Optimal Parameters of Gas Drainage and Carbon Dioxide Inerting Technology and Its Application in a High Gassy and Spontaneous Combustion Mine

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ABSTRACT: In the process of coupling disaster prevention and control of gas and coal spontaneous combustion in goaf, there is a great contradiction between the gas drainage and carbon dioxide inerting technology. The key performance indexes are put forward to solve the coupling disaster, such as the air quantity of the intake airway (A), the gas drainage rate (B), the carbon dioxide injection rate (C), and the injection depth (D). Using the numerical simulation method and the orthogonal test of four factors and three levels, we establish the coupling disaster model of the no. 7436 working face in the Kongzhuang coal mine. Using a combination of the relative membership degree method and range analysis, the optimal level of each factor is determined, which is $A_{II}B_{III}C_{II}D_{II}$. Furthermore, the distribution law of the airflow field is obtained under the conditions of different gas drainage rates and carbon dioxide injection rates. The results show that the gas concentration decreases with an increase in gas drainage in the upper corner, but it has little impact on the width of the oxidation zone. The gas concentration can be reduced to 1%, while the gas drainage rate is higher than 35 $m^3/min$. With an increase in gas injection rate, the carbon dioxide emission rate increases in the upper corner, but the width of the oxidation zone decreases. Also, the gas injection rate should be less than 800 $m^3/h$. Moreover, with an increase in injection time in the upper corner during the injection process, the carbon dioxide and gas concentrations increase, and the maximum carbon dioxide concentration is 1.3%, and the maximum gas concentration is 0.42%, which is consistent with the results of numerical simulations.

1. INTRODUCTION

Goaf is a mixed area composed of broken coal and rock mass, which is usually regarded as a porous medium. Limited by the special geographical conditions of the region, disasters frequently occur in the middle and lower areas of goaf, such as the coal mine gas disaster, water disaster, fire disaster, and so forth. They all have a great impact on mine safety production. Affected by the overlying strata, the coal and rock mass are fractured and form main gas channels in this area, which provide a storage space for toxic and harmful gases, such as methane and carbon oxides. Because the disaster is highly concealed and the airflow field is complex, it creates a good environmental condition for coal oxidation and spontaneous combustion, and it is difficult to monitor the area and locate the fire source due to the coupling of these disasters. Gas drainage is an effective method for gas disaster prevention in an underground coal mine. It adopts the principle of negative pressure to pump gas from the goaf to the ground or the main return airway through drilling, burying pipes, and so forth. However, the relationship between the gas drainage technology and the spontaneous combustion prevention and control is mutually restrictive and contradictory in a goaf with high gas and spontaneous combustion. Gas drainage increases the volume of air leakage, which provides enough oxygen for coal oxidation and improves the possibility of coal spontaneous combustion in goaf. Moreover, coal spontaneous combustion creates fires and a high-temperature environment for gas combustion or gas explosion accidents. Moreover, the coupling disasters of gas and coal spontaneous combustion greatly increase the difficulty of prevention and control in goaf.

Research on the coupling disaster is focused on establishing a mathematic model of gas drainage and coal spontaneous combustion prevention through the airflow field theory. Zhou et al. studied the disaster mechanism of the coexistence of gas and coal spontaneous combustion and established the
mathematical model under the condition of safe gas drainage. Zhang et al.14 proposed a collaborative control method of coal spontaneous combustion and a gas coupling disaster in goaf. Li et al.15,16 determined the mathematical relationship between the gas emission intensity and coal spontaneous ignition period. Li17 analyzed the law of dangerous area under different air quantities, mining speeds of the working face, and gas attenuation coefficients. Deng et al.18,19 studied the dangerous range of coal spontaneous combustion under the condition of gas drainage and determined the relationship between the pipeline position of gas drainage and the oxidation heating zone. Using the machine learning of UMAP and LSTM models, Kumari20 predicted the tendency of the mixed gas concentration, as well as the fire state, in a mine fire district. Chu et al.21 studied the disturbance effect and disaster mechanism of coal spontaneous combustion by using the gas drainage technology for pressure relief. Based on a gas distribution model, Xiang et al.22 assessed the degree of coal spontaneous combustion risk in the process of gas drainage. Qu et al.23 studied the correlation between the pore pressure of the coal seam and gas emission based on the difference between the actual gas displacement and simulation result. Xia24 studied the multifield coupling dynamic propulsion process of coal spontaneous combustion in goaf. Cheng et al.25 studied the reconstruction technology of the coupling disaster risk zone of gas and coal spontaneous combustion in fully mechanized goaf. Yu et al.26 established a coupling model to characterize carbon monoxide and methane desorption in goaf and proposed a method to assess the hazards of goaf based on the gas migration and the concentration of carbon monoxide and gas in the upper corner. Zhang et al.27 studied the coupling effect of the air leakage, oxygen field, heat storage temperature field, and gas distribution field on the symbiotic disaster of gas and coal spontaneous combustion in the fracture field. Xu et al.28 quantitatively analyzed the variation rule of the coupling disaster area of gas and coal spontaneous combustion. Shi et al.29 simulated the fire state and the laws of gas migration after the fire area was closed, which provides guidance for the prevention of gas accidents. Jia et al.30 established a fluid-chemical-thermal multifield coupling model and studied the disaster-causing law of multifield coupling.

From the perspective of coal spontaneous combustion, it is not only related to the oxidation of coal and heat release characteristics but also closely related to the air leakage, oxygen supply, and heat storage environment.31,32 Due to the limitations of roof collapse and pressure manifestation and other environmental conditions,15,24 it is difficult to arrange temperature sensors in goaf, and the monitoring range is too small. Especially under the condition of gas extraction, the airflow field is complicated and changeable under the influence of the disturbance of the extraction flow field. Therefore, in order to determine the balance between the gas drainage and coal spontaneous combustion in goaf, the distribution law of the airflow field and concentration field in goaf should be studied under the condition of gas drainage. It will provide a theoretical support for the prediction of the coupling disaster of gas and coal spontaneous combustion in goaf.

2. RESEARCH METHOD

2.1. Relationship between Gas Drainage and Coal Spontaneous Combustion. Gas and coal spontaneous combustion affects and restricts each other in the process of disaster prevention and control, and they are connected with the airflow field. Due to the bending, undirected nature, and randomness of the mining pores, the state of the airflow is extremely complex in goaf, which forms a nonlinear flow field including the turbulence, transition flow, and laminar flow.

The gas drainage is the most effective technology of gas control, which uses the electric energy to create a low negative pressure area in goaf. It increases the oxygen supply by air leakage and can promote the coal oxidation reaction. Coal spontaneous combustion changes the temperature field, concentration field, and wind speed field of goaf, which easily cause gas combustion and gas emission accidents. It may even cause gas explosion accidents when a high temperature or fire source is generated in the gas accumulation area.

Figure 1 shows the coupling disaster mechanism of gas and coal spontaneous combustion. In goaf, the coal spontaneous combustion is related to the accumulation state of oxidation heat generation and heat transfer characteristics. Its combustion state changes with the air leakage velocity, the gas concentration, and the ambient temperature. However, isolating coal and oxygen, or goaf inerting, is an effective way to prevent coal spontaneous combustion, which is in contradiction with gas drainage (Figure 2).

The goaf inerting technology is one of the commonly used technologies for coal spontaneous combustion prevention and control, which uses inert gases to displace oxygen, such as nitrogen or carbon dioxide. In the high gassy and easy
spontaneous combustion goaf, the air quantity of the intake airway, gas drainage rate, inerting gas injection rate, and depth are four key experimental factors to study the coupling disaster prevention and control.

2.2. Orthogonal Test. The orthogonal test of four factors and three levels is adopted, as shown in Table 1.

| Test | air quantity/m·min⁻¹ | gas drainage rate/m·min⁻¹ | CO₂ injection rate/m³·h⁻¹ | CO₂ injection depth/m |
|------|-----------------------|---------------------------|---------------------------|-----------------------|
| 1    | I (1000)              | I (20)                    | I (200)                   | I (30)                |
| 2    | II (2000)             | II (50)                   | II (1000)                 | II (500)              |
| 3    | III (3000)            | III (80)                  | III (1000)                | III (500)             |
| 4    | III                   | I                         | II (60)                   | I                     |
| 5    | II                    | III                       | II                        | I                     |
| 6    | I                     | III                       | III                       | II                    |
| 7    | III                   | I                         | III (90)                  | I                     |
| 8    | I                     | II                        | III                       | II                    |
| 9    | II                    | III                       | III                       | III                   |

The specific levels of each factor are determined as follows:
- Coal mine safety regulations prescribe that the air velocity cannot exceed 4 m/s in the working face. The air quantity range of the intake airway is usually 800–3000 m³/min, so the air quantity levels are determined to be 1000, 2000, and 3000 m³/min.
- The gas drainage rate is 20, 50, and 80 m³/min, respectively.
- According to the diffusion time of CO₂ in goaf, the injection rate of carbon dioxide is 200, 500, and 1000 m³/h.
- The injection depth is determined by the three zones of the goaf. Generally speaking, the width of the asphyxiation zone is about 100 m from the working face. Therefore, 30, 60, and 90 m are selected.

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2.3. Numerical Simulation Model. 2.3.1. Research Background. 2.3.1. Gas Geological Parameters of the No. 7436 Working Face. The no. 7436 working face is located in the IV1 mining area of the no. 7 coal seam in the Kongzhuang coal mine of Shanghai Datun Energy Co., Ltd. Figure 1 shows the 7436 working face. The thickness of the coal seam is 4.30–4.80 m, the average thickness is 4.50 m, and the gas content of the coal seam is 4.48 m³/t. The mine is a gassy coal mine without coal and gas outburst risks, and the absolute gas emission rate of the IV1 mining area is 0.49 m³/min.

The no. 7436 working face is adjacent to the goaf of the no. 7434 working face, and the other side is the edge of the mining area. The elevation of the working face is from -847 to -976 m, the strike length is 1301.0 m, the dip length is 230.2 m, and the average dip angle is 20°. The working face adopts fully mechanized caving mining technology; the mining height is about 2.5 m, the coal caving is about 1.7 m, and the recovery rate is 85%.

The air quantity of the no. 7436 working face is 2260 m³/min, and the absolute gas emission rate is 7.88 m³/min. As the gas overrun occurs in the upper corner of the no. 7433 working face, no. 7435 working face, and no. 7432 working face, a mobile gas extraction pump is used for gas drainage in the no. 7436 working face in the mining process.

2.3.1.2. Source Term of Gas Emission. Using the method of separate source prediction, the gas emission rate of the no. 7436 working face is calculated. Figure 3 shows the relationship between source and sink of mine gas emissions.

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Suppose that the adsorbed free gas is evenly distributed in the coal seam, the intensity of the gas source term on the floor is 5.52 × 10⁻⁶ kg/(m²·s) and near the coal pillar is 2.64 × 10⁻⁶ kg/(m²·s). It is added in porous media of the goaf through a user-defined function.

2.3.1.3. Gas Drainage in Goaf. The air leakage forms an airflow vortex near the upper corner of the working face, which makes the gas easy to accumulate. Prelaying the pipeline along the return airway, the gas drainage is carried out continuously in the goaf, which changes the airflow state and eliminates the gas accumulation in the upper corner.

Figure 4 shows the layout of gas drainage in the no. 7436 working face. There is only one gas drainage pipeline system in the no. 7436 working face; the inner diameter of the main
pumping pipeline is 500 mm, the inner diameter of the branch pipeline is 371 mm, and the nominal wall thickness is 6 mm. Adopting the step-by-step laying method, the interval between gas drainage openings is 20 m. Also, two mobile gas drainage stations are selected; their model is ZWY210/280-G, one for use and the other for reserve.

With the mining advance of the working face, the gas drainage outlet is adjusted outside the goaf by prelaying the drainage pipeline and drainage outlet. Furthermore, a simple sealing of the return airway of goaf in advance can effectively reduce the air leakage and improve the extraction effect. The sealing position is about 3 m away from the outlet of the pipeline, and the sealing distance is 10 m.

2.3.2. Physical Model. The physical model of the no. 7436 working face is divided into four areas, including the working face and airway, the goaf, the gas drainage pipeline, and the carbon dioxide injection pipeline.

Table 2 shows the specific physical parameters, and Figure 5 shows its physical model and meshing. The area type is the fluid type, and the goaf is the porous zone. The mesh is generated by Gambit software. In order to reduce the number of grids, the method of an irregular grid partitioning is used to encrypt the grid around the pipeline and the working face. Also, the element is tet/hybrid, and the type is TGrid.

Assuming that the air is incompressible gas in goaf, and some unimportant factors were ignored, such as the dispersion effect of the airflow in porous media, the heat loss of thermal radiation, thermal expansion, and thermal diffusion, as well as the influence of water evaporation and gas adsorption and desorption.

The gas flow in the stope obeys the gas flow theory of porous media. The continuity equation is as follows

$$\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho \vec{u}) = 0$$  \hspace{1cm} (1)

where $\rho$ represents the density, kg/m$^3$; $t$ represents the time, s; and $\vec{u}$ represents the velocity vector.

The equation of mass conservation is

$$\frac{\partial (\rho c_s)}{\partial t} + \text{div}(\rho \vec{u} c_s) = \text{div}(D_s \text{grad}(c_s)) + S_u$$  \hspace{1cm} (2)

where $c_s$ represents the volume concentration of component $s$; $D_s$ represents the diffusion coefficient of component $s$; and $S_u$ represents the mass of the component produced per unit volume per unit time.

The equation of energy conservation is

$$\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho \vec{u} T) = \text{div} \left( \frac{k}{c_p} \text{grad}T \right) + S_T$$  \hspace{1cm} (3)

where $T$ represents the temperature, °C; $k$ represents the heat transfer coefficient of the fluid; $c_p$ represents the specific heat capacity, J/(kg·°C); and $S_T$ represents the viscous dissipation term.

The momentum equation of each coordinate direction is

$$\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho \vec{u} u) = \text{div}(\mu \text{grad}(u)) \frac{\partial p}{\partial x} + S_u$$

$$\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho \vec{u} v) = \text{div}(\mu \text{grad}(v)) \frac{\partial p}{\partial y} + S_v$$

$$\frac{\partial (\rho w)}{\partial t} + \text{div}(\rho \vec{u} w) = \text{div}(\mu \text{grad}(w)) \frac{\partial p}{\partial z} + S_w$$  \hspace{1cm} (4)

where $u$, $v$, and $w$ represent the components of the velocity vector in $x$, $y$, and $z$ directions and $S_u$, $S_v$, and $S_w$ represent the generalized source terms, respectively.

Using the above equations, a multifield coupling mathematical model is established through the simultaneous equations of the airflow field, oxygen concentration field, and temperature field.

2.3.3. Boundary Condition Settings. The boundary condition settings of the numerical simulation model are shown in Table 3.

The inlet boundary of the intake airway is the velocity inlet. The oxygen concentration is 21%, the nitrogen concentration is 79%, and the inlet temperature is 295 K.

**Table 2. Parameters of the Physical Model**

| area                     | length $(x \times y \times z)$/m | fluid type | grid amount |
|--------------------------|----------------------------------|------------|-------------|
| goaf                     | 200 × 8.275 × 30                 | fluid type |             |
| porous zone              | 14401                           | fluid type |             |
| working face             | 14401                           | fluid type |             |
| intake and return airway | 80 × 5.5 × 3                    | fluid type |             |
| gas drainage pipeline    | 50 × 5.5 × 3                    | fluid type |             |
| injection pipeline       | 80/110/140 m (length) × 1 m (inside diameter) | fluid type |             |
Table 3. Boundary Conditions

| test | velocity/m s\(^{-1}\) | species | T/K | velocity/m s\(^{-1}\) | species | T/K |
|------|----------------------|---------|-----|----------------------|---------|-----|
| test 1 | 1.0101 | | | 0.0708 | | |
| test 2 | 2.0202 | | | 0.3539 | | |
| test 3 | 3.0303 | | | 0.1769 | | |
| test 4 | 3.0303 | O\(_2\), 21% | 295 | 0.0708 | CO\(_2\), 99% | 250 |
| test 5 | 3.0303 | N\(_2\), 79% | | 0.1769 | N\(_2\), 1% | |
| test 6 | 1.0101 | | | 0.3539 | | |
| test 7 | 3.0303 | | | 0.1769 | | |
| test 8 | 1.0101 | | | 0.3539 | | |
| test 9 | 2.0202 | | | 0.0708 | | |

The inlet boundary of the carbon dioxide injection is the velocity inlet. In order to reduce the impact of the small pipe diameter on the grid quality, the diameter of the injection pipeline is increased to 1 m, and then, the air velocity of the inlet boundary is converted by the air quantity and the section of the pipeline. The carbon dioxide fraction is 99%, and the nitrogen fraction is 1%.

The return airway and the inlet of the gas drainage pipeline are set as the outlet boundary of the outflow, and the outlet proportion is related to the gas drainage and the air quantity of the working face, as shown in Table 4. The interface between the goaf and working face is set as the interior face, the other external faces are set as walls, and the temperature is 283 K.

Table 4. Main Parameters of the Simulation

| number | type | control parameters |
|--------|------|---------------------|
| 1      | solver | pressure-based |
| 2      | tense | transient |
| 3      | gravity/m s\(^{-2}\) | z = -9.8 |
| 4      | energy equation | on |
| 5      | turbulence model | realizable k-epsilon |
| 6      | component model | species transport methane-air-2step |
| 7      | environment pressure/Pa | 101325 |
| 8      | solving method | simple and couple |
| 9      | initialization method | hybrid initialization |
| 10     | convergence accuracy | \(10^{-6}\) |

2.3.4. Control Parameters. 2.3.4.1. Permeability of Porous Media. Along the strike of the coal seam from the working face to the deep goaf, the caving coal and rock mass are gradually compacted, and then, the permeability of porous media decreases. Furthermore, the permeability decreases from both sides to the middle of the goaf along the inclined direction of the working face.

Based on the Blak–Kozeny formula, the permeability coefficient can be approximated as the following segmented function\(^{18}\)

\[
k = \begin{cases} 
    y(\alpha(x) - \alpha(0)) + \alpha(0)y & L_s < y \leq L_s \\
    \alpha(x)L_s < y \leq L - L_s \\
    (L - y)(\alpha(x) - \alpha(0)) + \alpha(0)L - L_s < y \leq L
\end{cases}
\]

where \(k\) represents the permeability coefficient of goaf, \(m^2\); \(x\) and \(y\) are the coordinates of the working face, respectively, in strike and inclination directions, \(m\); \(\alpha(x)\) is the porosity at \(x\), dimensionless; \(L_s\) is the distance between the basic stable point and the working face, \(m\); \(L\) is the inclined length of the working face, \(m\); and \(k\) is the permeability of goaf, \(m^2\).

According to the parameters of the no. 7436 working face, the distribution function of permeability is shown in Figure 6.

Figure 6. Permeability distribution of the no. 7436 working face.

2.3.4.2. Solver. The airflow field belongs to the solution of the uncompressible flow problem in goaf, and a simple pressure–velocity algorithm is adopted with a separable pressure-based solver. The turbulence selects the realizable \(k\)-epsilon model. In order to ensure sufficient accuracy of the simulation calculation results, steady-state simulation calculation is adopted, and the calculation is finished when the convergence residual is \(10^{-6}\). Furthermore, the convergence of calculation results can be dynamically monitored by checking the iterative residuals of each variable during the solving process.

The control parameters of the mathematical model are shown in Table 4.

3. RESULTS AND DISCUSSION

3.1. Orthogonal Test Analysis. 3.1.1. Results of the Orthogonal Test. The airflow distribution of the above nine tests is calculated by the fluent numerical simulation software. In order to intuitively observe the difference in gas concentration of the goaf, the plane with a distance of 1 m from the floor is taken as the research object. Figures 7 and 8 show the concentration...
distribution diagrams of oxygen and carbon dioxide in this fracture section, respectively.

From Figure 7, with an increase in carbon dioxide injection rate, the range of the oxygen concentration decreases near the outlet of the gas drainage pipeline. In the advancing direction of the working face, the oxygen concentration in the oxidation zone decreases, followed by that in the heat dissipation zone. The proportion between them varies with the injection intensity of
carbon dioxide and the air leakage volume in goaf. Moreover, because the density of carbon dioxide is higher than that of air, the oxygen concentration of the roof decreases less than that of the floor in the vertical direction of the goaf. The width of heat dissipation and oxidation zones increases with an increase in air quantity of the working face. The air quantity of test 1, test 6, and test 8 is 1000 m$^3$/min, and the width of the oxidation zone and dispersion zone is smaller in these tests. When the air quantity reached 2000 m$^3$/min, the zone width increased, such as test 2, test 5, and test 9. The width of the oxidation zone and dispersion zone of test 3, test 4, and test 7 is larger than others, and their air quantity is 3000 m$^3$/min.

Furthermore, the air injection rate has a great impact on the width of the oxidation zone in the same air quantity level, and the width of the oxidation zone decreases with an increase in injection rate. From Figure 8, with an increase in the injection rate of carbon dioxide, the inerting range increases. The injection rate of test 1, test 4, and test 9 is 200 m$^3$/h, and the injection rate of these samples is larger than that of test 3, test 5, and test 8, in which the injection rate is 500 m$^3$/h. When the injection rate reaches 1000 m$^3$/h, such as in test 2, test 6, and test 7, a large amount of carbon dioxide is emitted out to the upper corner, and the concentration exceeds the limit in the working face and return air roadway.

The main purpose of goaf inerting is to reduce the width of the oxidation zone and enlarge the inerting range, which increases with an increase in the depth of the gas injection port. The inerting effect of the low-pressure energy zone at the return air side of goaf is better than that in other zones, while the gas injection port is deep, as shown in Figure 7g,h. Their injection depth is 90 m. There is little impact on the distribution of the three zones near the inlet side of the goaf.

As the carbon dioxide gas has a lower temperature and strong heat absorption capacity, the temperature reduces in goaf. From Figure 9, the temperature decreases with an increase in injection rate of carbon dioxide. The injection rate of carbon dioxide in test 2, test 6, and test 7 is 1000 m$^3$/h, and their temperature decreases greatly than that in other tests. Because the injection rate is 200 m$^3$/h in test 1, test 4, and test 9, the temperature dropping degree is smaller than that in others. If the injection rate is the same, the shallower the injection port, the smaller the scope of the temperature drop due to the large leakage air quantity of the scattered belt. Furthermore, if the gas injection port is deep, the temperature influence range is larger.

3.1.2. Range Analysis. According to the division standard of the oxygen concentration in the three zones of goaf, the maximum width of the oxidation zone is calculated by the difference in the x coordinate between 8 and 18%. Moreover, the emission concentration of carbon dioxide and gas is

| test | test 1 | test 2 | test 3 | test 4 | test 5 | test 6 | test 7 | test 8 | test 9 |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| minimum width of the asphyxia zone/m | 24.46 | 32.99 | 51.32 | 60.45 | 39.87 | 21.15 | 46.99 | 24.22 | 42.78 |
| maximum width of the oxidation zone/m | 32.40 | 30.05 | 35.78 | 43.87 | 22.63 | 33.43 | 18.67 | 33.16 | 30.82 |
| gas concentration in/% | 1.26 | 0.71 | 0.21 | 0.69 | 0.67 | 0.26 | 1.18 | 0.46 | 0.25 |
| CO$_2$ concentration in/% | 0.61 | 1.36 | 0.26 | 0.31 | 0.7 | 1.03 | 1.84 | 0.88 | 0.31 |

Figure 9. Distribution of the temperature (1 m away from the floor).

Table 5. Results of the Numerical Simulation
extracted in the upper corner of the working face. The results of the above tests are presented in Table 5.

In order to avoid the incommensurability of evaluation factors caused by different dimensions in the multifactor analysis, the relative membership method is adopted to normalize and weight the multifactors.

\[
Fr_{ij} = \frac{F_{ij} - \min \{F_{ij}\}}{\max \{F_{ij}\} - \min \{F_{ij}\}}
\]

where \(Fr_{ij}\) represents the relative membership degree of set element \(F_{ij}\) and its value range is \([0, 1]\); \(\max \) \{\} represents the maximum value of a set element; and \(\min \) \{\} represents the minimum value of a set element.

Then, the experimental result

\[T_j = \sum_{j=1}^{3} \omega_j Fr_{ij}\]

(7)

where \(T_j\) represents the experimental result of factor \(j\) and \(\omega_j\) represents the weight of factor \(j\).

According to the above formula, the calculated evaluation results are shown in column \(T\) in Table 6.

### Table 6. Results of the Orthogonal Experiment

| test | minimum width of the asphyxia zone | maximum width of the oxidation zone | gas concentration | carbon dioxide concentration | \(T\) |
|------|------------------------------------|------------------------------------|-------------------|------------------------------|------|
| test 1 | 0.0843 | 0.5448 | 1.0000 | 0.2215 | 0.4923 |
| test 2 | 0.3014 | 0.4516 | 0.4762 | 0.6962 | 0.5023 |
| test 3 | 0.7677 | 0.6790 | 0.0000 | 0.0000 | 0.2893 |
| test 4 | 0.9999 | 1.0000 | 0.4571 | 0.0316 | 0.5466 |
| test 5 | 0.4763 | 0.1571 | 0.4381 | 0.2785 | 0.3417 |
| test 6 | 0.0000 | 0.5857 | 0.0476 | 0.4873 | 0.2776 |
| test 7 | 0.6575 | 0.0000 | 0.9238 | 1.0000 | 0.7086 |
| test 8 | 0.0782 | 0.5750 | 0.2381 | 0.3924 | 0.3198 |
| test 9 | 0.5504 | 0.4821 | 0.0381 | 0.0316 | 0.2274 |
| \(\omega_j\) | 0.2 | 0.2 | 0.3 | 0.3 | |

Using range \(R\) to express the influence of the level change of each factor on the test results, which is the maximum difference between the levels of the same factor. A greater \(R\) means that the corresponding factor has a great influence on the experimental results.

\[R = \max \{T_{ij}, T_{II}, T_{III}\} - \min \{T_{ij}, T_{II}, T_{III}\}\]

(8)

The results of range analysis are shown in Table 7.

From Table 7, range analysis of orthogonal experiments shows that the sequence of the factors affecting the degree is as follows: B, C, A and D. That is, the gas drainage rate has the greatest impact on the results, followed by the injection rate, the air quantity, and the injection depth.

The choice of a better combination of factor levels is related to the required indicators. According to the characteristics of the factors, a higher level should be selected if the factor is as large as possible. On the contrary, a lower level should be selected if the factor is as small as possible.

In the process of gas and coal spontaneous combustion disaster control,

- Since the air leakage increases with the air quantity of the working face, the smallest result of \(T\) is adopted for factor A. The experiment result is 1.0714, which is level II.
- If the gas drainage rate is too large, more methane and carbon dioxide gas will be pumped out of goaf. It also can reduce the gas concentration and prevent the carbon dioxide exceeding the limit in the upper corner. Therefore, the smallest result of \(T\) is adopted for factor B. The experiment result is 0.7943, which is level III.
- If the gas injection rate is too large, the carbon dioxide concentration can easily exceed the limit in the upper corner and can result in safety accidents. Therefore, the smallest result of \(T\) is adopted for factor C. The experiment result is 0.9508, which is level II.
- The greater the gas injection depth is, the larger the inerting range is. Therefore, the smallest result of \(T\) is adopted for factor D. The experiment result is 1.1659, which is level II.

Based on the above factors, it is concluded that the better factor level collocation is \(A_2B_1C_1D_2\).

3.2. Law of the Gas Drainage Rate and Air Leakage in Goaf. The actual air quantity of the no. 7436 working face is 2260 m³/min, and the injection depth is 60 m. If the injection rate is 0, the distribution of the airflow field is simulated, respectively, when the gas drainage rate is 20, 35, 50, 65, and 80 m³/min. According to the simulation results, the oxygen concentration distribution is obtained under the different gas extraction flows, and the contour map of the plane with a distance of 1 m from the floor is drawn, as shown in Figure 10.

From Figure 10, the oxygen concentration increases mainly near the return airway side of the goaf with an increase in gas drainage. With an increase in gas drainage rate, a low-pressure energy region is formed near the pipeline port. Plenty of air leakage enters the goaf from the upper corner and the oxygen countercurrent into the gas drainage pipeline with the airflow under the action of the negative pressure. The distribution of the airflow trace near the gas drainage pipe is shown in Figure 11.

As shown in Table 8, the gas concentration in the upper corner and the oxygen concentration of the plane with a distance of 1 m from the floor are extracted from the simulation result, and the maximum oxidation zone width is calculated. Then, the variation curves of the gas concentration in the upper corner and the maximum oxidation zone width in goaf under different gas drainage rates were drawn, as shown in Figure 12.

Figure 12 shows that the gas concentration in the upper corner gradually decreases with an increase in gas drainage. When the gas drainage rate is higher than 35 m³/min, the gas concentration can be reduced to 1%. However, the width of the oxidation zone increases slightly.

3.3. Law of the Injection Rate and Air Leakage in Goaf. The distributions of gas, carbon dioxide and oxygen, concentrations are simulated, while the carbon dioxide injection rate is 200, 400, 600, 800, and 1000 m³/h. According to the
simulation results, the airflow distribution is obtained under different injection rates. The contour maps of the carbon dioxide concentration and oxygen concentration are extracted, as shown in Figures 13 and 14.

From Figures 13 and 14, with an increase in gas injection, the inerting scope is expanded, and the width of the oxidation zone becomes narrower. It transits directly from the heat dissipation area to the asphyxiation zone near the carbon dioxide injection port. However, if the injection rate is too large, the carbon dioxide concentration in the upper corner increases to the working face space, which can easily cause secondary disaster accidents.

The concentrations of carbon dioxide and gas in the upper corner are extracted from the simulation result, and the maximum width of the oxidation zone is calculated, as shown in Table 9. Furthermore, the variation curves of the gas concentration in the upper corner, carbon dioxide, and oxygen concentration are extracted, as shown in Figures 13 and 14.

Table 8. Gas Concentration and Width of the Oxidation Zone with Different Gas Drainage Rates

| number | gas drainage rate/m$^3$/min$^{-1}$ | gas concentration/% | width of the oxidation zone/m |
|--------|-----------------------------------|----------------------|-----------------------------|
| 1      | 20                                | 1.60                 | 50.72                       |
| 2      | 35                                | 0.88                 | 50.80                       |
| 3      | 50                                | 0.47                 | 51.03                       |
| 4      | 65                                | 0.23                 | 51.13                       |
| 5      | 80                                | 0.11                 | 51.08                       |

Figure 10. Distribution of the oxygen concentration (1 m away from the floor).

Figure 11. Comparison of the local airflow trace near the gas drainage pipeline. (a, b) Local airflow trace near the gas drainage pipeline.

Figure 12. Variation curves of the gas concentration and width of the oxidation zone.
maximum width of the oxidation zone under different gas injection conditions are plotted, as shown in Figure 15.

Figure 15 shows that the emission rate of carbon dioxide gradually increases with an increase in gas injection rate in the upper corner. When selecting the inerting parameters, both the inerting range and the carbon dioxide concentration must be considered in the upper corner. If the gas injection rate is 1000 m$^3$/h, the width of the oxidation zone gradually decreases, but the carbon dioxide concentration can reach 2.13% in the upper corner. Therefore, in order to ensure that the carbon dioxide concentration is less than 1.5%, the gas injection rate must be less than 800 m$^3$/h.

### 3.4. Field Measurement

The carbon dioxide injection experiment was carried out from January 14, 2022 to January 15, 2022. The injection rate was 640 m$^3$/h, and the injection time was 24 h, from 9 am to 9 am next morning. The injection depth was 60 m, and the gas drainage rate was 0. The measured concentration of gas, carbon dioxide, oxygen and temperature of upper corner and return airway are shown in Table 10.

It can be seen from Table 10 that the injection rate has little impact on the gas concentration in the return airway but has a greater impact on the concentration of gas and carbon dioxide in the upper corner. The concentration variation of carbon dioxide and gas in the upper corner with the gas injection time is plotted, as shown in Figure 16.

From Figure 16, the carbon dioxide and gas concentrations gradually increase with an increase in injection time in the upper corner. The measured maximum carbon dioxide concentration is 1.3%, and the maximum gas concentration is 0.42%. The variation laws of the two parameters are basically consistent. The analysis shows that when the injection rate increases, gas and oxygen are driven out of goaf, and it results in a high gas concentration in the upper corner, and the law is consistent with the results of the numerical simulation.

### 4. CONCLUSIONS

(1) This paper analyzes the disaster mechanism of the coupling disaster of gas and coal spontaneous combustion in goaf. The key performance indexes are put forward to solve the coupling disaster, such as the air quantity of the intake airway, the gas drainage rate, the injection rate, and the injection depth of inerting gas.

(2) According to the actual parameters of the no. 7436 working face in the Kongzhuang coal mine, the value selection strategy of the source term of gas emission, the gas drainage layout, the injection of carbon dioxide, and the permeability of porous media are determined. Then, a coupled disaster numerical simulation model is estab-

![Figure 13. Distribution of the carbon dioxide concentration (1 m away from floor).](image1)

![Figure 14. Distribution of the oxygen concentration (1 m away from floor).](image2)

| number | injection rate/m$^3$/h | gas concentration/% | carbon dioxide/% | width of the oxidation zone/m |
|--------|------------------------|---------------------|-----------------|-----------------------------|
| 1      | 200                    | 0.49                | 0.49            | 38.03                       |
| 2      | 400                    | 0.54                | 0.95            | 29.39                       |
| 3      | 600                    | 0.59                | 1.39            | 22.08                       |
| 4      | 800                    | 0.65                | 1.75            | 19.53                       |
| 5      | 1000                   | 0.73                | 2.13            | 17.21                       |
lished, and the boundary conditions of the model are determined.

(3) Using an orthogonal table of four factors and three levels, the airflow field distribution of each test is obtained. Then, the relative membership method is adopted by extracting the values of the minimum depth of the suffocate zone, the maximum width of the oxidation zone, and the concentration of gas and carbon dioxide in the upper corner. The better factor level collocation is $A_{II}B_{III}C_{II}D_{II}$.

(4) The variation of the airflow field in goaf is obtained under the conditions of different gas drainage rates and injection rates of carbon dioxide. The gas concentration can be reduced to 1% in the upper corner, while the gas drainage rate is higher than $35 \text{ m}^3/\text{min}$. However, the width of the oxidation zone increases slightly. Furthermore, the emission rate of carbon dioxide gradually increases with an increase in gas injection rate in the upper corner. When the gas injection rate is $1000 \text{ m}^3/\text{h}$, the width of the oxidation zone gradually decreases, but the carbon dioxide concentration can reach $2.15\%$ in the upper corner. Therefore, in order to ensure that the carbon dioxide concentration is less than $1.5\%$, the gas injection rate must be less than $800 \text{ m}^3/\text{h}$.

**Figure 15.** Gas variation curves at different gas injection rates. (a) Relationship between the gas concentration and injection rate. (b) Relationship between the width of the oxidation zone and injection rate.

**Table 10. Measurement Results**

| Time            | Gas Concentration/% | Carbon Dioxide Concentration/% | Oxygen Concentration/% | Temperature/°C |
|-----------------|---------------------|-------------------------------|------------------------|---------------|
| Date            | Upper Corner        | Return Airway                 | Upper Corner           | Return Airway | Upper Corner | Return Airway |
| 2022-1-14 9:10  | 0.2                 | 0.4                           | 20.1                   | 20.1          | 31           | 26           |
| 2022-1-14 10:20 | 0.18                | 0.36                          | 20                     | 20            | 31           | 26           |
| 2022-1-14 11:50 | 0.16                | 0.3                           | 20                     | 20            | 31           | 26           |
| 2022-1-14 13:10 | 0.2                 | 0.5                           | 20                     | 20            | 31           | 26           |
| 2022-1-14 15:00 | 0.18                | 0.38                          | 20                     | 20            | 30           | 25           |
| 2022-1-14 16:00 | 0.2                 | 0.36                          | 20                     | 20            | 30           | 26           |
| 2022-1-14 17:30 | 0.16                | 0.28                          | 20                     | 20            | 30           | 26           |
| 2022-1-14 19:00 | 0.4                 | 0.6                           | 20.1                   | 20.1          | 31.5         | 26           |
| 2022-1-15 9:30  | 0.4                 | 0.8                           | 20.1                   | 20.1          | 30.8         | 26           |
| 2022-1-15 10:50 | 0.38                | 1.3                           | 20                     | 20            | 30.8         | 26           |
| 2022-1-15 12:30 | 0.42                | 1.3                           | 20                     | 20            | 26           | 26           |
| 2022-1-15 14:30 | 0.4                 | 1.3                           | 20                     | 20            | 31.4         | 26           |
| 2022-1-15 15:30 | 0.4                 | 1.1                           | 20                     | 20            | 31.5         | 26           |

**Figure 16.** Gas and carbon dioxide curves in the upper corner.
(5) According to the field test, the concentration of carbon dioxide and gas increases with an increase in injection time in the upper corner. The measured maximum carbon dioxide concentration is 1.3%, and the maximum methane concentration is 0.42%. Furthermore, the gas concentration is more than the maximum allowable value in the upper corner, which is consistent with the results of the numerical simulation.

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Notes
The authors declare no competing financial interest.

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