoning coordinated prevention standard and method for the GCSC symbiotic disaster is proposed. Furthermore, the prevention parameters such as air volume, gas drainage flow, and nitrogen injection flow of the complex working face are obtained. The effectiveness of this method in engineering practice is verified. The findings of this study facilitate mining safety and prevention of GCSC symbiotic disaster in the Hengda coal mine and could also act as a reference for
guidance on the coordinated prevention theory and technology of GCSC symbiotic disaster.

2. RESEARCH BACKGROUND

2.1. Slicing Mining Situation. The Hengda Coal mine is located in Fuxin City, China. The smoothly inclined coal seam is of medium thickness. At present, the flow of gas emission exceeds 179 m³/min, but the flow of gas drainage is only 112.8 m³/min. Coal seams, roadways, and gobs are the primary sources of mine gas. The spontaneous combustion period is 3–6 months. The coal seam permeability is less than 0.0760 m²/(MPa·d). Therefore, the coal seam in No. 153 mining area is highly gassy and spontaneous combustion-prone with a low permeability. The prevention of the GCSC symbiotic disaster is severe. The slicing mining method is adopted in No. 153 mining area, and the working face is arranged with 0.06–3.5 m inner thickness of coal seam as the boundary. According to the mining sequence from top to bottom, the upper layer with a thickness of approximately 3 m is mined first, and subsequently the lower layer with a thickness of approximately 5.5 m is then mined. The specific working face layout of No. 153 mining area is shown in Figure 1a.

At present, the upper 5331(A) working face has been mined and sealed and the gas in the sealed gob has been drained, while the lower 5333(B) working face is being mined. The upper and lower layers adopt a high-drainage roadway and corner buried pipe drainage, respectively. According to the actual situation of No. 153 mining area, the complex space composed of upper and lower layers is divided into three zones for coordinated prevention of GCSC symbiotic disaster, as shown in Figure 1b.

1. Completely connected zone of the upper and lower gob (completely connected zone).
2. Partial air leakage zone in the roof of the intake and return roadway (partially connected zone).
3. Sealing air leakage zone in upper gob (unconnected zone).

Among them, the completely connected zone is formed by the combination of the upper gob formed after the mining of 5331(A) working face and the lower gob of 5333(B) working face being mined. In the mining process of 5333(B) working face, the formed lower gob is connected with the upper gob in a large area. Meanwhile, the broken coal and rock in the caving zone of the upper gob fall into the lower gob, and the caving zone and fracture zone develop further, resulting in the development of the air leakage channel in the gob again, and the scope of air leakage is greatly expanded. The partially connected zone is the zone composed of upper gob and 5333(B) working face. In the process of lower coal seam tunneling, the loose circle of roadway is connected with the floor fracture caused by 5331(A) working face mining, forming a partially connected channel between the working space and upper gob. Compared with completely connected zone, air leakage is relatively small and mainly concentrated in the area of roadway and working face. In the unconnected zone, there is little air leakage due to the small effect of mining between coal seams.

In this study, the prevention of GCSC symbiotic disaster in No. 153 mining area is investigated, and it provides a practical engineering basis for subsequent numerical simulation.

2.2. Cause Analysis of GCSC Symbiotic Disaster. There are three main causes for the frequent occurrence of GCSC symbiotic disaster. First, slicing mining mode of spontaneous combustion-prone coal seams certainly enhances the hazard of secondary oxidation that happens with the residual coal in gob. Next, in the process of lower slicing mining the roadway loose circle is connected to the floor fracture caused by upper slicing mining, forming complex three-dimensional air leakage channels. Finally, it is hard to prevent high gas emissions, and the ventilation pressure and negative pressure of drainage together contribute to the air leakage power, further leading to the oxidation of floating coal in the gob.

3. MATHEMATICAL AND NUMERICAL SIMULATION MODEL

3.1. Mathematical Model Establishment. According to the mathematical model established in ref 24 and considering the interaction of gas migration, heat transfer, and gas desorption in gob, this paper established a GCSC symbiotic disaster model in gob based on continuity equation,
momentum equation, energy equation, and concentration component equation.

1) Flow Field Model
In the complex environment of underground mines, any mixing and transportation process of gas needs to follow the most basic law of conservation of mass and the law of fluid dynamics. The airflow control equation of gob and roadways under the action of gravity are shown as follows

\[
\frac{\partial}{\partial t}(\gamma \rho) + \nabla \cdot (\gamma \rho \vec{v}) = S_m
\]

(1)
where \( \gamma \) is the porosity of the porous medium (1/m\(^3\)), \( \rho \) is the mass density of the fluid (kg/m\(^3\)), \( \nabla \) is the Hamiltonian, \( \vec{v} \) is the seepage velocity of the fluid in porous media (m/s), and \( S_m \) is the gas mass source term (kg/m\(^3\)·s\(^{-1}\)).

2) Multicomponent Model
Because of the emission of gas and CO\(_2\) and the O\(_2\) consumption, the process of "generation–diffusion–consumption" of various components occurs in the gob space at all times, and each component satisfies the law of conservation of component mass; its equation expression is

\[
\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i
\]

(2)

For the convenience of analysis and calculation, the complex gob environments are ideal gases mixed with multiple components, and the state equations of multicomponent are as follows

\[
\frac{p}{\rho} = \frac{RT}{M}
\]

(3)
where \( M \) is the gas molecular weight, and \( R \) is the universal gas constant (\( R = 8.314 \text{ J} \cdot \text{mol}^{-1} \text{K}^{-1} \)).

3) Temperature Field Model
The air leakage provides oxygen for oxidation and takes away the heat generated by oxidation. The heat generated by oxidation heats up the coal, thus accelerating the oxidation of coal. Oxygen consumption \( R(O_2) \) of residual coal in gob usually uses the Arrhenius equation

\[
R(O_2) = A e^{E_a T} \phi(d)
\]

(4)
where \( A \) is preexponential factor of residual coal oxidation, s\(^{-1}\); \( E_a \) is activation energy; \( c(O_2) \) is oxygen volume fraction; \( \phi(d) \) is granularity function; \( T \) is physical field temperature, K.

Oxidation heat release of residual coal in gob can be expressed as

\[
W = q_t R(O_2)
\]

(5)

Table 1. Simulation Parameter Setting*  

| parameter                           | value                          | parameter                           | value                          |
|-------------------------------------|--------------------------------|-------------------------------------|--------------------------------|
| CCZ size (m)                        | 250 × 208 × 50                 | PCZ size (m)                        | 200 × 200 × 50                 |
| high-drainage roadway size (m)      | 2.5 × 2.5                      | corner buried pipe size (m)         | Φ 0.5                          |
| drag coefficient (N·S/m\(^3\))      | 0.0013                         | turbulence model                    | RNG k-ε model                  |
| gas emission intensity in the roadway and working face (mol/m\(^3\)·s) | 2.14 × 10\(^{-5}\)            | gas emission intensity in gob mol/(m\(^3\)·s) | 3.1 × 10\(^{-7}\)             |
| coal rock porosity (%)              | 0.1–0.45                       | residual coal thickness (m)         | 4                              |
| upper gob height (m)                | 43                             | ventilation flux (m\(^3\)/min)      | 1200                           |
| thermal conductivity (W·m\(^{-1}\)·K\(^{-1}\)) | 0.217                         | oxygen consumption intensity of residual coal mol/(m\(^3\)·h) | 0.098                          |
| intake roadway boundary conditions   |                                | return roadway boundary conditions  |                                |
| the first boundary                  |                                | the second boundary                 |                                |

*CCZ means the completely connected zone; PCZ means the partially connected zone.
where \( q_1 \) is heat of oxidation reaction of residual coal, J/mol.

Considering porous media as a system composed of solid and fluid phases, the energy equation of the heat transfer process of porous media in a gob is as follows:

\[
\frac{\partial}{\partial t} (\eta_1 E_f + (1 - \eta_1) E_s) + \mathbf{v} \cdot (\rho_i (E_f + p)) = \nabla \cdot (k_{\text{eff}} \nabla T - \sum_j h_{ij} \mathbf{T}_j + (\beta_{\text{eff}} \mathbf{T})) + S_f^H
\]

(6)

where \( E_f \) is the total fluid energy, \( E_s \) is the total energy of the solid frame, \( \rho_i \) is the fluid density, kg/m\(^3\); \( \Gamma \) is the porosity of the porous media; \( k_{\text{eff}} \) is the effective thermal conductivity of the medium, \( k_{\text{eff}} = \gamma k_i + (1 - \gamma) k_f \); \( k_i \) is the thermal conductivity of the fluid (including turbulence contribution, \( k_t \)); \( k_f \) is the solid phase thermal conductivity; and \( S_f^H \) is the heat release intensity of caving coal rock in unit volume per unit time (W/m\(^3\)).

3.2. Numerical Simulation Model. The 5333(B) working face strike length of U-shaped ventilation is 285 m, the mining height is 3 m, and the roof is the caving zone of the 5331(A) gob. The ventilation flux was 1200 m\(^3\)/min. Zoning modeling of the fully connected zone and partially connected zone was conducted according to the above analysis. The upper 5331(A) working face high-drainage roadway and the 5333(B) working face corner buried pipe drainage were used to control the gas overrun in the upper corner and return air.

The model is established according to the actual situation, and the specific simulation parameters are shown in Table 1. In the meshing process of the working face model, the mesh density is increased for the roadway, gas drainage port, and other positions, and the working face grid is obtained as shown in Figure 2.

Because the residual coal is numerous and there is poor fluidity in gob, this provides an appropriate heat storage environment for the oxidation and spontaneous combustion of...
residual coal in the gob. Cave mining, gas drainage, and the complicated air leakage with multizoned connectivity make the fire prevention situation in No. 153 mining area unprecedentedly severe. Therefore, it is necessary to analyze a reasonable range of ventilation flux, gas drainage mode, and drainage flow in the working face.

4. RESULTS AND DISCUSSION

4.1. Ventilation Flux Influence Effect. 4.1.1. Wind Flow Field Analysis. The air leakage is one of the vital factors leading to the spontaneous combustion of residual coal in gob. With the advancement of the working face, the compaction degree of coal and rock falling in the gob is different; accordingly, air leakage channels connected along the periphery of the gob are formed.

Considering the broken rock zone,26,27 there is an annular fracture zone near the intake roadway and return roadway in the lower working face that forms an air leakage channel between the roadway and the upper gob. For the mined area in the lower coal seam, the upper and lower gob are connected which makes the air leakage situation more complicated. By solving the model, the 3D wind flow field of the 5333(B) working face was obtained, as shown in Figure 3.

According to Figure 3, with the affection of wind pressure, a few air-leakage flows into the upper gob through the coal-rock fracture at the top of the intake roadway, and most of the air leakage in the area near the terminal line passed through the upper gob and subsequently merged into the wind flow of the return roadway through the coal-rock fracture. In the completely connected zone, the air leakage enters the gob from the sidewall of the working face on the intake roadway and flows out at the upper corner. The air leakage-affected zone covers almost the entire gob.

Therefore, the coal-rock fracture at the top of the intake and return roadway is the main channel for the air flow from the lower working face entering the upper-layered gob; the air leakage flow near the terminal line is the largest channel that significantly enhances the hazard of residual coal spontaneous combustion without measures for sealing.

4.1.2. Gas Concentration Field Analysis under Different Ventilation Fluxes. The ventilation flux of six intake roadways was set within the range of 1000–1500 m³/min, and the distribution of the gas concentration field in the gob under different ventilation flux conditions was obtained, as shown in Figure 4.

As shown in Figure 4, the upper part of the completely and partially connected zones are the main area of gob gas accumulation. The gas merges into the working face airflow from the top of the return roadway and the upper corner along with the gob air leakage, resulting in serious gas overrun of the roadway airflow in the upper corner. With the increase in ventilation flux in the working face, the air leakage in the upper and lower gob increases correspondingly which leads to a gradual decrease in the accumulated gas concentration in the gob, and this phenomenon is more prominent in the intake side of the gob. To quantitatively analyze the influence of ventilation flux on the roadway gas distribution, the average gas concentration data of the upper corner and return airflow under different ventilation fluxes are summarized in Figure 5.

According to Figure 5, with the increase in ventilation flux the gas concentration in the return airflow decreases, but increases in the upper corner. Therefore, when gas drainage meets the demand of gas control, it should be avoided by the control gas by increasing the ventilation flux.

4.1.3. Ventilation Flux Effect on Spontaneous Combustion of the Partially Connected Zone. With the increase in ventilation flux, the pressure difference between the intake and return roadways leads to an increase in air leakage between the two roadways through the upper gob in the partially connected zone. Figure 6 shows the oxygen concentration field in the upper gob under different ventilation fluxes and the distribution of three zones of spontaneous combustion according to the oxygen concentration of 7–18%.

On the basis of Figure 6, the high oxygen concentration zone in the upper gob is an inverted "L"-shaped, whereas the oxygen concentration in the upper area of the intake roadway of the working face is the highest. When the ventilation flux gradually rises from 1000 to 1500 m³/min, the zone of the upper area of the intake roadway with oxygen concentration greater than 18% increased, and the area of oxidation zone with oxygen concentration between 7 and 18% increases.

Figure 7 shows the temperature field distribution of residual coal in the upper gob. The spontaneous heating zone of residual coal appears near the terminal line of the working face and gradually narrows from the intake roadway to the return roadway, while the high-temperature center appears at the intake side of the terminal line with the highest temperature of approximately 30 °C. When the ventilation flux gradually rises from 1000 to 1500 m³/min, the range of high-temperature zone increases, which enhances the hazard of coal spontaneous combustion.

In summary, the high oxygen concentration and high-temperature zones of residual coal in the upper gob are mainly concentrated in the vicinity of the terminal line and the intake roadway. The residual coal around the terminal line is numerous, and the period of dismantling and sealing the working face after mining is long, and the coal oxidation heating time is long. In addition, the terminal line in the upper gob is located between the inlet of the intake roadway and the outlet of the return roadway in the lower working face. The ventilation pressure difference in this area is the largest, and the air leakage action time period spans between the excavation of the lower working face to the completion of mining.

4.1.4. Ventilation Flux Effect on Spontaneous Combustion of the Completely Connected Zone. In the process of slice mining, the broken residual coal in the upper gob falls into the gob of the 5333(B) working face, and these residual...
coals accumulate in the lower gob and undergo secondary oxidation that is more prone to the spontaneous combustion of coal. Figure 8 shows the distribution of oxygen concentration and the three zones in the lower-layered gob under different ventilation fluxes. On the basis of Figure 8, when the ventilation flux is raised the width of the oxidation zone gradually increases, it moves to the deep part of the gob, and the boundary of the oxidation zone (7%) shifts to the deep part of the gob, too. The maximum distance exceeds 50 m, and the width increases by approximately 40 m; this hinders fire prevention and extinguishing.

In the heat dissipation zone, when the air leakage flowing into the gob from the intake side of the working face flows through the floating coal, the oxygen in the airflow is continuously consumed because of the low-temperature oxidation, and the generated heat gradually accumulates in the deep part of the gob and the return side with the wind with the temperature constantly increasing. In the oxidation zone, the air velocity decreases, the heat generated by the oxidation of floating coal cannot be removed, and the temperature rises rapidly to its peak value. Inside the asphyxiation zone, the oxygen concentration in the gob decreases rapidly, the oxidation of the floating coal stops, and the heat carried by the leakage air is highly limited, such that the temperature gradually decreases and returns to the original rock temperature in the deep part of the gob.

On the basis of Figure 9, the change trend of the temperature field is consistent with that of the oxidation zone. The peak point of high temperature at 45 °C appears in the oxidation zone in the middle of the gob, and the risk of spontaneous combustion is obviously higher. When the ventilation flux is raised, the range of the high-temperature zone gradually expanded and moved into the deep part of the gob. Therefore, it is necessary to avoid the spontaneous combustion of residual coal caused by an unreasonable increase in ventilation flux for gas control in the process of lower coal seam mining.

4.2. Corner Gas Drainage Influence Effect. 4.2.1. Analysis of Gas Drainage and Wind Flow Field. In the mining process of No. 5333(B) working face, the gas emitted from the upper corner originates not only from the gob of this coal seam but also a considerable portion originates from the upper gob. By modifying the boundary conditions, the drainage of the corner buried pipe and ventilation flux were 94 and 1200 m³/min, respectively, and then the wind flow field was acquired, as shown in Figure 10. It can be clearly seen that part of the gas originally flowing to the upper corner is drained by the drainage pipeline that reduces the gas discharge pressure in the upper corner.

The curves of drainage gas concentration, pure gas drainage quantity, corner gas concentration, and return airflow gas concentration with an increase in drainage flow are drawn according to the monitoring data of the above numerical simulation results. According to Figure 11, when the drainage flow is raised, the gas concentration and pure gas drainage quantity of the corner buried pipe gradually decreased, while the corner gas concentration and return airflow gas concentration decreased almost exponentially and the drainage

Figure 6. Distribution of oxygen concentration and three zones.
efficiency decreased accordingly. When the drainage flow increased to 156 m³/min, the gas concentration in the upper corner was reduced to 0.51%, but the gas concentration in the return airflow was still as high as 1.03% because of the accumulated gas in the upper gob flowing into the return roadway from the roof fracture of the return roadway. Because of the limitation of the drainage pipeline, the maximum drainage flow of the corner buried pipe drainage is 160 m³/min; therefore, it is difficult to completely solve the problem of gas overrun in the working face by single buried pipe drainage.

4.2.2. Corner Gas Drainage Effect on Spontaneous Combustion in the Partially Connected Zone. The upper gob is relatively closed, and the leakage air flows into the upper gob from the roof fracture of the intake roadway. The mixed airflow containing gas flows into the return airflow from the upper corner and the roof fracture of the return roadway. However, the drainage port of the corner buried pipe is located outside the partially connected zone that has negligible influence on the upper gob flow field. Figures 12 and 13 show the distribution of the oxygen concentration and temperature fields in the upper gob.

From the simulation results in Figure 12, it can be seen that the corner gas drainage has minimal influence on the oxygen concentration field in the upper gob and the three zones. According to the temperature field in Figure 13, when the drainage flow is raised the self-heating temperature rise of residual coal decreases, and the relatively high-temperature area decreases. Thus, corner gas drainage reduces the air flow in the return roadway, reduces the air leakage in the upper gob slightly, and alleviates the fire prevention situation in the partially connected zone slightly.

4.2.3. Corner Gas Drainage Effect on Spontaneous Combustion of in the Completely Connected Zone. It can be seen from the distribution of the oxygen concentration field in Figure 14 that the three zones of spontaneous combustion change near the upper corner during corner gas drainage but have a negligible influence on the intake side and central zone of the gob.

From the temperature field in Figure 15, the change is still consistent with the position change of the three zones of spontaneous combustion. In the intake side and the middle of the gob, the range of the high-temperature zone changes negligibly with an increase in the corner drainage flow. On the return airflow side, the wind speed in the upper corner zone is increased by the corner gas drainage, and the accumulation of the heat released by the oxidation of residual coal is difficult and decreases the temperature in this zone.

4.3. High-Drainage Roadway Influence Effect.

4.3.1. Analysis of Gas Drainage Effect in High-Drainage Roadway. More than 60% of the gas in the 5333(B) working face arises from the gob formed after the upper slicing mining, and the corner gas drainage efficiency is low in this zone and makes it difficult to solve the problem of gas overrun in the return air. To study the gas control effect of a high drainage roadway and its influence on the spontaneous combustion of residual coal, the distribution of the wind flow field, oxygen

Figure 7. Distribution of residual coal temperature field with different ventilation fluxes
concentration field, and temperature field in the working face was obtained by simulation when the drainage flow was 13–118 m³/min. Figure 16 shows the distribution of the airflow field in the gob when the drainage flow was 63 m³/min.

Figure 8. Distribution of oxygen concentration and three zones in the lower-layered gob under different ventilation fluxes.

Figure 9. Distribution of temperature field in the lowed gob with different ventilation fluxes.
According to Figure 16, the wind flow field changed significantly under drainage flow of the high-drainage roadway. In the partially connected zone, the air leakage and mixed airflow containing gas in the upper gob are discharged through the high-drainage roadway that significantly reduces the gas gushing from the roof fracture of the return roadway into the working space. However, the high-drainage roadway drainage intensifies the air leakage from the working face to the upper-layered gob, and a part of the gas in the completely connected zone also flows to the drainage port through the fractured coal and rock, thereby significantly solving the gas overrun problem in the upper corner.

As shown in Figure 17, the curves of the gas parameters under different high roadway drainage flows are drawn. When the drainage flow is less than 60 m³/min, the gas concentration in the high-drainage roadway decreases significantly with the
increase in drainage flow. With the continuous increase in drainage flow, the concentration of drainage gas decreases linearly, and the increase in the quantity of drainage pure gas decreases. When the drainage flow increased to 97 m$^3$/min, the gas concentration in the return airflow dropped to 0.72%, while the gas concentration in the upper corner was still as high as 10.39%. In summary, a high drainage roadway can effectively control the gas concentration of the return airflow. However, because of the distance from the upper corner, there is still a large amount of gas from the completely connected zone concentrated in the upper corner that leads to gas overrun. Therefore, it is necessary to coordinate the drainage flow of the high-drainage roadway and corner drainage to prevent the gas overrun in the return airflow and corner.

4.3.2. Effect of High Drainage Roadway on Spontaneous Combustion in the Partially Connected Zone. With the increase in drainage flow in the high-drainage roadway, the air leakage in the upper gob of the partially connected zone is aggravated. Figure 18 shows the distribution of the oxygen concentration field in the upper gob under different drainage flows.

Because of the drainage negative pressure, more airflow in the upper gob flows to the drainage port of the high-drainage roadway that leads to an increase in the oxygen concentration at the intake side of the terminal line in the upper gob. On the return side of the terminal line, because the airflow containing gas originally flowing to the upper corner area flows to the drainage port, and the air leakage flowing in from the upper part of the intake roadway is discharged from the high-drainage roadway, the oxygen concentration in this zone decreases. With the increase in drainage flow, the oxygen concentration in the intake roadway and the zone near the working face increased significantly. Because of the change in the oxygen concentration field in the gob, the temperature field in the
residual coal area also changes. Figure 19 shows the distribution of the temperature field in the gob under different drainage flows.

High roadway drainage increases the air leakage from the working face area to the upper gob that results in residual coal near the working face zone in a higher oxygen concentration environment, thus increasing the temperature in this zone. The highest temperature in the residual coal zone is 30 °C, therefore a high-drainage roadway will not cause the residual coal to enter the accelerated oxidation stage.

4.3.3. Effect of High Drainage Roadway on Spontaneous Combustion in the Completely Connected Zone. High roadway drainage causes some amount of gas in the upper part of the completely connected zone to flow into the partially connected zone that increases the air leakage in the completely connected zone. Figure 20 shows the distribution of the
From the moving trend of the oxidation zone boundary with the increase in drainage flow, the width of the oxidation zone increases. According to the change in the boundary (oxygen concentration of 7%) of the oxidation zone in the deep gob, the drainage flow gradually rises to 100 m³/min, and the boundary shifted toward the deep part of the gob by approximately 3 m with negligible influence. The change trend of the temperature field is consistent with the oxygen concentration field, and the high-temperature zone is increased by high roadway drainage but has negligible influence, as shown in Figure 21.

### 4.4. Influence of Grout Sealing in Partially Connected Zone

During mining, roof grouting drilling is arranged in the intake roadway of the partially connecting zone, and fly ash mortar is injected into the upper gob and the terminal line by using a grouting pump to block the uncompacted coal rock and roof fractures in the upper gob. In the simulation setting, the ventilation flux is 1200 m³/min, the drainage flow of the high-drainage roadway is 51 m³/min, the corner gas drainage flow is 107 m³/min, and the nitrogen injection flow of the completely connected zone is 500 m³/min.

#### 4.4.1. Wind Flow Field Analysis after Grout Sealing

Figure 22 shows the distribution of wind velocity before and after grout sealing. Grout sealing significantly reduces the air leakage at the top of the intake roadway, resulting in a significant decrease in the air leakage velocity near the gob at the upper part of the intake roadway and the terminal line. Meanwhile, under the same drainage flow of high-drainage roadway, more wind flows into the upper gob from the working face and the return roadway, enhancing the wind velocity in the middle of the upper goaf and the air return side, especially the terminal line and the top of the return roadway.
4.4.2. Analysis of Gas Concentration Field under Grout Sealing.

On the basis of the distribution of gas concentration field in Figure 23 that after grout sealing, the gas concentration in the return side area of the partially connected zone increases, while sealing increases the air leakage in the intake side of the working face and the gas concentration decreases. Grout sealing reduces the total air leakage in the upper gob and increases the drainage concentration in the high-drainage roadway.

4.4.3. Grout Sealing Effect on Spontaneous Combustion of Partially Connected Zone.

To figure out the effect of grout sealing on the spontaneous combustion of residual coal in the vicinity of the partially connected zone, Figure 22 shows the distribution of wind velocity before and after grout sealing. Figure 23 shows the distribution of gas concentration field before and after grout sealing. Figure 24 shows the distribution of oxygen concentration field before and after grout sealing.
upper gob, the results of the oxygen concentration and temperature fields in the upper gob of the partially connected zone are shown in Figures 24 and 25.

According to Figure 24, grout sealing can significantly reduce the oxygen concentration and the width of the oxidation zone in the terminal line of the upper gob and intake roadway. However, due to more air leakage pouring into the upper gob from the top of the working face, the width of the oxidation zone near the working face is increased. It can be seen from Figure 25 that the high-temperature area near the terminal line disappears after grout sealing, while the area of the high-temperature zone near the working face increases and the temperature increases.

As the above results, grout sealing changes the distribution state of air leakage in the upper gob, reduces the air leakage from the roof fractures in the intake roadway, and increases the air leakage from the working face area and the completely connected zone to the upper gob. After sealing, the drainage efficiency of the high-drainage roadway increased, and the gas concentration in the upper corner and return airflow decreased significantly. Although the zone near the working face is located in the oxidation zone after sealing, the oxidation self-heating of the residual coal near the upper-layered terminal line is inhibited, so it has alleviated the hazard of spontaneous combustion in the upper gob.

4.5. Multizone Gas Drainage Interaction Effect. According to the above analysis, in terms of gas overrun the high-drainage roadway has a better prevention on the gas overrun of the return airflow. Although the efficiency of corner gas drainage is low, in the area of upper corner it has an obvious effect on preventing the gas overrun. With respect to the spontaneous combustion of residual coal in gob, a high-drainage roadway will significantly enhance the hazard of spontaneous combustion, while the corner buried pipe drainage has a negligible effect on spontaneous combustion.

To obtain the gas overrun control effect of two types of drainage methods under different drainage flows and to determine the benchmark of multipoint and zoning gas drainage under the conditions of a ventilation flux of 1200 m³/min and grout sealing of the upper part of the intake roadway, 5 × 5 models were designed for simulation research according to the difference in drainage flow between the high-drainage roadway and the corner buried pipe drainage. On the basis of the distribution features of the gas concentration field...
mentioned above, the top of the return roadway near the upper corner of the working face and the terminal line in the upper gob is the concentrated gas emission point and high gas concentration area. Thus, we consider the maximum gas concentration area.

Figure 27. Distribution of oxygen concentration in the gob under different nitrogen injection flows.

Figure 28. Distribution of temperature field in the gob under different nitrogen injection flows.
concentration of the return airflow and upper corner as the criteria for assessing the drainage effect.

As shown in Figure 26a, when both the high-drainage roadway and the corner buried pipe are drained the gas concentration in the upper corner is significantly decreased from 3.91% to 0.15% with the increase in drainage flow; therefore, the gas drainage effect in the upper corner area is remarkable. The influence degree of the two drainage methods on the gas concentration in the upper corner is relatively close. However, according to the analysis in Section 4.3 when the drainage flow of high-drainage roadway rises it will enhance the air leakage in the upper goaf, which will further aggravate the risk of coal spontaneous combustion in the partially connected zone. On the basis of Figure 26b, the drainage of the high-drainage roadway has a significant influence on the maximum gas concentration of the return airflow. Corner drainage has a large drainage flow, but it has a limited control effect on the gas overrun in return airflow. The return airflow gas concentration is still higher than 1%, and there is a phenomenon of gas overrun. Overall, the high-drainage roadway is located in a relatively closed partially connected zone. When the drainage flow raised, part of the gas in the upper gob and completely connected zone will flow to the drainage port, which will reduce the gas flowing to the upper corner, resulting in the decrease of the gas concentration in the corner and thus affecting the drainage of corner buried pipe. In addition, as shown in Figure 26, when the drainage flow of buried pipe in the corner and high-drainage roadway is 40–45 and 110–120 m³/min, respectively, the gas concentration is lower than 0.8%, which can effectively prevent the gas overrun and avoid gas accidents.

4.6. Influence of Nitrogen Injection and Drainage in Completely Connected Zone. 4.6.1. Oxygen Concentration Field. Nitrogen injection has a remarkable effect on spontaneous combustion of residual coal in gob. Under the conditions of 40 m³/min drainage flow in the high-drainage roadway and 110 m³/min drainage flow in the corner buried pipe, the variation law of oxygen concentration in the gob with different nitrogen injection flows in the completely connected zone was simulated.

As shown in Figure 27, since the nitrogen injection inlet is located in the middle of the heat dissipation zone, the width of the heat dissipation zone on the intake side is reduced after nitrogen injection, such that the width of the oxidation zone is significantly reduced and it moves toward the working face.

4.6.2. Temperature Field. The change in the temperature field is the result of the combined action of the oxygen concentration field, oxidation heat release of residual coal, and heat storage conditions in the gob. Figure 28 shows that the nitrogen injection significantly changes the distribution of the temperature field, and the high-temperature zone exceeding 40 °C of the oxidation zone on the intake side disappears after nitrogen injection. When the nitrogen injection flow is raised, the area of the residual coal self-heating zone is further reduced, and the medium-temperature zone around 30 °C appears only in the working face and the upper corner.

To further analyze the variation law of the oxidation zone and temperature field in the completely connected zone, the simulation results are plotted as shown in Figure 29. According to Figure 29, when the nitrogen injection flow is raised, the width of the oxidation zone on the intake side of the gob is significantly reduced. Before the nitrogen injection, the maximum temperature of the residual coal in the gob reached 46 °C. When the nitrogen injection was 500 m³/h, the temperature of the residual coal dropped sharply to approximately 36 °C. Thereafter, every increase in nitrogen injection flow was 500 m³/h, and the maximum temperature of residual coal decreased by approximately 1 °C.

4.6.3. Nitrogen Injection and Gas Drainage Interaction Effects. Nitrogen injection in the gob affects the air leakage field, dilutes the gas in the area, changes the gas extraction concentration, and affects the maximum gas concentration in the upper corner and the return airflow under the condition of constant drainage flow. In Figure 30, the drainage parameters and gas concentration changes under different nitrogen injection flows in the gob are given under the conditions of 40 m³/min in a high drainage roadway and 110 m³/min in a corner buried pipe.

According to the gas concentration change curve in Figure 30a, when the nitrogen injection flow is gradually raised to 2500 m³/h, the gas concentration in the corner buried pipes and high-drainage roadway decreases to different degrees, and the change range of the high-drainage roadway is more obvious. With an increase in the nitrogen injection flow, both the maximum gas concentration in the upper corner and return airflow increases, and their changing trends are shown in Figure 30b.

4.7. Influence of Nitrogen Injection and Drainage in Partially Connected Zone. After grout sealing in the intake roadway, the air leakage in the partially connected zone was significantly reduced, and the temperature in the high-temperature zone near the terminal line on the intake side was effectively controlled. However, the residual coal in the upper part of the roof of the intake roadway was still in the zone with an oxygen concentration higher than 7%. To prevent the spontaneous combustion of residual coal, it is essential to inject nitrogen into the gob above so that the residual coal is inert. Studying the inverting effect of nitrogen injection in the upper gob and its influence on gas drainage is the basis for determining reasonable nitrogen injection parameters. The nitrogen injection drilling was simplified with 37 drilling holes and 5 m spacing. Under the condition of nitrogen injection flow from 100 to 600 m³/h, the influence of spontaneous combustion in the three zones, residual coal temperature field, and gas drainage effect in the upper gob were simulated and analyzed.
4.7.1. Oxygen Concentration Field. On the basis of Figure 31, with the increase in nitrogen injection flow the zone of the upper part of the intake roadway where the oxygen concentration was over 7% narrowed. In the roof area of the intake roadway with the maximum air leakage, when the nitrogen injection rate increased to 600 m$^3$/h, the oxygen concentration dropped below 7%, thus eliminating the hidden danger of spontaneous combustion caused by air leakage from the roof of the intake roadway.

4.7.2. Temperature Field. Figure 32 shows the change in the temperature field of residual coal in the upper gob under different nitrogen injection flows. It can be seen that the high-temperature zone in the upper gob is mainly located near the working face, and its area is gradually reduced when the nitrogen injection flow was raised; the maximum temperature of residual coal also decreases but the cooling range is small.

4.7.3. Nitrogen Injection and Gas Drainage Interaction Effect. The upper gob belongs to the partially connected zone, and nitrogen injection has a significant impact on the wind flow field; thus, it has a more obvious impact on gas drainage. In Figure 33, the drainage parameters and changes in the gas concentration in the roadway airflow under different nitrogen injection flows in the upper gob are given. On the basis of Figure 33, nitrogen injection in the upper gob significantly
reduces the gas concentration in the high-drainage roadway, resulting in a decrease in the drainage efficiency of the high-drainage roadway, and subsequently a part of the gas is forced to flow back into the return airflow through the fractures at the top of the return roadway and upper corner; the gas concentration in the corner buried pipes increases, while the maximum gas concentration in the upper corner and the return roadway increase to varying degrees. Thus, if the nitrogen injection flow is extremely high the gas drainage effect that is not conducive to controlling the gas overrun in the return airflow and upper corner is weakened.

4.7.4. Multipoint Gradient Nitrogen Injection Fire Prevention Technology. From the above analysis, nitrogen injection in the upper gob can obviously prevent the residual coal spontaneous combustion in the partially connected zone. However, there is a trade-off between nitrogen injection and gas drainage. Increasing the nitrogen injection flow reduces the drainage efficiency of the high-drainage roadway and increases the difficulty of gas control in the upper corner and return...
airflow. In addition, the air leakage flow is different at different positions of the intake roadway, and the nitrogen injection flow required to eliminate the oxidation zone is also different.

The length of the partially connected zone was 200 m, and nitrogen injection holes were arranged at intervals of 5 m from the working face to the direction of the terminal line with a nitrogen injection flow of approximately 18 m³/h per hole. If the equality nitrogen injection method is adopted, a total nitrogen injection flow of 666 m³/h is required that is not conducive to controlling air leakage and spontaneous combustion of residual coal. Therefore, according to the range of the oxidation zone in the upper area of the intake roadway under the different nitrogen injection flows mentioned above, this study adopts the gradient nitrogen injection technology. First, the total nitrogen injection is 350 m³/h, that is, 47.4% lower than that required by the equality nitrogen injection. The nitroge injection holes were arranged at intervals of 5 m from the working face to the direction of the terminal line with a nitrogen injection flow of approximately 18 m³/h per hole. If the equality nitrogen injection method is adopted, a total nitrogen injection flow of 666 m³/h is required that is not conducive to controlling air leakage and spontaneous combustion of residual coal. Therefore, according to the range of the oxidation zone in the upper area of the intake roadway under the different nitrogen injection flows mentioned above, this study adopts the gradient nitrogen injection technology. First, the total nitrogen injection flow of 666 m³/h is evenly distributed in each nitrogen injection hole. The simulated time step is set to 1 h, and the oxygen concentration data of each nitrogen injection hole is determined at the end of each time step. Taking 7% as the upper limit, when the oxygen volume fraction of nitrogen injection hole is higher than 7%, the flow of nitrogen injection hole increases by 3 m³/h. With the oxygen volume fraction of 5% as the lower limit, when two adjacent nitrogen injection holes are lower than 5% the nitrogen injection flow is reduced by 3 m³/h until the flow rate is 0. After repeated adjustment, when the flow rate of each nitrogen injection hole is no longer changed, the adjustment process of nitrogen injection amount ends, and the oxygen volume fraction in the upper goaf is controlled at 5%–7%. Considering the effects of equalizing pressure after nitrogen injection that reduce air leakage and dilute oxygen, allowing the air leakage flow to adapt to the nitrogen injection flow, and reducing the nitrogen injection quantity. As shown in Figure 34, different nitrogen injection flows were set according to the different positions of the nitrogen injection holes.

According to Figure 35, when multipoint gradient nitrogen injection is adopted, the oxygen concentration at the top of the intake roadway is controlled below 7%. The center of the spontaneous heating zone of the residual coal is located in the oxidation zone, and the highest temperature in the center is below 30 °C. From the simulation results, under the condition of ensuring the fire prevention effect in the upper gob, the multipoint gradient nitrogen injection technology not only significantly reduces the nitrogen injection flow but also ensures the gas drainage effect.

4.8. Establishment of Multipoint and Zoning Coordinated Prevention Method. 4.8.1. Regulation Benchmark for Nitrogen Injection Flow. Usually, the oxygen concentration of gob after nitrogen injection is used to reflect the effect of nitrogen injection on fire prevention. According to experimental research, when the oxygen content in the air drops to 7–10%, the self-heating process of coal oxidation is inhibited. Therefore, the critical value of 7% oxygen content was set as the index of fire prevention and inerting, and it is considered as one of the design benchmarks of the coordinated prevention method in this study.

For the partially connected zone of the working face, the key area for fire prevention is the upper part of the intake roadway; thus, an oxygen concentration of 7% is considered as the benchmark for regulating the nitrogen injection flow in this area. For the completely connected zone, there is the following dynamic equilibrium relationship among the maximum width of the oxidation zone, the mining speed, and the shortest spontaneous combustion period of the residual coal that serves as the benchmark for regulating the nitrogen injection flow in the completely connected zone

\[ t \geq t_s + \frac{L}{v} \]  

where \( t \) is the shortest spontaneous combustion period, d; \( t_s \) is the stagnation time, d; \( L \) is the maximum width of the spontaneous combustion oxidation zone, m; and \( v \) is the mining speed of the working face, m/d.

4.8.2. Regulation Benchmark of Multipoint Drainage. According to the Coal Mine Safety Regulation, the gas concentration of the working face in the upper corner and the return airflow should not exceed 0.8%. On the basis of the No. 153 mining area actual situation and simulation results, the top of the return roadway near the terminal line in the upper gob and the upper corner is the key area for gas overruns. Therefore, a gas concentration <0.8% in these two areas was considered as the regulation benchmark of the gas drainage flow.

4.8.3. Prevention Method of Nitrogen Injection in the Partially Connected Zone. The nitrogen injection holes and observation holes were alternately arranged in the roof area of the intake roadway, and the oxygen concentration and temperature in the observation holes were regularly detected. If the oxygen concentration exceeds the oxygen concentration standard (7%) in the asphyxiated zone of the gob or the temperature rises, the roof fractures should be grout sealing in time and the nitrogen injection flow adjacent holes should be increased to prevent the upper gob and roof coal from spontaneous combustion.

4.8.4. Prevention Method of Nitrogen Injection in the Completely Connected Zone. Nitrogen injection in the gob of a fully connected area has a significant influence on the width of the oxidation zone. Regression analysis was performed.
between the maximum width of the oxidation zone $L_{\text{max}}$ and the gas injection flow $q$, and eq 8 was obtained

$$L_{\text{max}} = A_0 + A e^{t/B}$$  \hspace{1cm} (8)

where $A_0 = 11.81245$, $A = 125.7686$, and $B = -511.79364$. The fitting curve is shown in Figure 36.

![Figure 36. Variation curve of the maximum width of oxidation zone with nitrogen injection flow](image)

Combined with the dynamic equilibrium relationship among the maximum width of the spontaneous combustion oxidation zone, mining speed, and the shortest spontaneous combustion period of residual coal in eq 7, the reasonable nitrogen injection flow can be obtained as follows

$$q \geq B \ln \left(\frac{v(t - t_0)}{A} - A_0\right)$$  \hspace{1cm} (9)

The shortest ignition period $t$ of residual coal is 15 days, the average advancing degree in a single day is 3.2 m, and the reasonable nitrogen injection flow in the gob of the completely connected zone is 637.6 m$^3$/h.

4.8.5. Prevention Method for Multipoint Drainage. Changes in ventilation flux, gas emission quantity, and nitrogen injection flow have an impact on the gas emission situation in the gob. This type of influence is most obvious in the upper corner of the working face and the top of the return roadway (near the terminal line in the upper gob) that easily leads to gas overruns in the two areas. Therefore, by arranging gas concentration monitoring devices in the upper corner area and the top of the return roadway, the change in gas concentration can be monitored in real time, and the coordinated control of gas drainage can be realized by linkage with the drainage system.

According to the changes in the maximum gas concentration in the upper corner and return air with the gas drainage flow (Figure 26) discussed in Section 4.5 and considering the intersection point of 0.8% gas concentration line as the regulation benchmark point, the corresponding drainage flow of high-drainage roadway is 40.2 m$^3$/min and the drainage flow of corner buried pipe is 109.9 m$^3$/min. When the gas emission situation in the gob changes, the gas concentration in the upper corner and the maximum gas concentration in the return airflow change, and the intersection of the changed concentration lines is called the unregulated state point. The horizontal distance between the regulation benchmark point and the unregulated state point corresponds to the corner buried pipe drainage adjustment flow, and the vertical distance corresponds to the high-drainage roadway drainage adjustment flow, as shown in Figure 37.

4.8.6. Verification of Multipoint and Zoning Coordinated Prevention Method. To confirm the regulation benchmark and determine the normal parameters of the multipoint and zoning coordinated prevention method for GCSC symbiotic disaster, simulation analysis was conducted in the order of regulation benchmark, correction of nitrogen injection flow and correction of drainage flow, and the data of gas concentration in the upper corner and maximum gas concentration in the return airflow were obtained, as shown in Table 2.

From the simulation results, the proposed method can effectively balance the disturbance of gas emission caused by nitrogen injection and the other factors and maintain the gas concentration in the upper corner and the maximum gas concentration in the return air within a reasonable range (less than 0.8%), as shown in Figure 38 illustrating the distribution...
of the oxygen concentration field and temperature field in the completely connected zone after regulation; when the nitrogen injection flow in the completely connected zone is 640 m$^3$/h, the maximum width of the oxidation zone in the lower gob is close to 50 m, and the center of the spontaneous heating zone of residual coal appears at approximately 35 m from the return side to the working face with the highest temperature of approximately 36 °C. According to the simulation results, the hazard of coal spontaneously combusting was basically eliminated under mining.

According to the Figure 39, multipoint gradient nitrogen injection makes the high oxygen zone (oxygen concentration >7%) disappear in the upper part of the intake roadway; meanwhile, the maximum width of the oxidation zone is controlled at 38 m, and the highest temperature is 29.4 °C. Therefore, the drainage flow of the high-drainage roadway was 45.4 m$^3$/min, the drainage flow of the corner buried pipe was 112.1 m$^3$/min, the total flow of multipoint gradient nitrogen injection in the partially connected zone was 350 m$^3$/h, and the nitrogen injection flow in the completely connected zone was 640 m$^3$/h that could be regarded as the normal

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Table 2. Data of Multipoint and Zoning-Coordinated Prevention Method

| ventilation flux (m$^3$/min) | corner gas drainage flow (m$^3$/min) | high-drainage roadway flow (m$^3$/min) | nitrogen injection flow in CCZ (m$^3$/h) | nitrogen injection flow in PCZ (m$^3$/h) | upper corner gas concentration (%) | upper corner gas concentration (%) |
|-------------------------------|-------------------------------------|----------------------------------------|-----------------------------------------|----------------------------------------|----------------------------------|----------------------------------|
| 1200                          | 110                                 | 40                                     | 500                                     | 0                                      | 0.756                            | 0.796                            |
| 1200                          | 110                                 | 40                                     | 640                                     | 350                                    | 1.077                            | 0.952                            |
| 1200                          | 112.1                               | 45.4                                   | 640                                     | 350                                    | 0.775                            | 0.794                            |

*CCZ means the completely connected zone; PCZ means the partially connected zone.*

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Figure 38. Oxygen concentration field and temperature field in the gob of the completely connected zone after regulation.
parameters of gas drainage flow and nitrogen injection flow in 5333(B) working face.

In summary, through the coordinated prevention method of multipoint and zoning proposed in this paper the nitrogen injection flow and the corresponding gas drainage flow in the upper and lower gob are efficiently determined. This avoids the waste of resources and mitigates accident risk caused by the frequent adjustment of drainage parameters and lays a theoretical foundation for the coordinated prevention of GCSC symbiotic disaster.

5. ENGINEERING APPLICATION

According to the above analysis, the multipoint and zoning prevention method is applied to the complex working face composed of upper and lower layers in No. 153 mining area. The layout of the prevention measures for the GCSC symbiotic disaster in the completely connected zone, partially connected zone, and unconnected zone is shown in Figure 40.

5.1. Application of Completely Connected Zone Prevention Method. During the mining period of the 5333(B) working face, to effectively prevent the widening and deep shift of the oxidation zone in the gob caused by air leakage in the gob nitrogen injection pipelines were arranged in the intake roadway at intervals of 20 m, and nitrogen injection was initiated 20 m deep into the gob. This cycle ensures that the nitrogen injection point in the gob is 20 m away from the working face. During mining, the regulated nitrogen injection flow in this zone is approximately 650 m³/h. The pipeline is laid, as shown in Figure 40.

5.2. Application of Partially Connected Zone Prevention Method. The following prevention measures were taken for the partially connected zone:

1. Parting and roof fracture grout sealing. During the intake and return roadway driving in the 5333(B) working face, the upper gob was drilled with layer holes and grouted, the interlayer fractures were sealed, and the residual coal in the overlying gob was covered to prevent spontaneous combustion caused by gas leakage from the fractures.

2. Nitrogen injection into the upper gob. In the roof of the intake roadway, drill holes are drilled by injecting nitrogen into the layer, and nitrogen is injected into the upper gob to balance the air leakage. The observation hole was drilled 5 m near the nitrogen injection hole, and the air pressure around the nitrogen injection point in the gob was observed. Thus, the air

![Figure 39. Oxygen concentration field and temperature field in the partially connected zone after regulation.](a) Oxygen concentration %

(b) Temperature field °C

![Figure 40. Measures of multipoint and zoning coordinated prevention method.](https://doi.org/10.1021/acsomega.2c01271)
pressure in the upper gob was greater than that in the 5333(B) intake roadway or return roadway, and the pressure difference was controlled between 0 and 50 Pa. According to the detection results of the oxygen concentration in the drainage pipeline, the gas drainage and nitrogen injection were adjusted in real time to ensure that the oxygen concentration in the gas drainage pipe in the sealed gob be below 7%. During mining, the actual nitrogen injection flow in this zone was approximately 350 m³/h. The pipeline is laid as shown in the purple circle marked at the center of Figure 40.

5.3. Effect of Prevention Method. No. 5333(B) mining face lasted for 90 days, during which the gas mixture flow was drained

\[ Q_{\text{Mix}} = q \times t \]  \hspace{1cm} (10)

where \( Q_{\text{Mix}} \) is the gas drainage mixed flow (10,000 m³); \( q \) is the drainage pump flow; \( t \) is the drainage time, 90 d. After the multipoint and zoning coordinated prevention method was adopted, the flow in the high-drainage roadway was 45.4 m³/min, and the flow in the corner buried pipe was 112.1 m³/min. Thus, \( Q_{\text{Mix}} = (45.4 + 112.1) \frac{m^3}{min} \times 1440 \frac{min}{d} \times 90 \frac{d}{d} = 2041.2 \times (10,000 \ m^3) \)

Accumulated pure gas drainage flow is

\[ Q_{p} = Q_{\text{Mix}} \times C \]  \hspace{1cm} (11)

where \( Q_p \) is the pure gas drainage flow (10,000 m³), and \( C \) is the gas drainage concentration. After the multipoint and zoning coordinated prevention method was adopted, the high-drainage roadway was 57.59%, and the corner buried pipe was 12.92%. Thus, \( Q_p = (45.4 \times 57.59\% + 112.1 \times 12.92\%) \frac{m^3}{min} \times 90 \frac{d}{d} \times 1440 \frac{min}{d} = 526.56 \times (10,000 \ m^3) \)

(2) Nitrogen injection quantity

\[ Q_N = (Q_1 + Q_2 + Q_3) \times t \]  \hspace{1cm} (12)

where \( Q_N \) is the total nitrogen injection quantity (10,000 m³). \( Q_1 \) is the nitrogen injection chamber flow, 50 m³/h. \( Q_2 \) is the intake roadway nitrogen injection flow, 640 m³/h. \( Q_3 \) is nitrogen injection flow of cross-layer drilling, 350 m³/h. \( t \) is the nitrogen injection time during mining, 90 d.

Thus, \( Q_N = (50 + 640 + 350) \frac{m^3}{h} \times 24 \frac{h}{d} \times 90 \frac{d}{d} = 224.64 \times (10,000 \ m^3) \)

The application results of the 5333(B) working face show that during the mining period, the mixed quantity of gas drainage was 20,412 million m³, the pure quantity of gas drainage was 5,265.6 million m³, and the nitrogen injection quantity was 2,246.4 million m³. With the successful application of the proposed method, the gas concentration in the working face of No. 153 mining area was below 0.8%, and there was no risk of spontaneous combustion. Thus, coordinated prevention of GCSC symbiotic disaster was successfully achieved.

6. CONCLUSIONS

(1) The main reason behind the frequent occurrence of GCSC symbiotic disasters in No. 153 mining area is that the slicing caused the coal and rock fractures to develop, and complex air leakage channels are formed between the coal seams, which leads to the secondary oxidation of residual coal.

(2) Corner buried pipe drainage can effectively prevent gas overrun in the upper corner and has relatively marginal effect on the coal spontaneous combustion with limited control on gas overrun in the return airflow. High-drainage roadway can significantly reduce the gas emission from the roof of the return roadway, but the coal spontaneous combustion in the upper gob intensifies when the drainage flow is raised.

(3) When nitrogen is injected into the completely connected zone, the width of the oxidation zone on the intake side and the range of the self-heating heating zone in the gob are significantly reduced, but the gas concentration in the upper corner and return airflow is increased. When nitrogen is injected into the partially connecting zone, it can effectively reduce the width of the oxidation zone in the gob at the upper part of the intake roadway and working face, but it significantly reduces the gas concentration in the high-drainage roadway.

(4) The prevention was performed based on the proposed multipoint and zoning coordinated prevention method, and the prevention parameters of GCSC symbiotic disaster in the complex working face of No. 153 mining area were determined: the high-drainage roadway flow was 45.4 m³/min, the corner buried pipe flow was 112.1 m³/min, the total flow of gradient nitrogen injection in the gob of partially connected zone was 350 m³/h, and the flow of buried pipe nitrogen injection in the intake roadway of gob in the completely connected zone was 640 m³/h.

(5) In the completely connected zone of No. 153 mining area of the Hengda coal mine, the prevention measures of the upper corner buried pipe drainage and nitrogen injection were adopted. In the partially connected zone, high drainage roadway and grout sealing were adopted. During the mining period, the gas concentration in the return airflow, upper corner, and working face area were all below 0.8%, and no risk of spontaneous combustion of coal was in the gob.

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Notes

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