

Characteristics and Safety of CO₂ for the Fire Prevention Technology with Gob-Side Entry Retaining in Goaf

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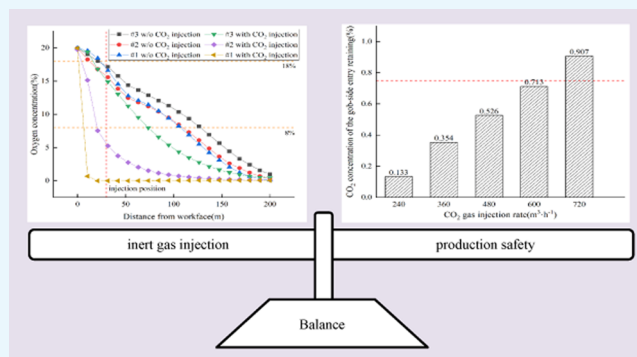


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ABSTRACT: The mining technology of gob-side entry retaining without a coal pillar is gradually becoming a mature and increasingly important mining technology. As it maintains the roadway near goaf, the air leakage should be greater than a U-type ventilation system in goaf, so it is prone to cause coal spontaneous combustion problems. CO₂ is an inert gas, and it is usually used to prevent spontaneous combustion and extinguish coal fire. However, there is a lack of research on characteristics and safety of CO₂ for the mining technology of gob-side entry retaining without the coal pillar. In this paper, the indexes of influencing factors were proposed on gas, pipelines, and mining technical parameters. Using a three-dimensional physical model of coal stope, the gas migration law of CO₂, the relationship between gas injection rate and the oxidation zone area, and the safety of the CO₂ inerting technology were analyzed. The results indicate that the O₂ concentration is diluted between the working face and the injection port, especially in the air intake side. Furthermore, the CO₂ injection rate is an important parameter to the fire prevention and extinguishing technology. When the gas injection rate ranges from 240 to 720 m³/h, the oxidation zone area varies from 7380 to 14 760 m², and the gas injection rate grows exponentially with the area of the oxidation zone. Moreover, the redundant CO₂ gas flows to the retaining roadway, and it reduces the O₂ concentration, resulting in asphyxia accidents of miners. The research results are helpful to balance the relationship between inert gas injection and production safety and provide guidance for the practical application of the inert gas fire prevention technology.



1. INTRODUCTION

Coal spontaneous combustion (CSC) is one of the major disasters of underground coal mine.^{1,2} From the statistics of coal mine fire accidents in China, the United States, India, Poland, and Australia, more than 70% of the CSC fire accidents are located in goaf.^{3–7} With the increase in coal mining depth and intensity, the temperature and pressure of underground roadway become higher,⁸ and the CSC problems become more serious.^{9,10} Therefore, it is urgent to study the prevention and control technology of CSC.

The CSC is affected by coal oxidation, heat accumulation, and pore characteristics of the porous media,^{11–16} in which coal oxidation is the fundamental cause. The inert gas can dilute the O₂ concentration and prevent CSC.¹⁷ CO₂ is an inert gas, which can prevent heat accumulation^{18,19} and settle quickly on the floor of goaf as it has heavier density. The coal and rock mass have strong adsorption on CO₂, and CO₂ can form a protective layer on the coal surface to prevent oxidation. Zhang et al. analyzed the burnout temperature of coal samples through a temperature-programmed experiment, and studied the inhibitory effect of inert gas on coal combustion in the high-temperature stage.²⁰ Abunowara et al. studied the adsorption characteristics of coal for CO₂ and N₂ by the

volumetric technique.²¹ Zhu et al. analyzed the fire prevention technology, inerting mechanism, cooling effect, and the distribution law of CO₂ in goaf.²²

The goaf with a U-type ventilation system is relatively closed, which is friendly to the gas fire prevention and extinguishing technology. As it is difficult to obtain the data by a situ measurement technology from the goaf, the numerical simulation method is often adopted to study the problem. Liu et al. established a three-dimensional (3D) porous media model and studied the relationship between CO₂ gas injection and O₂ distribution; then, a reasonable position and time were obtained.²³ Shao et al. established a three-dimensional geometric model and studied the flow law of CO₂ in the process of gas injection.²⁴ Hao et al. studied the influence of CO₂ injection temperature and the injection flow rate on the

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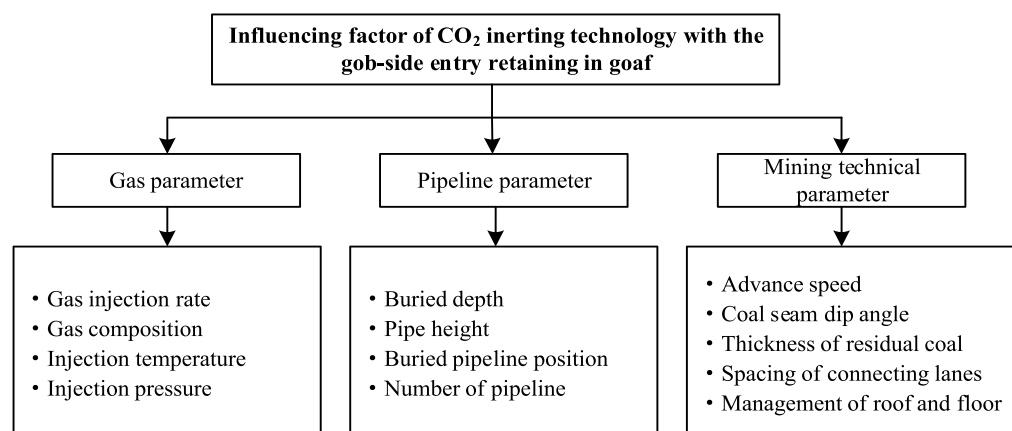


Figure 1. Index system of influencing factors for the CO₂ inerting technology with the gob-side entry retaining in goaf.

temperature and the gas concentration field in goaf.²⁵ Wang et al. studied the distribution law of spontaneous combustion “three zones”, and put forward the calculation method of the minimum flow rate.²⁶ Liu studied the migration law, proportion, and the injection position using a mixed gas of N₂ and CO₂.²⁷

With the development of the mining technology, the gob-side entry retaining technology without coal pillar matures gradually, in which Y-type ventilation is generally used. Because there is no pillar retaining in goaf, the air leakage increases, which creates a good condition for CSC in goaf. Tian et al. studied the law of air leakage in goaf by the SF₆ tracer detection technology and verified it by numerical simulation.²⁸ Based on the heterogeneous seepage and diffusion equation, Li et al. studied the distribution law of the O₂ concentration in the Y-ventilated goaf after N₂ injection, determined the relationship between the N₂ injection rate and the position of O₂ concentration,²⁹ and the reasonable ratio of the advance speed of the working face and N₂ injection.³⁰ Wang et al. proposed the calibration limit method to measure the fragmentation coefficient of goaf and studied the distribution law of the airflow field under Y-type ventilation.³¹ Wang et al. combined the method of single-factor analysis and numerical simulation and studied the influence of gas extraction measures on the distribution of air leakage and the oxidation zone in goaf.³²

Scholars focus on the law of air leakage in goaf, distribution law of the gas flow field, and three-zone distribution of goaf under Y-type ventilation. However, the study on the distribution of the O₂ flow field and three-zone distribution under a Y-type ventilation system is insufficient in goaf. Furthermore, there is a lack of research on prevention and extinguishing with CO₂ injection into goaf. Therefore, this paper established the index system of influencing factors of the CO₂ inerting technology. Using the CFD numerical simulation method, gas migration law of CO₂ and the effects of CO₂ injection rate on spontaneous combustion zone and O₂ distribution with gob-side entry retaining in goaf were studied. Besides, the safety of gas injection was discussed. The research provides a basic theory for on-site application and security production.

2. THEORETICAL ANALYSIS AND FIELD MEASUREMENT

2.1. Analysis of Influencing Factors. The three zones of CSC are the heat dissipation zone (O₂ > 18%), the oxidation zone (8% ≤ O₂ ≤ 18%), and the suffocation zone (O₂ < 8%) in goaf.^{33,34} The purpose of the CO₂ inerting technology is to reduce the O₂ concentration, form an inerting zone, and reduce the width of the heat dissipation zone and the oxidation zone by injecting CO₂ into the caving zone and the residual coal zone in goaf. Figure 1 shows the index system of influencing factors for the CO₂ inerting technology with the gob-side entry retaining in goaf. The inerting effect of CO₂ is mainly affected by gas parameters, pipeline parameters, and mining technical parameters. Gas parameters mainly refer to the gas injection rate, gas composition, injection temperature, and pressure. The phase of CO₂ is affected by the temperature and pressure. Although the gasification process is an endothermic reaction for liquid and solid CO₂, the gaseous CO₂ is usually adopted due to high cost of the liquid and solid CO₂ and the complex gasification process in the fire prevention technology.

The pipeline parameters include the depth, height, position, and the number of the injection pipeline. The depth of the injection pipeline refers to the vertical distance between the gas injection port and the working face. A heat dissipation zone is close to the working face, in which the heat generated by the oxidation of coal is taken away by the air leakage, so the CSC does not occur. The good conditions are created for the CSC by the oxidation zone, for it has a moderate speed of air leakage and the heat generated by oxidation is greater than the heat dissipated in goaf. With the continuous progress of the working face, goaf gradually enters the suffocation zone, in which goaf is constantly compacted by the caving rock, and the speed of air leakage is quite less. The CSC state is not maintained due to limited O₂, greater heat dissipation, and lower temperatures. Thus, it can be seen the reasonable depth is near the oxidation zone in goaf. CO₂ can be injected into the intake airway and the return airway, but it is worth noting that the gas injection from the return airway may gush out of the goaf and flow into the working face. Thus, the gas injection pipeline is usually located in the intake airway.

Mining technical parameters include the advance speed, coal seam dip angle, thickness of residual coal, etc. The CSC occurs when the advance length is less than the width of the oxidation zone in goaf. There is a positive correlation between the

movement distance of caving residual coal and the coal seam dip angle. With different coal seam dip angles, the kinetic energy transformed by gravity work of caving residual coal is different, which leads to uneven accumulation of residual coal. For gently inclined and steep seam, the residual coal thickness increases gradually from the high point to the low point. The accumulation of residual coal causes heat accumulation, which is one of the conditions of CSC. In addition, the spacing of connecting lanes has an effect on the width of the oxidation zone, and the management of the roof and the floor affects pore characteristics of porous media, which leads to the risk of spontaneous combustion. These factors could obtain the spontaneous combustion risk area in time, which is helpful to determine the injection location and gas injection intensity so as to improve the inerting effect and reduce the wastage of resources.

The production conditions of different mines vary greatly, so it is necessary to balance the relationship between the injection parameters and the mining technology according to the actual conditions.

2.2. In Situ Test. Figure 2 shows the schematic diagram of the field experiment of the no. 316 working face in Hongjingta

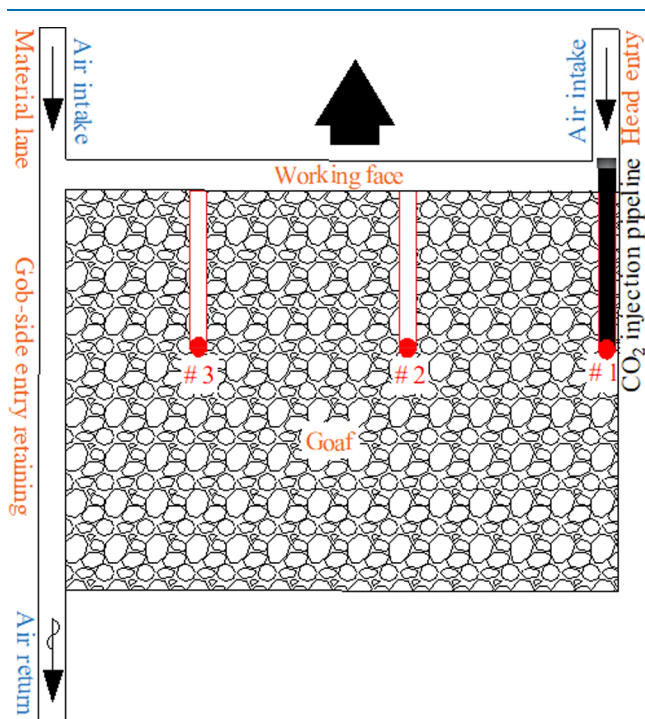


Figure 2. Schematic diagram of the field experiment.

mine, Inner Mongolia, China. Y-type ventilation under the gob-side entry retaining is adopted in the working face. The length is 246 m, the thickness of the coal seam is 1.5–2.0 m, an average 1.6 m, which belongs to spontaneous combustion coal seam, and the spontaneous combustion period is 28 days. The roof is managed by the full caving method. The air volume in the head entry is 576 m³/min and the air volume in the material lane is 310 m³/min.

To study the active inerting effect in goaf, it is important to characterize the initial O₂ concentration distribution, including the detailed monitoring of gas distribution. Therefore, three measuring points were determined in goaf according to the length of the working face, and the gas was collected by a beam

tube. As shown in Figure 2, the depth of the measuring point is 8–109 m, and the distance from the horizontal direction to the air intake side of the head entry is about 1, 90, and 165 m respectively, denoted as #1–#3. To avoid damage to the beam tube caused by falling down of a rock and ensure the accuracy of test results, the path and the tip of the beam tube were protected by a casing and dust filter. The experiment was repeated three times at each measuring point.

2.3. Determination of the Value Range of CO₂ Gas Injection. The simulated value range of the CO₂ gas injection rate is determined to accurately simulate the distribution of three spontaneous combustion zones after CO₂ injection into goaf. There are usually two methods for the gas injection design, which are calculated according to the daily coal production of the working face and the O₂ concentration calculation of the oxidation zone in goaf. The formula is as follows

$$Q_N = \begin{cases} k \frac{A}{24\rho'N_1N_2} \left(\frac{C_1}{C_2} - 1 \right) \\ 60Q_0k \frac{C_3 - C_2}{C_N + C_2 - 1} \end{cases} \quad (1)$$

where Q_N is the gas injection rate (m³/h); K is the additional coefficient; A is the daily output of coal, t ; ρ' is the density of coal; N_1 is the efficiency of transporting inert gas in pipelines; N_2 is the gas injection efficiency of goaf; C_1 is the O₂ volume fraction of goaf; C_2 is the oxidation volume fraction of goaf to realize inerting; Q_0 is the air leakage rate of oxidation zone in goaf; C_3 is the average O₂ volume fraction of the oxidation zone in goaf; and C_N is the volume fraction of CO₂ injected into goaf. After calculation, the range of gas injection was determined to be 272.34–691.14 m³/h (with two decimal places reserved).

3. MODEL ESTABLISHMENT

3.1. Mathematical Model. The goaf is regarded as a porous medium space composed of coal, rock, air, and other mixes, which is isotropic. The gas in goaf is assumed to be incompressible. Based on the Navier–Stokes equations, the flow of multicomponent gases satisfies the mass conservation, energy conservation, momentum conservation, and gas component transport equations,¹⁴ as shown in (formula 2).

$$\begin{cases} \frac{\partial \rho}{\partial t} + \text{div}(\rho u_i) = S_m \\ \frac{\partial(\rho u_i)}{\partial t} + \text{div}(\rho u_i u_j) = \text{div}[\mu \text{grad}(\rho u_i)] + S_i - \frac{\partial p}{\partial x_i} \\ \frac{\partial(\rho T)}{\partial t} + \text{div}(\rho u_i T) = \text{div}\left[\frac{i}{c} \text{grad}(\rho T)\right] + S_T \\ \frac{\partial(\rho C_s)}{\partial t} + \text{div}(\rho u_i C_s) = \text{div}[D_s \text{grad}(\rho C_s)] + S_s \end{cases} \quad (2)$$

where ρ is the fluid density (kg/m³); t is time (s); S_m is the increase or the decrease of the gas mass in goaf, kg/(m³·s); u_i is the velocity component in the i direction (m/s); u_j is the velocity component in the j direction (m/s); μ is dynamic viscosity (Pa·s); S_i is the additional momentum loss source term of gas in the process of migration of porous media in goaf in the direction of (i); p is the gas pressure (Pa); x_i is the i

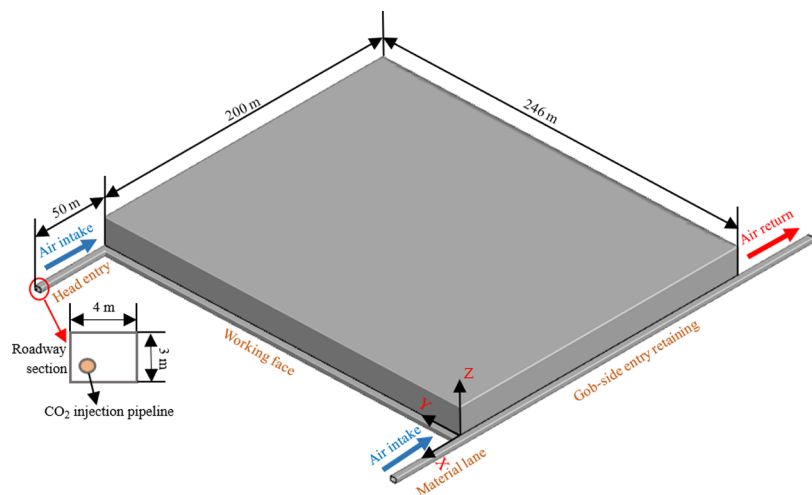


Figure 3. 3-D geometric model used in simulation.

Table 1. Boundary Conditions and Parameter Settings

position of boundary	boundary conditions	parameter settings
air intake of head entry	velocity inlet	velocity magnitude = 0.8 m/s (576 m ³ /min) turbulent intensity = 5% hydraulic diameter = 1 m temperature = 300 K species mass fractions: $w(\text{O}_2) = 20\%$, $w(\text{N}_2) = 80\%$
air intake of material lane	velocity inlet	velocity magnitude = 0.43 m/s (310 m ³ /min) $w(\text{CO}_2) = 99.9\%$
CO ₂ injection pipeline	velocity inlet	injection intensity (corresponding velocity value): 240 m ³ /h (0.085 m/s), 360 m ³ /h (0.127 m/s), 480 m ³ /h (0.169 m/s), 600 m ³ /h (0.212 m/s), 720 m ³ /h (0.255 m/s).
goaf	porous media	user defined function
air return	outflow	

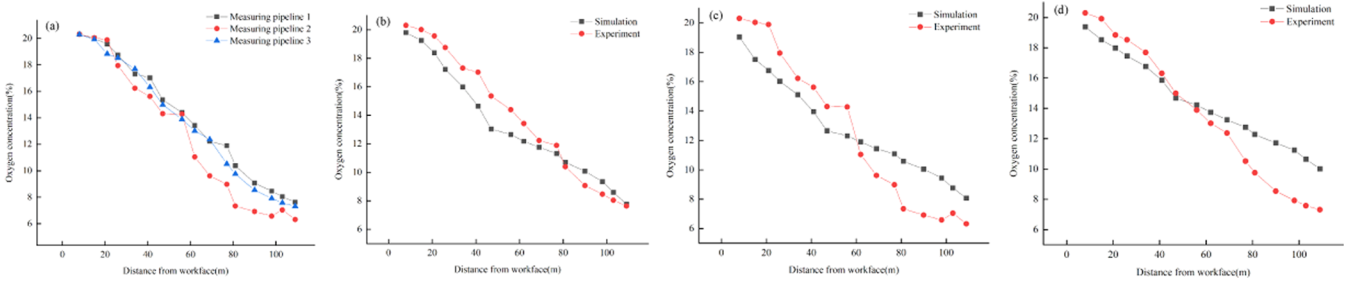


Figure 4. O₂ distributions from field measurement and simulation. (a) O₂ distribution from field measurement without injection of inert gas in goaf. (b–d) Comparison between the field measurement and simulation in goaf at measuring points #1, #2, and #3, respectively.

direction in three-dimensional space; T is the thermodynamic temperature (K); i is the gas thermal conductivity of goaf W/(m·k); c is specific heat capacity, J/(kg·k); S_T is the energy source term (J/kg); C_s is the volume fraction of component s (%); D_s is the diffusion coefficient of component s (m²/s); and S_s is the mass of component s produced by a chemical reaction in a unit volume within unit time in goaf, kg/(m³·s).

3.2. Physical Model. Using Gambit software, a three-dimensional physical model of goaf was established, as shown in Figure 3. The goaf is 246 m in length, 200 m in width, and 40 m in height. The coal seam is a flat seam with an average dip angle from 0°. Fresh airflow enters from the head entry and the material lane, and return air flows out of the retaining roadway. The origin of coordinates is located at the junction of

the working face and the air intake side of the material roadway in goaf ($X = 0, Y = 0, Z = 0$). The section of the working face and the roadway is rectangular with a width of 4 m and a height of 3 m. The length of the roadway is 50 m and the retaining roadway is 250 m. The section of the CO₂ injection pipeline is circular. Because the actual size of the injection pipe is significantly different from the size of the goaf, irregular areas are likely to appear during mesh division, which affects the convergence of the calculation results. Therefore, the diameter of the pipe is enlarged to 1 m, and it is buried in the air intake side of the head entry in goaf with a height of 1 m. Liu et al. indicated that the ideal inert gas injection location for controlling CSC is the transition zone between the heat dissipation zone and the oxidation zone.²³ The measured range

of the oxidation zone is between 26–34 m and 103–109 m from the working face in goaf, so the buried depth is determined to be 30 m in this simulation. The goaf is divided into uneven grids, and the total number of grids was 1 007 259. The setting of boundary conditions is shown in Table 1. The convergence residuals of all variables are less than 10^{-3} .

4. RESULTS AND DISCUSSION

The O_2 distribution from field measurement without the injection of inert gas in goaf is shown in Figure 4a. As shown in Figure 4a, the O_2 concentration decreases with an increase in the distance away from the working face. The quantity of air leakage is subjected to the ventilation pressure difference of the goaf. The pressure difference is one of the causes of the low O_2 concentration in the deep goaf. The chemical adsorption and the oxidation reaction of the residual coal also consume part of O_2 . Furthermore, the O_2 concentration of measuring 1 and 3 is higher than measuring 2. The reason is that the porosity is smaller and the vicious resistance is larger in the central part of the goaf, which is compacted by the overburden caving, thereby hindering the gas seepage. However, there is no coal pillar support along the retaining roadway, the porosity on both sides of the goaf is larger, so the viscous resistance is smaller, and the gas is easy to flow through.

The correctness and applicability of the numerical simulation method are the basis for accurate analysis. The simulation results of the O_2 concentration in goaf without inert gas injection were compared with the field measured data under the condition that the measured ventilation parameters obtained are the same as those set by simulation. Figure 4b–d shows the comparison between the field measurement and simulation in goaf. The numerical simulation results are consistent with the variation trend of the O_2 concentration measured in the field, which indicates that the calculated results accurately reflect the gas migration state in goaf. After verification, the numerical simulation model is used in the following studies.

The cloud map of O_2 on the plane $Z = 1$ m when there is no injection of inert gas is shown in Figure 5. The distribution of O_2 shows a stripe pattern along the direction of the working

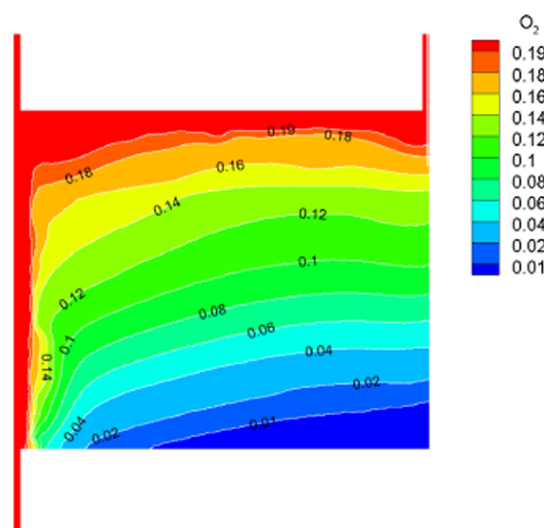


Figure 5. Cloud map of O_2 without the injection of inert gas on the plane $Z = 1$ m.

face in the shallow goaf. In the range 50 m near the retaining roadway, the gas deflects, and the deflection angle is close to 90° . The concentration of O_2 increases near the retaining roadway in goaf. The oxidation zone is mainly divided into two parts: the area near the working face and the area near the retaining roadway. The width of the oxidation zone parallel to the working face is 95 m and that parallel to the retaining roadway is 8 m. The total area of the oxidation zone is about 24 600 m^2 .

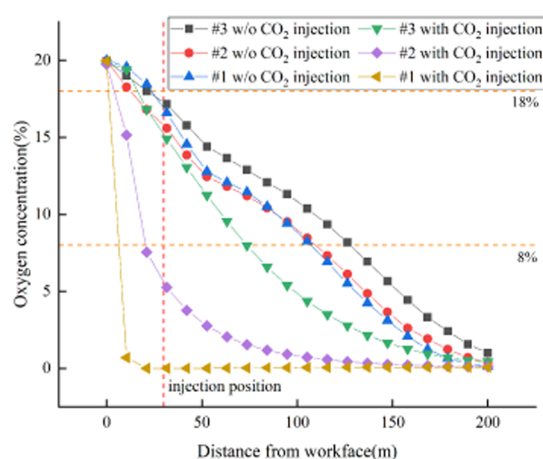
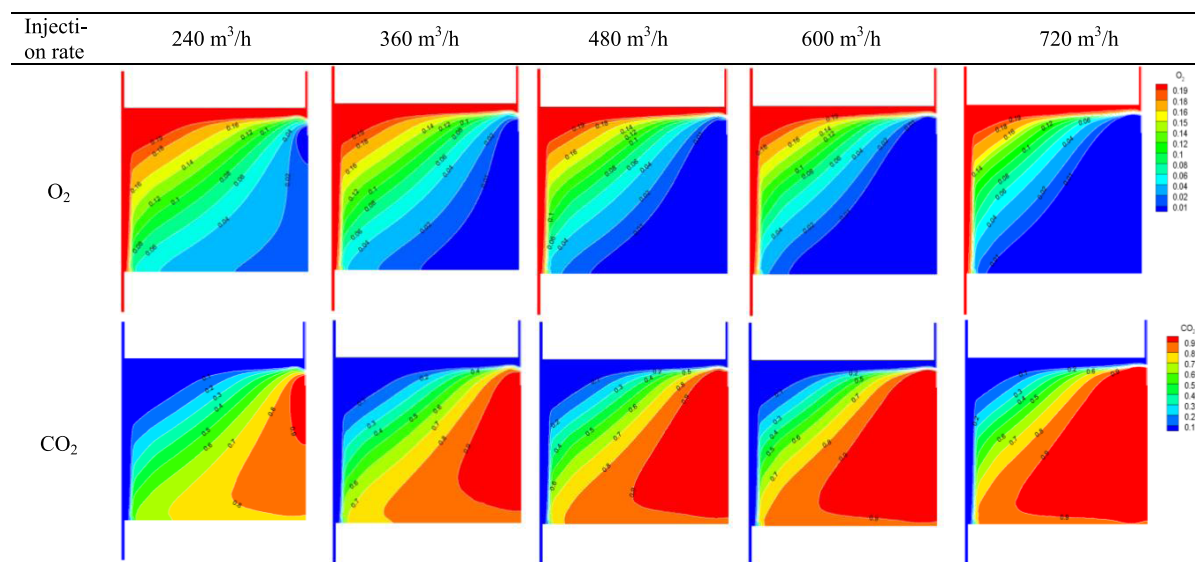
The numerical simulation is divided into five groups to obtain the cloud maps of O_2 and CO_2 in goaf under different gas injection rates, as shown in Table 2. The gas injection rates of each group are 240, 360, 480, 600, and 720 m^3/h , respectively. The distribution of O_2 is varied with the CO_2 injection rate in goaf, especially near the injection point. The oxidation zone moves diagonally toward the origin of the coordinates, and its area decreases after CO_2 injection. When the gas injection rates are 240, 360, 480, 600, and 720 m^3/h , the corresponding oxidation zone areas are 14 760, 11 808, 8856, 8364, and 7380 m^2 , respectively. With the increase in the gas injection rate, the area affected by a high concentration of CO_2 gradually becomes larger, and the gas flow field tends to be stable after the gas injection rate reaches 600 m^3/h .

Figure 6 shows a comparison of O_2 distribution with/without CO_2 gas injection at the three measurement points, indicating that CO_2 dilutes O_2 in the area between the working face and the injection port. The injection of CO_2 increases the gas pressure, and the pressure difference between the air intake side of the head entry and the inside of the goaf decreases or even reaches a state of equal pressure.¹¹ The air leakage from the working face to the goaf decreases, and the O_2 concentration decreases significantly. Figure 7 shows the simulated O_2 concentrations at the three measurement points under different gas injection rates. When the gas injection rate is 600 and 720 m^3/h , the effect on the gas in goaf is the same. Therefore, CO_2 injection dilutes O_2 and reduces the risk of CSC in goaf, and the gas injection rate of 600 m^3/h has a higher inerting effect.

The distributions of the O_2 concentration at 10–50 m of the retaining roadway and at 30–150 m of the working face are shown in Figure 8 when the gas injection rate is 0 and 600 m^3/h on the plane $Z = 1$.

As shown in Figure 8, when there is no injection of inert gas, the goaf with a depth less than 185.7 m within a range of 10–20 m from the retaining roadway is always in the heat dissipation zone and the oxidation zone. The O_2 concentration is large near the retaining roadway, especially at the end of the retaining roadway. After CO_2 injection into the goaf, the O_2 concentration decreases in goaf, and the O_2 concentration fluctuates greatly in the area 10 m away from the retaining roadway and a depth of more than 150 m. Since there is long-term O_2 supply and the area is perpendicular to the advancing direction of the working face, it has a high risk of CSC in the goaf near the retaining roadway. When the distance of goaf is close to the working face, the O_2 concentration is low. Thus, air leakage is serious near the working face and retaining roadway.

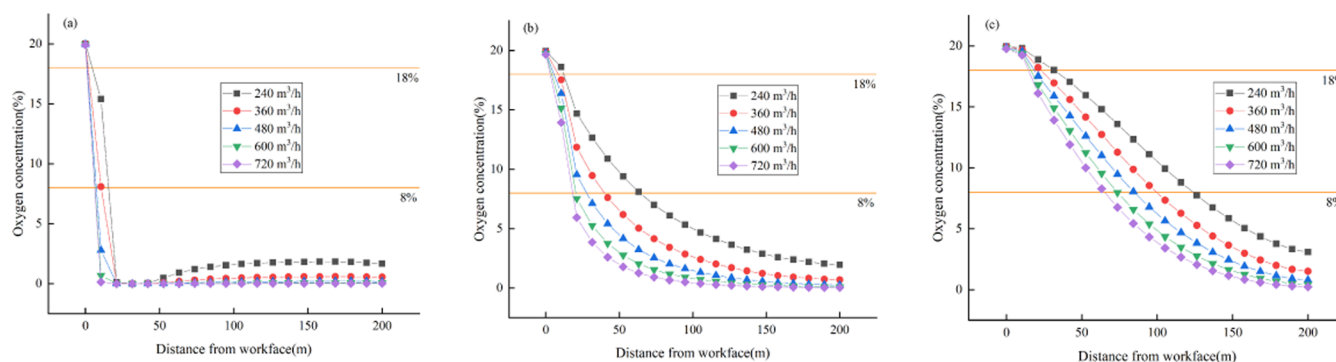
The injection rate of inert gas is seldom considered in the process of applying the inert gas fire prevention technology in coal mines. As shown in Table 2, in the process of continuous injection of CO_2 , the change of gas can be divided into three stages. In the first stage, the gas injection rate is small. CO_2 accumulates around the gas injection port, and there is a gas

Table 2. O₂ and CO₂ Field in Goaf with Different Gas Injection RatesFigure 6. Comparison of O₂ distributions with 600 m³/h and without CO₂ injection.

injection radius in the inclined direction of the goaf. The second stage is the stage of sufficient injection. CO₂ permeates to the middle of the goaf and drives O₂ to diffuse in the direction of the retaining roadway. There is a negative exponential relationship between the gas injection rate and

the oxidation zone area, as shown in Figure 9. The third stage is when the injection rate is too high. The inert gas injection into goaf reaches a new balance with the gas in goaf. The oxidation zone slowly decreases or remains stable, and the CO₂ continues to infiltrate the retaining roadway with a small range. Therefore, the injection rate of inert gas should be controlled in a reasonable range. If the injection rate is insufficient, a good inerting effect cannot be achieved, but the excessive gas injection rate can bring economic cost and resource wastage. Because of weak toxicity of CO₂, the excessive CO₂ not only causes safety problems in production but also threatens the safety of underground workers.

Generally speaking, the CO₂ concentration in the total airflow of the mining face should not exceed 0.75%. Figure 10 shows the CO₂ concentration along the retaining roadway with five gas injection conditions. As shown in Figure 10, when the gas injection rate exceeds 600 m³/h, the average concentration of CO₂ in the retaining roadway exceeds the standard. The excess CO₂ concentration is related to the gas flow law and the injection rate in goaf. When the CO₂ gas injection rate reaches 600 m³/h, the gas flow field changes slowly or tends to be stable, and CO₂ still moves to the retaining roadway in a small range along the direction of the working face, which eventually leads to the excess of the CO₂ concentration.

Figure 7. Simulated O₂ distribution with different gas injection rates. (a)–(c) Variation of the O₂ concentration with the goaf depth with different gas injection rates in #1, #2, and #3, respectively.

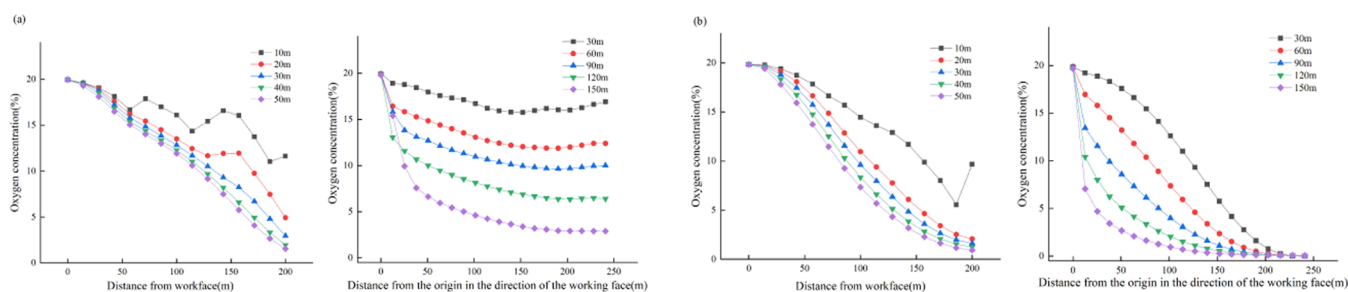


Figure 8. O₂ concentration on the plane $Z = 1$. (a) Gas injection rate is 0 m³/h. (b) Gas injection rate is 600 m³/h.

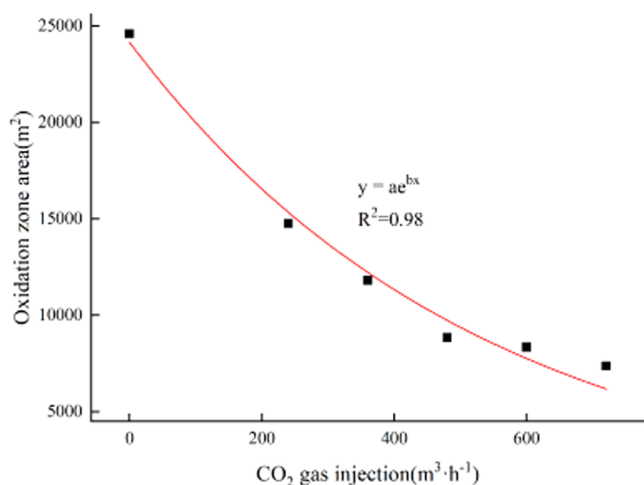


Figure 9. Relationship between the area of the oxidation zone and CO₂ gas injection.

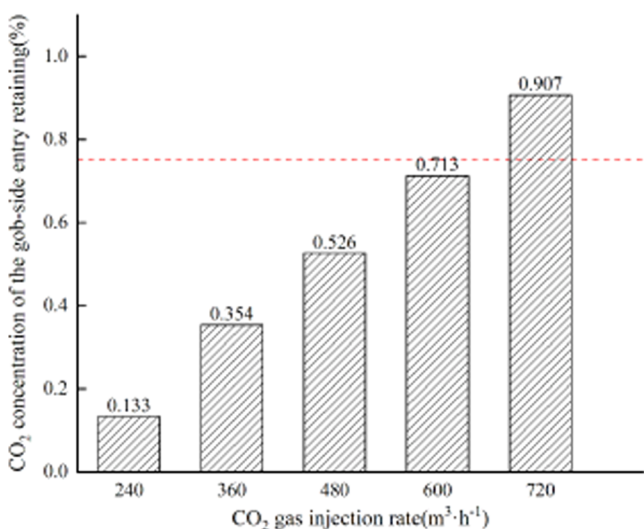


Figure 10. CO₂ concentration at the retaining roadway with different gas injection rates.

5. CONCLUSIONS

In this paper, an index system of influencing factors of the CO₂ inerting technology was established with the gob-side entry retaining in goaf. Fluent software was used to simulate the distribution of the gas field. By comparing with the O₂ concentration measured in the field test, the concentration distribution trend is basically consistent, which verifies the reliability of the numerical simulation. Then, the effects of the CO₂ injection rate on the spontaneous combustion zone and

O₂ distribution and the safety of the CO₂ inerting technology were analyzed. Reasonable perfusion parameters were determined to balance the relationship between the CO₂ inerting effect and production safety. The main conclusions are as follows:

- (1) Air leakage is serious in the vicinity of the working face and near the retaining roadway of goaf. The O₂ concentration decreases with an increase in the distance away from the working face. When there is no injection of inert gas, the distribution of the oxidation zone shows a stripe pattern with an area of about 24 600 m².
- (2) The distribution of the O₂ flow field varies with the CO₂ injection rate in goaf. O₂ in the area between the working face and the injection port is diluted, especially O₂ in the air intake is markedly reduced. The area of the oxidation zone decreases with an increase in CO₂ gas injection and moves diagonally toward the intersection of the retaining roadway and the working face. When the gas injection rate is 240–720 m³/h, the oxidation zone area ranges from 7380 to 14 760 m².
- (3) As CO₂ continues to be injected into the goaf, the evolution of the gas flow field can be divided into three stages. When the gas injection volume is small, CO₂ accumulates around the gas injection port and there is a gas injection radius. The second stage is the stage of sufficient injection, where CO₂ permeates to the middle of goaf and drives O₂ to diffuse in the direction of the retaining roadway. There is a negative exponential relationship between the injection rate and the oxidation zone area. In the stage of excessive gas injection, the oxidation zone slowly decreases or remains stable and CO₂ continues to infiltrate the retaining roadway with a small range, resulting in an excess of the CO₂ concentration in the retaining roadway.

It is suggested that the reasonable injection rate of CO₂ could be determined by formula calculation and numerical simulation before the CO₂ fire prevention technology is adopted, combining with the actual production conditions of a mine. Meanwhile, beam tubes should be buried at the retaining roadway to monitor the changes in the gas concentration in the process of gas injection. Taking the gas injection pipeline with a buried depth of 30 m and wind speed of 0.8 m/s as an example, the CO₂ injection rate is 600 m³/h from the perspective of economic rationality and safety. More influencing factors and their coupling effects should be considered in further research, which will provide guidance for the practical application of the CO₂ fire-suppression technology.

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Notes

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