INTRODUCTION

The spontaneous combustion of coal is one of the major hazards in the mining, storage, and transportation of coal. There are numerous examples of spontaneous coal fires in major coal-producing countries such as the United States, China, Australia, India, and South Africa.1-4 The safety hazards, resource losses, and environmental issues caused by this persistent problem have attracted widespread attention.3,5

Targeted inertization with flue gas injection in fully mechanized caving gob for residual coal spontaneous combustion prevention with CFD modeling

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Abstract
To effectively prevent and control the spontaneous combustion of residual coal at the bottom of a large fully mechanized gob space, we proposed a targeted inertization technology based on the injection of power plant flue gas. Based on the real onsite conditions of the gob, the three-dimensional distributions of the overburden fractures, gas emission, and residual coal were added to the multiphysics coupled model of spontaneous coal combustion. The simulation method based on moving coordinates was used to complete the risk evaluation and the locating of the spontaneous combustion in the fully mechanized gob, and the key control factors of the inerted zone and the fire prevention effect of the flue gas injection were analyzed. The results showed that the mismatch between the inerted zone and the spontaneous combustion risk zone was the root cause of the poor fire prevention effect of the inert gas injection. Because the density of the flue gas was greater than that of the leaked air, the flue gas mainly migrated and diffused in the lower part of the gob. At a distance of 100 m from the working face, the flue gas with 3%-9% oxygen content injected at a rate of 2000 m3/h completely covered the high-temperature residual coal. This caused the maximum temperature \( T_{\text{max}} \) to drop from 334.2 K upon nitrogen injection to below 310 K. Additionally, the effect of the oxygen content fluctuation on \( T_{\text{max}} \) was controlled within 2.6 K. The methods and the results in this study can serve as a reference for efficiently preventing and controlling local spontaneous combustion hazards in large spaces for underground coal mining.

KEYWORDS
gob area, multiphysics coupling, safety engineering, spontaneous combustion, targeted inertization
The fully mechanized top coal mining technology with the characteristics of high output and high efficiency has been widely used in the mining of extra-thick coal seams.\textsuperscript{5-8} As mining intensity increases, the quantity of gas emission also increases. Unavoidably, the ventilation intensity and air pressure in a working face are substantially enhanced, causing the air leakage in a gob to be much larger than the air leakages of ordinary working faces.\textsuperscript{9} Drainage measures, which are commonly used in the gas control of gobs, will further aggravate an air leakage and make the three-dimensional flow field more complicated.\textsuperscript{10,11} The caving process of top coal expands the height of a broken zone while leaving a large amount of crushed coal in the lower part of the gob.\textsuperscript{8} These factors, which are related to spontaneous combustion, have obvious 3D characteristics, and they greatly increase the risk of spontaneous combustion in fully mechanized caving gobs. In this situation, accurately locating the risk area and taking targeted measures are the key issues to be solved in order to eliminate hidden dangers of spontaneous fire.

Among various fire-fighting technologies, inert gas injection technology eliminates the risk of spontaneous combustion by reducing the oxygen concentration in a target area.\textsuperscript{12-15} Because of the advantages of wide coverage and strong applicability, it has become one of the main technical means for the prevention of spontaneous combustion fire in a gob. Nitrogen injection technology is the most mature and widely used fire-fighting technologies. However, because the density of nitrogen is slightly smaller than that of air, nitrogen can easily diffuse with air leakage.\textsuperscript{14,16} When applied in a fully mechanized caving face, it is difficult for nitrogen to accumulate in the lower part of a gob to form a large-area inerted zone. Therefore, in order to ensure the inerting effect, the gas injection flow rate needs to be increased significantly, which further increases the production cost to a certain extent. Related research studies have shown that under the effect of gravity, the density of a gas mixture will affect its migration trend in the vertical direction in a gob.\textsuperscript{17,18} There are many coal-fired power plants in China’s major coal-producing regions, and a correspondingly, large amount of low-oxygen flue gas is produced in the production process. Table 1 compares the relevant characteristics of the N\textsubscript{2}, CO\textsubscript{2}, and power plant flue gas for fire prevention in a gob.\textsuperscript{13,16} Power plants have abundant flue gas, which has the advantages of suppressing oxygen adsorption and easily accumulating in a residual coal area. In addition, the use of large quantities of flue gas in the process of spontaneous combustion prevention is economically and environmentally sound because it provides the resource disposal of a waste material\textsuperscript{19} while efficiently addressing the problem of spontaneous fire in a gob. However, there is no precedent for the use of flue gas to prevent spontaneous fire in a gob, especially when there are operators in the working face. Therefore, it was necessary to conduct a comprehensive analysis of the diffusion, and migration rules, the inertization mechanism, and the spontaneous combustion prevent effect of flue gas in combination with the onsite environmental factors of a gob.

The development of the spontaneous combustion of coal is a complicated process. Many scholars have chosen experimental methods to analyze the oxygen consumption, products, and thermal effects at different stages of coal spontaneous combustion.\textsuperscript{20-26} These analyses have provided the necessary theoretical support for further understanding of the coal spontaneous combustion mechanism. However, simply performing physical experiments has inevitably caused some important influencing factors to be ignored. Moreover, due to the complexity and inaccessibility of the gob area, onsite observation and measurement of the oxidation and self-heating process of the residual coal are difficult to perform.\textsuperscript{27} Based on the computational fluid dynamics (CFD) technique, relevant scholars have studied the evolution process,\textsuperscript{28} influencing factors\textsuperscript{27,29-32} and prevention measures\textsuperscript{17,18,33-37} of coal spontaneous combustion in gobs. Yuan and Smith studied the self-heating process of coal in a longwall gob with 3D numerical simulation and analyzed the influence of the ventilation system and coal properties.\textsuperscript{29} Xia et al\textsuperscript{28,30} proposed a fully coupled hydro-thermo-mechanical model for the quantitative analysis of the spontaneous combustion fire evolution of coal during the dynamic expansion of gobs, but the model was a two-dimensional simulation that ignored some 3D flow field factors. Liu et al\textsuperscript{31,32} added moving coordinates into a 3D dynamic simulation to solve the problem of gob area growth caused by the movement of a longwall working face and analyzed the spontaneous combustion influence factors such as the longwall advance rate, the thickness of the crushed coal, and the ventilation flux. Based on a 3D simulation of the flow field in a gob, Ren et al\textsuperscript{33} optimized a nitrogen injection scheme using oxygen concentration as an indicator. Zhang et al\textsuperscript{34-36} analyzed the effects of nitrogen injection on the temperature rise process of a gob and proposed inertization schemes for different mining periods, but the effects of the vertical permeability difference and gas emission on the seepage in the gob were ignored. The research of Wang et al\textsuperscript{11} showed that gas drainage in gobs would increase the risk of spontaneous combustion of residual coal. Suppression measures were proposed based on nitrogen injection. Liu et al\textsuperscript{18} used an empirical 3D porosity model to compare an oxygen concentration field and an inerted region after carbon dioxide and nitrogen were injected into a gob. Shi et al\textsuperscript{37} conducted a quantitative analysis of the cooling effect and the development of a low-temperature zone after the injection of liquid nitrogen in a gob. Based on the brief review described above, the feasibility of multiphysics coupled simulation for the quantitative analysis of spontaneous combustion in a gob has been demonstrated. However, previous
studies, to varying degrees, have ignored the 3D distribution differences of permeability, residual coal, and other factors in a gob space. These 3D distribution differences would directly affect the accuracy of flow field analysis and the locating of a spontaneous combustion risk area.

In this research, based on the No. 8105 fully mechanized caving face in the Tashan coal mine (Shanxi, China), a fully coupled 3D model of coal spontaneous combustion in a gob was established, including multiphysics coupling and on-site factor coupling. Using this model, we analyzed the flow field, gas concentration field, and temperature field related to spontaneous combustion in the fully mechanized caving gob. The results were verified by field monitoring experiments. The density differences between the injected inert gas, leaked air and emitted gas in the gob were discussed, and the influences of which on the 3D migration of the injected inert gas and the prevention of spontaneous combustion of the residual coal was analyzed. Additionally, we analyzed the inertization mechanism of flue gas injection by measuring the coupled changes of the inerted zone, high-oxygen concentration zone, and high-temperature zone with different gas injection parameters, including the injection location, injection rate, and oxygen content of the flue gas, and we further optimized the flue gas injection scheme. The results were of significance for assessing the usefulness of flue gas injection on the prevention of residual coal spontaneous combustion in fully mechanized caving gobs.

## 2  |  MATHEMATICAL MODEL

### 2.1  |  Basic assumptions

The spontaneous combustion of coal originates from a series of complex physical and chemical reactions after the coal is exposed to air. The development and prevention of spontaneous combustion in gobs also involve multifield coupling problems that include underground fissure fields, flow fields, oxygen concentration fields, and temperature fields.

In this research, the 3D coupling model of coal spontaneous combustion in a fully mechanized caving face was established based on the following basic assumptions: (a) Each component of the mixture gas in the gob was treated as an

### Table 1  |  Comparison of the fire prevention characteristics of the N₂, CO₂, and flue gas

| Properties          | Nitrogen          | Carbon dioxide | Flue gas of power plant |
|---------------------|-------------------|----------------|-------------------------|
| **Composition**     |                   |                |                         |
| O₂                  | <3%               | <1%            | 3.2%-8.6% (average: 5.6%) |
| N₂                  | ≥97%              |                | ~80%                    |
| CO₂                 | -                 | ≥99%           | 11.21%-16.6%            |
| Others              | -                 |                | SO₂, CO, NOₓ <50 mg/Nm³ |
| **Inerting**        |                   |                |                         |
| 1. Diluting oxygen  |                   | 1. Diluting oxygen | 1. Diluting oxygen |
| 2. Displacing air leakage |         | 2. Displacing air leakage | 2. Displacing air leakage |
| 3. Inhibiting oxygen adsorption | | 3. Inhibiting oxygen adsorption |                       |
| **Leakage hazard**  | Asphyxiant        | Asphyxiant     | Asphyxiant              |
| (vs air)            |                   | Slight toxicity| Low concentration toxic gases |
| **Relative density**| 0.97              | 1.52           | 1.04-1.07               |
| **Acquisition cost**| Lower             | Relatively high| Least                   |
| **Advantages**      | 1. Gas source is sufficient | 1. Heavier than air, can easily accumulate in the residual coal area near the floor | 1. Slightly heavier than air |
|                     | 2. Large coverage  | 2. No production cost, easy access to large injection flow rate | 2. No production cost, easy access to large injection flow rate |
| **Weaknesses**      | 1. Lighter than air, can easily diffuse with air leakage and short residence time | 1. Limited gas source and high cost | 1. Relatively high and unstable oxygen content |
|                     | 2. Expensive equipment, high operating and cycle maintenance costs | 2. Due to the high risk of leakage, it is difficult to achieve high-flow continuous gas injection. | 2. Contains small amounts of toxic substances |

2.2  |  Mathematical representation

The mathematical representation includes discrete governing equations to describe the physical and chemical processes involved in spontaneous combustion. These equations are solved using a computational fluid dynamics (CFD) approach.

2.3  |  Numerical method

The numerical method involves discretizing the governing equations using a finite volume method and solving the resulting system of equations using iterative algorithms. The method is validated against published data and field experiments.
ideal gas and its flow diffusion was approximated as a stable process. (b) The residual coal and the rock mass in the gob were regarded as continuous and isotropic porous media. (c) The physical properties of the coal and rock mass in the gob did not change with temperature and time. (d) The transfer of heat in the gob merely involved convection, conduction, and natural convection in the mixture gases. (e) The effects of water within the coal in the model were ignored.

2.2 | Governing equations

2.2.1 | Transport equations

To accurately simulate the flow in a porous medium and to obtain the correct results for the increase in air leakage velocity in the porous area of a gob, it is necessary to solve the true physical velocity in the entire flow field. Therefore, we established the following governing equation by introducing the effects of voids into the transport equation:

1. Continuous equation:

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

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

2. Momentum conservation equation:

\[
\frac{\partial}{\partial t} (\gamma \rho_f \vec{v}) + \nabla \cdot (\gamma \rho_f \vec{v} \vec{v}) = -\gamma \nabla p + \nabla \cdot (\gamma \vec{F}) + \gamma \rho_f \vec{g} + \gamma S
\]  

where \( \vec{F} \) is the viscosity stress tensor, \( p \) is the gas pressure in Pa, \( \vec{g} \) is the acceleration of gravity, and \( S \) is the added momentum loss source term of the airflow in the porous medium in units of \( N/m^3 \). In an isotropic porous medium:

\[
S = -\left( \gamma \frac{\mu}{\alpha} \nabla v_i + \gamma^2 C_2 \frac{1}{2} \rho_f |v| v_i \right)
\]  

where \( \mu \) is the dynamic viscosity coefficient of the fluid in \( kg \cdot m \cdot s^{-1} \), \( \alpha \) is the permeability in \( 1/m^2 \), and \( C_2 \) is the internal resistance coefficient. According to Blake-Kozeny,\(^4\) the empirical equations for a nonlinear flow condition are

\[
a = \frac{D_p}{150} \frac{\gamma^3}{(1-\gamma)^2}
\]  

where \( D_p \) is the mean grain diameter of the gob medium in meters.

3. Equation of state

For the convenience of analysis and calculation, we assumed that an ideal gas with multiple components filled the working faces and the environment of the gob. The equation of state for each component can be written as:

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

where \( M \) is the molecular weight of the gas and \( R \) is the universal gas constant.

2.2.2 | Multicomponent diffusion model

During a coal mining operation, the emission of gases such as methane and the consumption of oxygen by the residual coal cause dynamic changes for the gas components. This process exhibits the following relationship:

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

where \( Y_i \) is the mass fraction of the gas component \( i \), \( S_i \) is the source term of the gas component \( i \) in units of \( kg/m^3 \cdot s^{-1} \), and \( \vec{J}_i \) is the diffusion flux of component \( i \), given by Fick's law and expressed as follows in the turbulence model:

\[
\vec{J}_i = -\left( \rho D_{im} \frac{\mu_i}{S_{ij}} \right) \nabla Y_i - D_{ti} \nabla T
\]  

where \( D_{im} \) is the mass diffusion coefficient of component \( i \), \( D_{ti} \) is the thermal diffusion coefficient of component \( i \), and \( S_{ij} \) is the turbulent Schmitt number with the value assumed to be 0.7.

2.2.3 | Thermal field model

The heat transfer process between the fractured coal rocks and the gas environment in a gob is very complex and it is dominated by both the laws of heat transfer and the behavior of the gas flow. The self-heating process in the early stage of coal spontaneous combustion is very slow. The gas and the fractured coal rocks can be regarded as being in a state...
of thermal equilibrium. The energy equation of the thermal process can therefore be written as:

\[
\frac{d}{dt} (\rho E_I + (1 - \rho) E_s) + V \cdot \nabla (\rho E_I + p) = V \cdot \left( k_{eff} \nabla T - l \sum h_j \nabla T \right) + S
\]

(9)

where \(E_I\) is the total energy of the fluid in Joules, \(E_s\) is the total energy of the solid frame in Joules, \(\rho_f\) is the density of the fluid in \(\text{kg/m}^3\), \(\rho_s\) is the density of the solid frame in \(\text{kg/m}^3\), \(\gamma\) is the porosity of the medium, \(k_{eff}\) is the effective thermal conductivity of the medium, \(k_f\) is the thermal conductivity of the fluid, \(k_s\) is the thermal conductivity of the solid, and \(S_h\) is the exothermic strength of the fractured coal rocks in units of \(\text{W/m}^3\).

2.3. Quantification of the key influence factors

2.3.1. Three-dimensional distribution of the fracture field

Air leakage in a gob supplies oxygen to the residual coal while taking away the heat generated by oxidation. The void characteristics of fractured coal rocks are the key parameters affecting the volume and path of air leakage. Therefore, there is a relationship between the void fraction and the bulking factor of fractured coal rocks in a gob:

\[
\gamma = 1 - \frac{1}{K_p}\]

(10)

where \(K_p\) is the bulking factor of the fractured coal rocks.

As the working face advances, coal and rock seams cave from the bottom to the top of the caving zone sequentially and pile up to form a porous structure. The fractured coal rocks are gradually compacted by the caving rocks of upper layers. Based on this behavior, the change of the bulking factor in the middle of a gob can be described by the following equation:

\[
K_{p,x} = \begin{cases} 
K_{ini} + (K_{max} - K_{ini}) \cdot \exp \left( -2 \cdot \left( \frac{x - x_c}{\omega_1} \right)^2 \right), & x \leq x_c \\
K_{end} + (K_{max} - K_{end}) \cdot \exp \left( -2 \cdot \left( \frac{x - x_c}{\omega_2} \right)^2 \right), & x > x_c 
\end{cases}
\]

(11)

where \(K_{ini}\) is the bulking factor before the rock layer fractures, \(K_{end}\) is the residual bulking factor after the fractured coal rocks are compacted and stabilized, \(K_{max}\) is the maximum bulking factor, \(x_c\) is the coordinate of \(K_{max}\) on the x-axis, \(\omega_1\) is the distance from the fracture point of the rock layer to point \(x_c\), which is assumed to be the length of the rock block in meters, and \(\omega_2\) is the horizontal distance from point \(x_c\) to the line of compaction stability of the fractured coal rocks in meters.

Figure 1 shows a graph of the development of the fractures in the overburden rock at the cross section along the centerline of the gob in this research. During the advancement of the fully mechanized top coal caving face, the layers of the overburden strata of the gob collapsed sequentially. As the breaking fracture progressed upward, the break length \(\omega_1\), the compaction stability distance \(\omega_2\), and the peak position of the bulking factor \(x_c\) all changed. The fitted curves are given below:

\[
\omega_1 = a_\omega x + b_\omega
\]

(12)

\[
\omega_2 = 2\omega_1 + l
\]

(13)

\[
x_c = \omega_1 + \cot \theta \cdot (z - H_0)
\]

(14)

where \(l\) is the step distance of the periodic weighting in meters, \(H_0\) is the initial caving height in meters, \(\theta\) is the roof collapse angle in degrees, and \(a_\omega\) and \(b_\omega\) are the regression coefficients.

According to the definition of the bulking factor, the maximum bulking factor \(K_{max}\) after caving could be determined according to the slump height of the rock at position \(x_c\), the mining thickness of the coal seam, and the sinkage of the upper rock layer:

\[
K_{max} = \frac{H_1 - \Delta h}{H_1 - M_1}
\]

(15)

where \(H_1\) and \(\Delta h\) can be expressed by the following formula:

\[
H_{1,x} = \frac{H - H_0}{x_c (H)} \cdot x + H_0
\]

(16)

\[
\Delta h_x = (H - K_{end} \cdot (H - M_{max})) \cdot \exp \left( -\exp \left( -\frac{x - x_c (50) + l}{l} \right) \right)
\]

(17)

where \(H_1\) is the development height of the roof rock caving in meters, \(\Delta h\) is the sinkage of the upper rock layer in meters, \(H\) is the maximum development height of the caving zone in meters, and \(M_1\) is the cumulative mining thickness of the coal seam in meters. Its distribution was significantly affected by the coal seam occurrence and the mining processes.

As shown in Figure 2, when the fully mechanized top coal caving process was adopted, the top coal was not mined in the tunnel or its adjacent areas, and the actual mining thickness
was about the height of the tunnel. Combined with reality, the fitting formula of the cumulative mining thickness of the coal seam was:

$$M_1 = M_{\text{max}} - (M_{\text{max}} - M_0) \cdot 1 + \exp \left(-a_c \cdot (D_y - W_c)\right)^2$$ \hspace{1cm} (18)

where

$$D_y = \frac{W}{2} - \left|\frac{W}{2} - y\right|$$ \hspace{1cm} (19)

where $M_{\text{max}}$ is the maximum mining thickness of the coal seam in meters, $D_y$ is the minimum distance between point $(x, y)$ and the coal wall of the gob, $W$ is the width of the gob in meters, $M_0$ is the cutting thickness in meters, $W_c$ is the width of the unmined top coal in meters, and $a_c$ is the regression coefficient for the cumulative mining thickness.

According to the “O”-ring theory and field measurements, the caving of the roof rock strata under the support of coal pillars behaved similarly. Therefore, assuming that the bulking factor of the fractured coal rocks in the middle of the gob conformed to Equation (11), and taking into account the influence of the sustainment of the coal pillars, we defined an equivalent distance from any point in the gob to the side wall as:

$$D_{xy} = x \cdot \left[1 - \exp \left(-a_y \cdot D_y\right)\right]$$ \hspace{1cm} (20)

where $a_y$ is the influence coefficient of the boundary coal pillar of the gob.

By substituting Equations (11)-(20) into Equation (10), we finally obtained a 3D distribution model of the coal-rock porosity in the gob:

$$\gamma = \begin{cases} 
1 - \left[K_{\text{in}} + (K_{\text{max}} - K_{\text{in}}) \cdot \exp \left(-2 \cdot \left(\frac{D_{xy} - x_c}{\alpha_1}\right)^2\right)\right]^{-1}, & D_{xy} \leq x_c \\
1 - \left[K_{\text{end}} + (K_{\text{max}} - K_{\text{end}}) \cdot \exp \left(-2 \cdot \left(\frac{D_{xy} - x_c}{\alpha_2}\right)^2\right)\right]^{-1}, & D_{xy} > x_c 
\end{cases}$$ \hspace{1cm} (21)

**FIGURE 1** Schematic diagram of the fracture development in the overburden strata

### 2.3.2 Distribution of the crushed residual coal

Related studies have shown that there is a positive correlation between the thickness of residual coal in a gob and the risk of spontaneous combustion. Furthermore, an uneven distribution of residual coal can also directly affect the location and area of a high-risk zone for spontaneous combustion. As a working face advances, the caving of top coal alternates with the coal cutting process. The thickness distribution of a mixed stack of loose residual coal and fractured rocks can be approximated by the following formula:

$$H_c = \frac{K_p}{1 - \eta} \cdot (M - M_1)$$ \hspace{1cm} (22)

where

$$\eta = \eta_0 \cdot 1 + \exp \left(-a_c \cdot (D_y - W_c)\right)^{-1}$$ \hspace{1cm} (23)

where $M$ is the coal seam thickness in meters, $\eta$ is the proportion of gangue in the height of the residual coal, and $\eta_0$ is $\eta$ at the center of the gob.

### 2.3.3 Gas emission source

The methane desorbed from the fractured coal rocks in a gob will dilute oxygen in the air leakage, and the accumulation of methane can change the density of the gas mixture in a gob and to some extent affect the flow field. For working faces rich in methane that are susceptible to spontaneous combustion, properly determined gas source location and emission intensity can improve the simulation accuracy of spontaneous combustion in a gob.

In fully mechanized caving gobs, the released methane comes mainly from the fragmented top coal, the residual coal in the gob, and other coal seams in the mining area. The structure of top coal is broken under the action of mining pressure, causing some of the gas flows into a gob from the fracture boundary. The amount of methane emission during the advancement of a working face is approximately a constant that may be simplified as the fixed source terms of the boundary elements of the top coal:

$$S_1 = \frac{Q_1}{d_1 W (M - M_0)}$$ \hspace{1cm} (24)

where $Q_1$ is the amount of methane leaked from the top coal into the gob in units of mol/min and $d_1$ is the width of the boundary unit in meters.

The residual coal slowly releases gas into the gob, and the emission intensity decreases gradually with increasing exposure time. This can be expressed by the following formula:
where $S_0$ is the initial emission intensity of the gas per unit volume of coal in units of mol/m$^3$ min$^{-1}$, $\lambda$ is the attenuation coefficient of the gas emission intensity in units of d$^{-1}$, and $v_d$ is the advancing speed of the working face in m/d.

In terms of the dynamic range, the intensity of gas emission from other coal layers is small and attenuates slowly. The gas emission from nonresidual coal regions in a gob may therefore be regarded as a constant, at an intensity of:

$$S_3 = \frac{Q_3}{\int (H-H_c) \, dx \, dy}$$

(26)

where $Q_3$ is the gas emission from nonmineable coal layers in units of mol/min.

### 2.3.4 Oxygen consumption and exothermic rate

In many studies, the oxygen consumption and exothermic rates of coal have been described by the Arrhenius equations.\textsuperscript{28,29,34} However, the reaction of coal with oxygen at low temperatures is extremely complicated and there are significant differences in the main forms of the reaction, reaction products, and reaction rates at different temperatures. These factors have affected the applicability of the Arrhenius equation to some extent.\textsuperscript{20,21,23,25}

In this study, we measured the relationship between the oxygen consumption, the products, and the temperature for samples acquired from the No. 3-5 coal seams in the Datong Mining Area through temperature-programmed experiments. According to the experimental results, the heat release rate was calculated by the method described in the literature.\textsuperscript{21,31} The experimental process is omitted here. The regression equation of the experimental result is:

$$V_{O_2}(T) = k_0 e^{b_0 T}$$

$$Q_h(T) = k_1 e^{b_1 T}$$

(27)

where $V_{O_2}(T)$ is the oxygen consumption rate of the coal sample at 20.96% oxygen concentration in units of mol/m$^3$ s$^{-1}$, $Q_h(T)$ is the heat release intensity in units of W/m$^3$, $T$ is the reaction temperature in degrees Kelvin, and $k_0$, $k_1$, $b_0$, and $b_1$ are the regression coefficients of the experimental results.

The oxygen consumption and heat release rates of the residual coal in the gob were directly proportional to the ambient oxygen concentration, and they were affected by the grain size and stacking condition of the crushed coal. In actual production, the grain size of the crushed residual coal fluctuated within a certain range, and its influence on the oxygen consumption heat release rate could be simplified to a fixed value. From this, we obtained the expression of the source term for the oxygen consumption and heat release intensity per unit volume of the residual coal region in the gob:

$$\begin{align*}
S_{O_2}(T) &= \frac{C_{O_2}}{C_0} k_d \exp \left( -k_q (1 - \eta) \right) V_{O_2}(T) \\
S_h(T) &= \frac{C_{O_2}}{C_0} k_d \exp \left( -k_q (1 - \eta) \right) Q_h(T)
\end{align*}$$

(28)

where $C_{O_2}$ is the ambient oxygen concentration in %, $C_0$ is the oxygen concentration in air, which is 20.96%, and $k_d$ and $k_q$ are the coefficients for the grain size effect and the gangue rate effect.

### 3 BASIC MODEL AND VALIDATION

#### 3.1 Simulation case

The model was based on the fully mechanized top coal caving face No. 8105 in Tashan Coal Mine, with a running length of 2960 m and an inclined width of 207 m. The spontaneous combustion tendency of the No. 3-5 coal seams was type II (GB/T 20104-2006: spontaneous combustible coal), with a spontaneous combustion period of 68 days, an inclination angle of 3° to 5°, and an average thickness of 14.81 m. The mining height was 4 m, the thickness of the caving top coal was 10.81 m, and the mining rate was about 81%. The immediate roof thickness was only 4.9 m, and the periodic weighting length of the basic roof was 24-33 m. The methane emission quantity of the working face was 44.6 m$^3$/min, with 60% coming from the gob. The ventilation mode was the “U + I” type with an air supply rate of 3000 m$^3$/min and a gas drainage rate of 1000 m$^3$/min from the high-level suction roadway. In order to prevent spontaneous combustion, nitrogen gas was pumped in continuously through buried pipes at the windward side of the gob. The nitrogen injection location was 50 m away from the working face and the flow rate could be up to 2000 m$^3$/h. However, the air leakage in the caving
gob was large and complex and the noticeable self-heating of residual coal could still occur.

3.2 Physical model and simulation conditions

Based on the actual situation at the No. 8105 working face, a physical model centered on the working face was established. The model included part of the gob, the air intake and return roadway, and the high-level suction roadway. The model size and the 3D porosity distribution determined from Equation (21) are shown in Figure 3. The origin of the coordinate was chosen at the intersection of the air return corner and the floor. The x-axis was along the workface advancing direction and it was pointed toward the deep part of the gob, the y-axis was pointed along the incline toward the inlet side, and the z-axis was pointed upward perpendicular to the floor. The horizontal distance between the high-level suction roadway and the air return roadway was 30 m, and the vertical height from the coal seam floor was 27 m. The inert gas injection ports were located near the windward side of the gob.

Most of the model parameters adopted in this study were obtained through field observations and experiments, with reference to the results of other studies. The main parameters are shown in Table 2.

3.3 Model validation

Under complicated field conditions, the spontaneous combustion problem in the gob of the 8105 fully mechanized caving face had distinct 3D characteristics. Figure 4 shows the 3D air leakage flow field, the methane concentration field, the oxygen concentration field, and the temperature field in the gob of the 8105 fully mechanized caving face when no fire prevention measures were adopted.

1. Figure 4A shows that the air leakage flowed from the working face to the side of the return air and to the deep part of the gob. The figure also shows that the wind speed diminished in the deep part and the upper part of the gob. Most of the air leakage entered the high-level suction roadway in the area near the working face. A small amount of the air leakage flowed from the inlet corner to the deep part of the gob and it was sequestered in the gob as the working face advanced.

2. Figure 4B shows the methane concentration field in the gob. The emitted methane gradually accumulated during the diffusion and migration process of the air leakage, making the concentration on the air return side of the gob significantly higher than that on the air inlet side. At the same time, under the action of gravity, the gas emitted from the upper part of the caving zone accumulated in the slow-flowing area. The highest concentration of methane was about 35%.

3. Figure 4C,D show the oxygen concentration field and the temperature field in the gob. The wind speed near the working face was relatively high, which provided enough oxygen and disrupted the thermal storage conditions. Therefore, the oxygen concentration was maintained at about 20%, while the phenomenon of the residual coal temperature rising was not prominent. As the working face advanced, the air leakage velocity gradually decreased and the oxidation heat in the residual coal accumulated, forming a high-temperature area near the floor of the gob. The center of this high-temperature zone appeared to be in the accumulation area of the top coal on the windward side. As the air leakage flowed through the high-temperature residual coal, oxygen was quickly consumed, and under the synergistic action of gas dilution, the oxygen concentration in the residual coal area and in the upper part of the caving zone was significantly lowered. In the deep part of the gob, the oxygen concentration was insufficient to maintain the oxidation heating process of the residual coal, and the temperature of the coal rocks gradually dropped to its original level.

To verify the reliability of the model, the air volume distribution on the working face was measured on site and the oxygen concentration in the gob was continuously monitored using the bundle tube monitoring system. The layout of the onsite measuring points is shown in Figure 5.

During the inspection of the working face, the air volume of each measuring point was obtained by professional technicians through measurements of the average wind speed and the cross-sectional area. The actual measured air volume distribution was compared with the simulation results, as shown in Figure 6. The results showed that the numerical simulation results were generally consistent with the onsite measured air volume change law and the maximum relative error was smaller than 4%.

The bundle tube monitoring points gradually went deep into the gob area as the working face advanced, so the oxygen concentrations at different depths were obtained. The on-set observation lasted for 90 days. The comparison between the monitored data and the corresponding simulation results is shown in Figure 7. There was a small deviation between the simulation oxygen concentrations and the onsite monitoring, but the overall trend was consistent, which further verified the feasibility of the basic model.
4 | TARGETED INERTING EFFECTS OF FLUE GAS INJECTION

4.1 | Migration law and inerted region

The key to inert gas fire suppression technology is to control the oxygen concentration in the risk zone of spontaneous combustion. The entire caving space was full of air leakage, but the risk of spontaneous combustion only appeared in the residual coal area in the lower part of the gob. Therefore, the migration path of the injected inert gas directly affected the fire prevention effect.

In order to determine the migration and diffusion paths of the injected inert gas, a tracer gas with a concentration of 100 ppm was added and the volume fraction of the injected inert gas in the air leakage flow was determined according to its concentration. Through simulation, we determined the migration behavior of the injected inert gas and the 3D distribution of the oxygen concentration (Figure 8), in which nitrogen (3% O2) or flue gas (6% O2) was injected into the gob at X = 50 m on the windward side with a flow rate of 2000 m3/h.

Figure 8A,C show the volume fraction of the nitrogen injected into the gob and the oxygen concentration distribution. The density of the nitrogen was between that of the air leakage and the methane, and the nitrogen was transported to the upper and deep parts of the gob under the influence of buoyancy and air leakage. The injected nitrogen always maintained a high concentration during the movement, and the oxygen concentration in the inerted zone was reduced to 3% or less.

The density of the flue gas was about 1.05 times that of air. Figure 8B shows that the power plant flue gas had a significant settlement effect after being injected into the gob. It gradually mixed with the air leakage during the diffusion and migration process in the area of the residual coal, and its concentration was significantly reduced. Figure 8D shows that the oxygen concentration in the high-temperature zone of the original gob after the injection of the power plant flue gas was reduced to about 6%.

4.2 | Spontaneous combustion prevention effect

Under the action of multifield coupling, the risk of spontaneous combustion in the gob of a fully mechanized caving face is concentrated in the residual coal region. We therefore carried out a quantitative analysis of the oxygen concentration field and temperature field at the horizontal cross section at Z = 3 m (Figure 9) to evaluate the fire prevention effect of nitrogen and the injected power plant flue gas.

Figure 9A shows the original distribution of the oxygen concentration field in the gob. Based on the oxygen concentration of 7%-18%, the risk of spontaneous combustion of the residual coal was divided into “three zones.” The width of the heat dissipation zone was 46-107 m, and the width of the oxidation zone was 5-152 m. After 235 m, the residual coal completely entered the suffocation zone. According to Figure 9D, the phenomenon of self-heating of the residual coal had already occurred in the heat dissipation zone. The area with a temperature higher than 313 K was 41-237 m away from the working face, and the center temperature was as high as 364.5 K. Therefore, the area where the oxygen concentration was greater than 7% was defined as the high-oxygen area. Furthermore, the maximum width \( W_{\text{max}} \) of the high-oxygen zone and the maximum temperature of the residual coal \( T_{\text{max}} \) were used as the basis for judging the effect of fire prevention by inertization.

Figure 9B,E depicts the oxygen concentration field and the temperature field of the residual coal during nitrogen injection. The effect of nitrogen injection on the oxygen distribution in the residual coal region was mainly experienced in the intake roadway side and the deep part of the gob, reducing
TABLE 2 Parameters used in the numerical simulation

| Parameter                                      | Value     | Parameter                                      | Value     |
|------------------------------------------------|-----------|------------------------------------------------|-----------|
| Longwall working face width (W, m)             | 207       | Initial caving height (H₀, m)                 | 20        |
| Maximum height of caving zone (H, m)           | 50        | Initial bulking factor of gob (kₑ₀, −)         | 1.02      |
| Virgin rock temperature (T₀, K)                | 295       | Compaction bulking factor of gob (kₑₘₙ, −)     | 1.1       |
| Advance rate of workface (v₀, m/d)             | 4         | Periodic weighting length (l, m)               | 28        |
| Thickness of coal seam (M, m)                  | 14.81     | Roof caving angle (θ, °)                       | 60        |
| Coal cutting thickness (M₀, m)                 | 4         | Regression coefficient of fracture length (a₀, −) | 0.4       |
| Maximum thickness of mining coal seam (Mₘₙ, m) | 12        | Regression coefficient of fracture length (b₀, −) | 8         |
| Top coal width at face end (W₀, m)             | 10        | Influence coefficient of protective coal pillar (α₀, −) | 0.05     |
| Regression coefficient of total coal mining thickness (a₀, −) | 0.4 | Gangue ratio of residual coal in the middle of gob (η₀, −) | 0.5 |
| Regression coefficient of oxygen consumption rate (k₀, −) | 8.14e10⁻⁷ | Gas emission from top coal (Q₁, mol/min) | 300 |
| Regression coefficient of oxygen consumption rate (b₀, −) | 0.01677 | Unit width at the boundary (d₁, m) | 1 |
| Roadway ventilation resistance per unit length (r, N S²/m⁹) | 1.2e-4 | Initial gas release intensity from the residual coal of gob (S₀, mol/m³ min⁻¹) | 0.02 |
| Regression coefficient of exothermic intensity (k₁, −) | 0.07308 | Gas emission from unworkable seam (Q₁, mol/min) | 200 |
| Regression coefficient of exothermic intensity (b₁, −) | 0.01894 | Attenuation coefficient of gob gas release (λ, d⁻¹) | 0.0376 |
| Gas constant (R, J/mol K⁻¹)                    | 8.314     | Specific heat capacity of coal-rock (C₀₀, J/kg K⁻¹) | 1003.2 |
| O₂ concentration at roadway boundary (C₀₀, %)   | 20.96     | Heat conduction coefficient of coal (k₁₀₀, W/m K⁻¹) | 0.2 |
| Coal density (ρ₀₀, kg/m³)                      | 1400      | Heat conduction coefficient of rock (k₀ₙ₂, W/m K⁻¹) | 2.1 |
| Rock density (ρ₀₂, kg/m³)                      | 2200      | Impact factor of particle size (k₂₀, −)        | 0.15      |

Wmax to 175 m. After nitrogen injection, the temperature of the residual coal in the gob was significantly reduced and the area of the high-temperature zone was reduced, shifting the center of the high-temperature zone to the middle of the gob and lowering Tmax to 334.2 K.

Figure 9D,F shows the simulation results of the power plant flue gas injection. The boundary of the heat dissipation zone was about 20 m from the working face and Wmax was 91 m. The inerting and cooling effects of the power plant flue gas gradually diminished outward from the injection port. The center of the self-heating area transferred to the suffocation zone and Tmax was lowered to 306.2 K.

The relative magnitude of the density of the inert gas and the density of the gas in the gob determined the vertical distribution of the inerted zone in the gob. Additionally, the increase in the inert gas density weakened the effect of the air leakage flow field on its percolation path; that is, the displacement effect of the inert gas on the air leakage was enhanced. Since the density of the power plant flue gas was greater than that of the air, the power plant flue gas mainly migrated and diffused in the lower part of the gob. The inerted zone of the flue gas in the region of the residual coal was much larger than that of nitrogen, which was conducive to suppressing the accumulation of the oxidation heat and eliminating the risk of high-temperature spontaneous combustion.

5 | SENSITIVITY OF FLUE GAS INJECTION PARAMETERS

According to the inertization theory for fire prevention, injecting power plant flue gas into a gob produces a displacement effect on the air leakage in the residual coal area, a dilution effect on the oxygen gas, and a cooling effect on the high-temperature residual coal. The spontaneous combustion process can therefore be retarded or prevented. In this study, the oxygen content, injection location, and flow rate of
the flue gas injected into the gob had non-negligible effects on the migration and diffusion behavior and the fire prevention efficiency.

5.1 Effect of the injection location

Figure 10 shows the isolines of the oxygen concentration and the flue gas concentration distribution field at the horizontal cross section at \( Z = 3 \) m when the power plant flue gas with 6% oxygen content was injected at different locations with a speed of 500 m\(^3\)/h.

As shown in Figure 10A, the injection port was 50 m away from the working face, at a location where the influence of the injected flue gas on the oxygen concentration field was mainly that of dilution. The flue gas was continuously mixed with the air leakage during the migration process, and the effect on the oxygen concentration was gradually attenuated. The maximum width of the high-oxygen zone was \( W_{\text{max}} = 234 \) m. As the injection port moved deeper into the gob, the accumulated concentration of flue gas increased and the overlap of the passing area and the high-oxygen zone gradually decreased. In other words, the influence of the injected flue gas on the oxygen concentration gradually
changed from dilution to displacement. In this process, the width of the oxidized zone decreased while moving to the deep part of the gob and the width of the high-oxygen zone rapidly decreased and then slowly increased.

The inerted zone was defined as the region where the concentration of flue gas was greater than 5%. Figure 11 shows the contour line for the 5% flue gas concentration and the nephogram of the temperature field for the horizontal cross-sectional plane at \( Z = 3 \) m when the flue gas was injected at different locations. As the working face advanced, the temperature of the residual coal increased exponentially and the high-temperature center appeared near the boundary of the inerted zone. The trend of the rising temperature of the coal in the inerted zone was greatly weakened, and the temperature might have even declined. As the injection port moved deeper into the gob, the width of the flue gas inerted zone on the inlet side decreased and the area of the high-temperature residual coal increased. At the same time, the high-temperature center shifted from the return side to the inlet side and moved toward the deeper part of the gob. The maximum temperature \( (T_{\text{max}}) \) also increased gradually from 316.5 K to 364.3 K.

### 5.2 Effect of the injection rate

Figure 12 shows the isolines of the oxygen concentration and the flue gas concentration distribution field at the \( Z = 3 \) m cross section of the residual coal for different injection rates of the flue gas. An increase in the injection rate increased the concentration of the flue gas and enhanced the displacement effect. The oxygen supply from the air leakage was...
**FIGURE 8** Diffusion regularity of the injected flue gas or the nitrogen and their influences on the $O_2$ concentration field in the gob. (A) Concentration of the injected nitrogen. (B) Concentration of the injected flue gas. (C) $O_2$ concentration field with nitrogen injection. (D) $O_2$ concentration field with flue gas injection.

**FIGURE 9** $O_2$ concentration and temperature field at the horizontal cross section at $Z = 3$ m before and after inert gas injection. (A) $O_2$ concentration field without inert gas injection. (B) $O_2$ concentration field with nitrogen injection. (C) $O_2$ concentration field with flue gas injection. (D) Temperature field without inert gas injection. (E) Temperature field with nitrogen injection. (F) Temperature field with flue gas injection.
greatly weakened, the inerted zone near the injection port enlarged, and the oxygen concentration in the area gradually approached the oxygen content of the injected flue gas (6%). The width of the high-oxygen zone decreased.

Figure 13 shows the temperature field on the Z = 3 m horizontal cross section for different gas injection rates. The increase of the gas injection rate weakened the oxidation and temperature rise of the residual coal in the inerted zone. The region centered on the injection port, where the injected flue gas lowered the temperature, increased in size. When the center of the high-temperature zone moved away from the injection port, the maximum temperature $T_{\text{max}}$ dropped. However, a significant increase in the gas injection rate brought the boundary of the inerted zone on the return air side closer to the working face and increased the potential risk of flue gas leakage.

The graph in Figure 14 was drawn with the maximum width $W_{\text{max}}$ of the high-oxygen zone and the maximum

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**FIGURE 10** Concentration of flue gas and O$_2$ at the cross section at $Z = 3$ m when flue gas was injected at different locations. (A) $X = 50$ m. (B) $X = 100$ m. (C) $X = 150$ m. (D) $X = 200$ m. (E) $X = 250$ m. (F) $X = 300$ m

**FIGURE 11** Inerted zone and temperature field at the cross section at $Z = 3$ m when flue gas was injected at different locations. (A) $X = 50$ m. (B) $X = 100$ m. (C) $X = 150$ m. (D) $X = 200$ m. (E) $X = 250$ m. (F) $X = 300$ m
temperature $T_{\text{max}}$ of the residual coal as the ordinate and with the gas injection rate as the abscissa. As the injection rate increased, $W_{\text{max}}$ and $T_{\text{max}}$ decreased exponentially. At the same time, the difference in $W_{\text{max}}$ and $T_{\text{max}}$ between different injection locations decreased. As the gas injection rate increased from 500 m$^3$/h to 3000 m$^3$/h, $W_{\text{max}}$ decreased by 64.7 m ($X = 250$ m) to 168.4 m ($X = 50$ m), and $T_{\text{max}}$ decreased by 11.5 K ($X = 50$ m) to 43.6 K ($X = 250$ m). When the gas injection rate exceeded 1500 m$^3$/h, $W_{\text{max}}$ could be made a minimum by injecting flue gas at the location of $X = 100$ m and $T_{\text{max}}$ could be reduced to less than 310.5 K.
Effect of the O₂ content

Power plant flue gas is a combustion product; as its oxygen content increases, the concentration of carbon dioxide decreases, and the overall density decreases slightly. In this study, under the action of gravity, the tendency for the flue gas to sink was weakened, resulting in an increased concentration of the flue gas and an increased effect on the migration pathway affected by the air leakage flow field. At the same time, the oxygen content increased and the dilution ability of the injected flue gas on the oxygen in the air leakage weakened. Figure 15 shows the diffusion cloud of the gas and the contours of the oxygen concentration for a horizontal cross section at $Z = 3$ m when flue gases with different oxygen contents were injected. (A) $X = 50$ m, 3% O₂ content. (B) $X = 50$ m, 9% O₂ content. (C) $X = 250$ m, 3% O₂ content. (D) $X = 250$ m, 9% O₂ content.

### 5.3 Effect of the O₂ content

Power plant flue gas is a combustion product; as its oxygen content increases, the concentration of carbon dioxide decreases, and the overall density decreases slightly. In this study, under the action of gravity, the tendency for the flue gas to sink was weakened, resulting in an increased concentration of the flue gas and an increased effect on the migration pathway affected by the air leakage flow field. At the same time, the oxygen content increased and the dilution ability of the injected flue gas on the oxygen in the air leakage weakened. Figure 15 shows the diffusion cloud of the gas and the contours of the oxygen concentration for a horizontal cross section at $Z = 3$ m when flue gases with different oxygen contents were injected. As the oxygen content of the injected flue gas increased, the oxygen concentration in the inerted zone and the width of the high-oxygen zone near the working face increased. When the oxygen content of the flue gas that was injected into the deeper part of the gob ($X = 250$ m) exceeded 7%, a new high-oxygen zone was formed near the gas injection port.
Figure 16 shows that the increase in the oxygen content of the injected flue gas could move the boundary of the inerted zone to the deeper part of the gob, leading to a slight increase in the temperature of the residual coal. However, even though the oxygen content of the gas injected at $X = 250$ m reached 9%, the temperature in the high-oxygen zone near the gas injection port was still lower than 313 K.

As the oxygen content of the flue gas injected into the power plant increased, the maximum temperature $T_{\text{max}}$ of the gob increased exponentially. The maximum temperature increase in the gob that was caused by the increase of the oxygen content from 3% to 9% under the same gas injection parameters was defined as $\Delta T_{\text{max}}$, and its relationship with the injection location was as shown in Figure 17. The range of $\Delta T_{\text{max}}$ was 2.6 K-9.9 K. At the same flow rate, the injection of flue gas near the working face or deep in the gob tended to show a single effect (Dilution effect or displacement effect), which increased $\Delta T_{\text{max}}$. When the inertization effect was dominated by dilution, the increase of the gas injection rate increased $\Delta T_{\text{max}}$. Whereas when the inertization effect was dominated by the displacement effect, the increase of the injection rate decreased $\Delta T_{\text{max}}$. Under these circumstances, the value of $\Delta T_{\text{max}}$ was the smallest (2.6 K) when the flue gas was injected at $X = 100$ m with a rate of 2000 m$^3$/h.

In summary, as the injection location moved deeper into the gob, the influence of the power plant flue gas on the high-oxygen zone gradually changed from dilution to displacement. When the power plant flue gas was injected near the working face, it produced a larger inerted zone, which was more conducive to preventing the accumulation of oxidation heat in the residual coal and reducing the risk of high-temperature spontaneous combustion. The effect of the flue gas oxygen content fluctuations on $T_{\text{max}}$ could be minimized by injecting the gas at $X = 100$ m. For gas injections made deep in the gob, the increased concentration was more conducive to the adsorption and sequestration of toxic and harmful substances such as carbon dioxide in the power plant flue gas.

**CONCLUSION**

1. A large amount of air leakage filled the caving space, but the risk for high-temperature spontaneous combustion was concentrated in the accumulated residual coal on the floor of the gob, resulting in a low efficiency for fire prevention via overall nonspecific inertization.
2. Because the density of the power plant flue gas was greater than that of the leaked air, the flue gas mainly migrated and diffused in the lower part of the gob, covering an area of the residual coal far greater than that covered by the nitrogen. Such targeted inertization was more conducive than nitrogen injection to suppressing residual coal oxidation and preventing high-temperature formation.

3. Moving the gas injection port toward the working face and increasing the gas injection rate both increased the area of the inerted residual coal, causing the $T_{\text{max}}$ to decrease significantly. However, an excessive gas injection rate could increase the risk of a potential leak. Additionally, there was a balance point of the dilution and displacement effects at the windward side of the gob, where the injected flue gas could minimize the disturbance of the temperature field by the oxygen content fluctuation of flue gas. Injecting the power plant flue gas with a flow rate of 2000 m$^3$/h at $X = 100$ m could completely cover the high-temperature residual coal in the inerted zone and control the values of $T_{\text{max}}$ and $\Delta T_{\text{max}}$ to be below 310 K and 2.6 K, respectively.

4. The targeted inertization fire prevention technology was based on the accurate location of the spontaneous combustion hazard. By judiciously selecting the formulation and injection scheme of the inert gas, the inerted zone of the injected inert gas could be made to coincide with the high-temperature risk area in the gob and minimize the diffusion of the inert gas into nontarget areas. As a result, the efficiency and the effectiveness of the inert gas fire extinguishing in the large space of the gob were greatly improved.

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