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Research Article

Method for Determining Spontaneous Combustion Risk in Roof Cutting Gob-Side Entry Retaining U+L Ventilation Goaf for Mining Safety

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It is difficult to accurately determine the risk of spontaneous combustion in the U + L ventilation goaf of the first mining face when using the method of roof cutting gob-side entry retaining (RCGSER). To address this problem, the I2101 working face of Qipanjing Mine was considered as the research object in this study. Laboratory experiments, field measurements, and CFD numerical simulation were used to study the continuous oxygen consumption characteristics of coal samples and the distribution of spontaneous combustion danger areas in U + L goaf. The results showed that the oxygen consumption capacity of the coal samples was weak. The continuous oxygen consumption rate of the coal samples had a negative exponential distribution, and the oxygen volume fraction in the smothering zone (critical) was 15%. Furthermore, the three likely areas for spontaneous combustion in the RCGSER goaf were near the open-off cut, within 5–10 m near the RCGSER roadway, and behind the working face. Additionally, the relationship between the dangerous area (S_f) and the different positions (x) of the working face was expressed as $S_f = a + b \cdot \exp(c \cdot x)(b < 0, c < 0)$. On this basis, the fire prevention and extinguishing measures of nitrogen injection was recommended near the open-off cut as well as inhibitor injection at the RCGSER roadway. Because the maximum width of the spontaneous combustion oxidation zone in Qipanjing Mine is 80 m and the minimum daily advancing speed is 1.2 m, spontaneous combustion risk did not exist. This research slightly fills the theoretical gap in the relatively new field of fire prevention in RCGSER goaf.

1. Introduction

The flow field distribution of U + L ventilated goaf is more complex to determine with the method of roof cutting gob-side entry retaining (RCGSER). The RCGSER roadway is directly connected to the goaf, and an increase in the air leakage range and volume considerably change the spontaneous combustion danger area of the goaf [1–6]. However, only a few studies have investigated this phenomenon, and the applicability of the existing prevention and control methods for the RCGSER goaf is still uncertain.

Nowadays, China's economy is tipping toward high-quality development, placing higher demands on coal companies to supply coal efficiently, conserve energy, and reduce emissions [7, 8]. In 2017, Manchao et al. proposed a green and efficient coal mining method, called the 110 method, ushering in the third revolution in mining science and technology [9]. Recently, many studies have confirmed the feasibility of this method in implementing supply-side reforms and achieving the "Hit peak emissions and Carbon Neutrality" goal in mining enterprises [10, 11]. Scholars all over the world have conducted extensive research on the spontaneous combustion characteristics of residual coal in traditional U-shaped ventilation goaf. Zhang established a PFC-fluent coupled dynamic model for goaf porosity, the model is used to simulate the airflow field in a goaf, and the regular airflow pattern is obtained, with the oxygen concentration as the index, the areas prone to spontaneous combustion of residual coal in the goaf are identified [12]. Wen noted that oxygen concentration, air leakage intensity, and spontaneous combustion period are the main factors affecting the spontaneous combustion of residual coal. Spontaneous combustion in a goaf occurs under dynamic and stable conditions, and the corresponding risk is typically predicted using the temperature distribution of the goaf [13]. Yu et al. used MATLAB to superimpose measured O_2, CO_2, and CH_4 concentrations and temperature to predict goaf areas prone to spontaneous combustion risks [14]. These studies have introduced many relevant laws and proposed methods that can predict spontaneous combustion in a goaf. Usually, a 10% or 8% oxygen fraction is used to classify the oxidation spontaneous combustion zone during practical field applications [15–18]. However, different coal types have different spontaneous combustion characteristics; thus, their corresponding values also differ [19]. The air leakage from the RCGSER roadway inevitably affects the remaining coal in the goaf [20]; therefore, a relatively complex relationship exists among the risk characteristics of spontaneous combustion in the RCGSER goaf. Previous research has mostly focused on the U-shaped goaf with coal pillar retention, which is substantially different from the U + L-shaped RCGSER goaf.

Consequently, this study aimed to more accurately determine the risk of spontaneous combustion in the goaf of the I2101 first working face in the Qipanjing Mine. Hence, the closed oxygen consumption experiment was used to study the oxygen consumption characteristics of each sample in this mine, the continuous oxygen consumption rate of the coal samples, and the critical oxygen volume fraction of the suffocating zone [21]. According to field data, a solid similarity model was established to obtain the air leakage distribution in the goaf at different locations of the working face. The model was used to study the dynamic relationship between the spontaneous combustion risk characteristics of the RCGSER goaf in the first mining face and different advancement positions of the working face; the model was also used to recommend targeted fire prevention measures. A CFD simulation software was used to simulate the gas flow field distribution of the “three spontaneous combustion zones” goaf model in six working faces at different advancement positions. Furthermore, nitrogen injection and inhibitor injection were proposed to prevent fire outbreak. Theoretical verifications showed that the proposed nitrogen injection measures can guide fire prevention in the RCGSER goaf of the first mining face. This research is an exploration of the relatively new field of fire prevention in RCGSER goaf.

2. General Situation of Working Face and Goaf

The I2101 working face was 240 m long, 3 m high, and 5 m wide. Within the mining range, the coal seam was approximately 3 m thick, and the inclination angle was 3–5°. The full-height mining method of longwall comprehensive mechanization was used in this study; the advance speed was 4 m per day, and the strike advance distance was approximately 2,000 m. Figure 1 shows the schematic of the roadway layout. The maximum relative and absolute gas emissions were 4.01 m^3/t and 10.31 m^3/min, respectively, according to the results of the “Prediction of Mine Gas Emission and Gas Grade Evaluation Report” and the “Identification Report of Coal Spontaneous Combustion Tendency” published by Chongqing Research Institute. These values indicate that the mine has a low gas volume. The spontaneous combustion tendency grade of coal seam 9-2 is II, which corresponds to spontaneous combustion coal seams. The shortest spontaneous combustion period of the coal sample during the I2101 working face was 66 days.

The beam tube used to monitor oxygen volume fraction in the goaf was buried in the return airway. Figure 2, a scatter line chart, illustrates the retrieved data acquired by the beam tube as the working face progressed.

The blue line in the figure is the fitted prediction line of oxygen volume fraction. Through linear regression analysis, the relationship between oxygen volume fraction in the goaf and the working face distance is obtained as

$$L_i = 756 - 36.8C_i, \tag{1}$$

where C_i is the volume fraction of oxygen in the goaf, %; and L_i is the position from the working face, m. The regression correlation coefficient is 0.9278.

It is easy to deduce from Equation (1) that 10% and 8% of this part are located about 390 m and 460 m away from the working face, respectively. The U-shaped ventilation mining method uses coal pillars to determine the various spontaneous combustion possibilities in a goaf; the propulsion speed of the I2101 working face in the Qipanjing Mine should be greater than 6 m (or 7 m) per day; otherwise, the spontaneous combustion possibility in the goaf will remain very high.

However, the working face has currently advanced and exceeded 600 m with no detection of self-ignition identification gases, such as ethylene and acetylene, in the return airway. The temperature monitoring data were stable and normal, and no signs of spontaneous combustion were found in the goaf. According to an analysis of the likely reasons for the above phenomenon, the following can be concluded: (1) coal oxygen consumption characteristics differ by the type of coal being observed, and the coal oxygen consumption capacity of the Qipanjing Mine is weak; (2) the distribution of the “three spontaneous combustion zones” in the RCGSER goaf of the first mining face is different from that in coal pillar mining.

3. Closed Oxygen Consumption Experiment of Coal Sample

The oxygen supplement and temperature of the air leakage in the goaf gradually decreased to zero; therefore, it can be concluded that oxidation in a deep goaf progresses in a closed state. A closed oxygen consumption experimental device can help simulate the environment of a deep, abandoned coal in mined-out areas [22]. In this study, the main parameters determined using this device were (1) the critical oxygen volume fraction of coal sample 9-2 in the Qipanjing

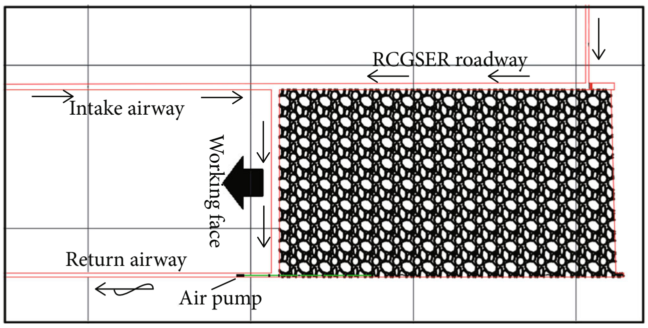


Figure 1: I2101 working face roadway layout.

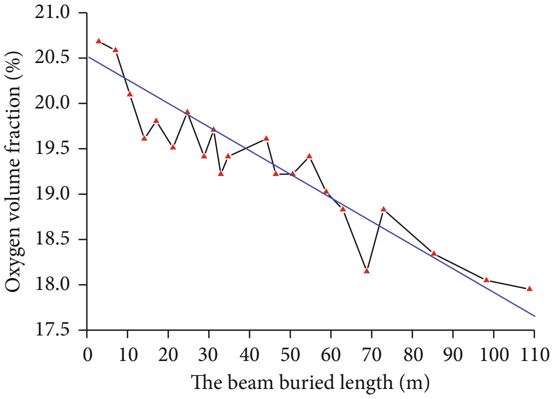


Figure 2: Oxygen volume fraction in goaf, monitored by beam tube.

Mine and (2) the oxygen consumption rate of the coal sample with a continuous decrease in the oxygen volume fraction.

The coal samples used in the experiment were collected on-site, transported to the laboratory in a sealed package, and placed in a low-temperature storage room to prevent coal oxidation. In each group of experiments, the collected massive fresh coal blocks were crushed, and 2 kg of coal with a particle size of 0.4–2.4 mm was screened out as the experimental coal samples.

The experimental device mainly comprises a computer, an air pump, a gas concentration sensor, a special data collector, and other interrelated parts. Figure 3 shows the internal pipeline connection of the device, where the coal sample tank is at standard atmospheric pressure. The experiment was prepared as follows. The air inlet pipe and temperature detector were inserted into the coal sample tank after cleaning and drying up the tank; the coal sample was placed in the tank after crushing and screening the sample to obtain the specific coal particle size. The tank was sealed to prevent leakage. Before the experiment began, air was allowed to flow into the tank for a short time to wash the coal sample gas and eliminate the interference of other gases. The incubator was run at 20°C. The data acquisition software recorded the O_2 and CO concentrations during the experiment by regulating the coal temperature. The temperature control system after being leveled off data curve of coal sample can be critical of smothering extinguishes the oxygen density. At this point, the experiment was terminated.

The closed oxygen consumption method was used to measure the critical oxygen volume fraction of the coal sample in the I2101 working face of the Qipanjing Mine.

3.1. Determination of Critical Oxygen Volume Fraction in the Suffocating Zone. Air leakage is a necessary condition for spontaneous coal combustion in a goaf. The oxidation reaction between residual coal and oxygen in the leaked air results in spontaneous combustion under certain heat storage conditions. According to the theory of coal oxidation spontaneous combustion, the oxygen concentration in the air leakage airflow is the decisive factor of spontaneous combustion. Therefore, it is suitable to use the oxygen volume fraction to divide the oxidation “three spontaneous combustion zones” in a goaf [23, 24]. To determine the oxygen extinguishing zone, scholars mostly use a critical oxygen volume fraction of 10% (or 8%) when dividing the “three spontaneous combustion zones” by the oxygen volume fraction. However, because of the different spontaneous combustion characteristics of different coal types, the corresponding values differ. Therefore, using 10% (or 8%) uniformly to determine the spontaneous combustion risk in different zones in a goaf will yield inaccurate results and hinder safe and efficient coal production.

Figure 4 shows the oxygen consumption curve of Qipan well coal samples in the closed oxygen consumption experiment: the oxygen volume fraction in the closed device remains stable, corresponding to an ordinate value of 15.2%. Considering the presence of preoxidation in the coal sample, the (critical) oxygen volume fraction in the asphyxiation zone of Qipan well was taken as 15%. When the oxygen volume fraction is greater than 15%, the possibility of residual coal burning is extremely high. Therefore, the gob area with an oxygen volume fraction greater than 15% was marked as a spontaneous combustion hazard area.

3.2. Continuous Oxygen Consumption Rate of 9-2 Coal Sample. The oxygen consumption characteristics of the coal sample differed under various oxygen concentration conditions [25–27]. Therefore, while the oxygen concentration in the deep goaf gradually decreased, the residual coal oxygen consumption rate varied accordingly. Hence, the experimental device not only can measure the oxygen volume fraction of the coal sample to determine the boundary position of the oxygen extinguishing zone but also can obtain the oxygen consumption rate under various oxygen concentration conditions. This value is significant in simulating the flow field distribution in the goaf using the fluid simulation software.

The principle of the algorithm for determining the experimental parameters is described as follows. Assume that the oxygen concentration volume fraction $C(\tau)$ in the sealed tank approximately follows the distribution of the negative exponential function:

$$c(\tau) = c_b + (c_0 - c_b) \cdot e^{-\lambda c \tau}. \tag{2}$$

where C_0 is the initial volume fraction of oxygen, %; λ_c is the decay rate of the oxygen volume fraction, s^{-1}; C_b is the stable oxygen volume fraction value, %; τ is the oxidation time, s.

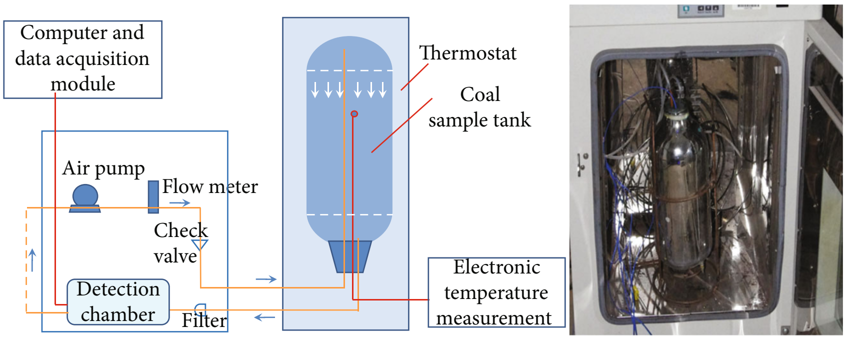


FIGURE 3: Schematic of closed oxygen consumption experimental device.

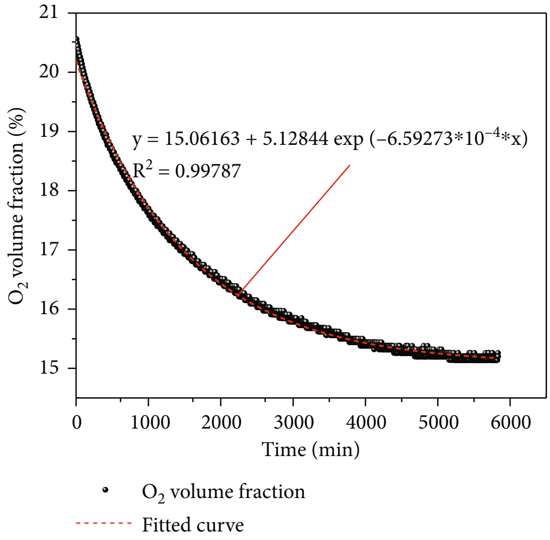


FIGURE 4: Variation curve of oxygen volume distribution in the experimental device.

Taking the derivative of Equation (2) with respect to time τ, the mass change rate of the oxygen mole consumed by the coal sample per unit time and volume in the closed tank can be obtained as follows:

$$\gamma = \begin{cases} 0 & , (c(\tau) < c_b), \\ -0.4464\lambda c(c_0\text{-}c_b)e^{-\lambda_c \tau} & , (c(\tau) \geq c_b), \end{cases} \tag{3}$$

where 0.4464 is the amount of substance per unit volume, mol·m^{-3}; γ is the volumetric oxygen consumption rate, mol·(m^3·s)$^{-1}$.

Substituting Equation (3) into Equation (4) yields

$$\gamma = -0.4464\lambda_c[c(\tau) - c_b]. \tag{4}$$

Equation (4) shows that the oxygen consumption rate of the coal sample tank is directly proportional to the oxygen volume fraction (establishing a linear relationship). This relationship can be observed for the coal in a loose accumulation state.

Thus, the volumetric oxygen consumption velocity constant of the coal sample tank is obtained when the oxygen volume fraction is C_0:

$$\gamma_0 = -0.4464\lambda_c(c_0 - c_b), \tag{5}$$

where γ_0 is the volumetric oxygen consumption velocity constant of the initial coal sample.

4. Field Data

Air leakage in the RCGSER roadway directly affects the distribution of “spontaneous combustion” in a goaf. Therefore, it is necessary to accurately determine the location and volume of air leakage. To achieve this, the air volumes along the I2101 working face and RCGSER roadway were measured during coal production in Qipanjing Mine in October 2021. Owing to the complexity of the field situation, which had a certain impact on the measurement work, some of the measured data were inaccurate. The air volume on the return side of the working face was found to be considerably higher than that on the inlet side. Figures 5 and 6 are based on the measured data and illustrate the variation curves of the air volume along the route.

In Figure 5, the visible x-axis indicates that the working face changes from an air inlet port to an air return port. The red line is the fitting curve of the air volume at each measuring point. The curve in the figure shows that the air volume of the I2101 working face increases from the air inlet end to the air return end. The complexity of the working face during production prevents accurate air volume measurement at certain locations; however, the changing trend of air volume in the working face is obvious, and the air volume gradually increases from the inlet end to the return end.

The air volume along the RCGSER roadway was also measured. In Figure 6, the x-axis range of 0 to 600 represents the positions from the current working face to the open-off cut (air inlet port) along the RCGSER roadway. The air leakage of the RCGSER roadway is mainly concentrated approximately 200 m near the open-off cut and the working face.

Figures 5 and 6 show the variation trend of the measured air flow along the working face and RCGSER roadway. Figure 7 shows the track chart of the air leakage airflow in the RCGSER goaf of the first mining face.

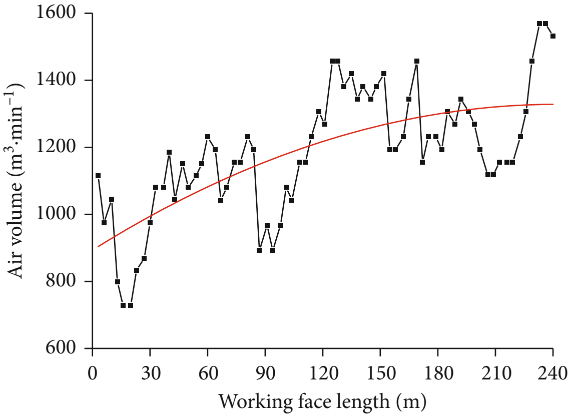


Figure 5: Air volume along the I2101 working face.

5. Distribution of Natural Danger Areas in the Goaf

It is almost impossible to directly obtain the continuous gas flow field distribution in a goaf through field observation because of the inherent complexity of a goaf. Therefore, air leakage behavior and oxygen flow field distribution were determined through similarity experiments and simulations in the RCGSER goaf of the I2101 first mining face in Qipanjing Mine. The experiments and simulations were performed by creating solid similarity and simulation models.

5.1. Air Leakage Distribution of Goaf Solid Similarity Model. According to the roadway size measured on site, a solid similarity model composed of multiple components was established at the ratio of 400 : 1. The model contains holes in the wall near the goaf to enable the components of the RCGSER roadway and working face simulate air leakage pores of the underground roadway. The model can simulate and analyze the distribution of air leakage in the goaf at advancing working face positions according to the measured data. The solid similarity model is only used to measure the distribution characteristics of air leakage airflow in a goaf to play comparative and guiding roles for the fluid simulation software. Therefore, the accuracy of the experimental results of the solid similarity model does not need to be very high. The similarity experimental model was used to obtain the smoke flow in the goaf, as shown in Figure 8. However, thin smoke is difficult to observe; thus, it was difficult to accurately determine the air leakage behavior of the roadway and working face. Therefore, the observed airflow temperature was considered to reflect the air leakage in the goaf.

The air leakage behavior depended on temperature change in the solid similarity model before and after the experiment. Before the experiment, the model's ambient temperature was relatively low. After the experiment, an air flow above the temperature level of the model was introduced into the air inlet of the model. The air leakage distribution characteristics of the goaf were recorded by studying the goaf areas with a high temperature. The temperature data for the whole experimental model were collected using the GY-MCU/MLX90640 IR 32 × 24 infrared temperature measurement dot matrix sensors (Guangyun Electronics, Guilin, Guangxi Province, China). The leakage airflow field distribution of three groups with different goaf lengths was tested, and the three model groups corresponded with the actual mine working face, which advanced at 200 m, 600 m, and 800 m. The collected temperature data were plotted, and the experimental results of the three model groups are shown in Figure 9. The figure shows that the temperature of the goaf changes under the influence of a high temperature air inlet flow. However, when the goaf length changes, the distribution pattern of the temperature variation areas in the goaf also changes. As the goaf length increases, the proportion of the high-temperature areas to the total area of the goaf decreases.

5.2. Simulation and Analysis of the Goaf Flow Field

5.2.1. Simulation of Goaf Flow Field Distribution. Owing to the complexity of the actual goaf, the results of the solid similarity model are only suitable for qualitative analyses of the air leakage distribution in the RCGSER goaf. Advances in computer technology in the 21st Century have facilitated the feasibility of using fluid simulation software in determining the "three spontaneous combustion zones" in a goaf [28–31]. This method was used to qualitatively and quantitatively explore the oxygen flow field distribution and spontaneous combustion risk in the RCGSER goaf of the first mining face.

The setting of model porosity in fluid simulation is crucial to achieving accurate simulation results in a goaf, and this setting mainly depends on the correct description of the rock fragmentation coefficient. Generally, the compaction distribution of the RCGSER goaf still follows the "O" circle rule [32]; however, the rock fragmentation coefficient differs considerably near the entranceway [33, 34].

Six simulation model groups with working face propulsion positions of 200 m, 400 m, 600 m (current position), 800 m, 1000 m, and 1200 m were established. All models were meshed with a hexahedral mesh in a structured mesh. The mesh element was a regular hexahedron (1 m length). The steady-state calculation mode was selected while the RNG model in k-epsilon and the standard wall function were used; the solution method was SIMPLEC. The groups corresponded with the roadway size of the actual mine, and their boundary conditions were set according to the measured data. During the simulation, the oxygen volume fraction distribution of the 600 m model was first adjusted to maintain consistency with the oxygen data monitored by the beam tube, that is, 18% of the oxygen volume was approximately 110 m away from the working face. Other models were simulated according to the setting of the 600 m model. A profile with a height of 0.5 m was selected from the simulation results of each group; Figure 10 illustrates the distribution of the oxygen volume fraction greater than 15% in the goaf. As shown in the figure, when the oxygen volume fraction is greater than 15%, the coal in this mine may undergo spontaneous combustion; hence, the area is labeled a spontaneous combustion danger zone.

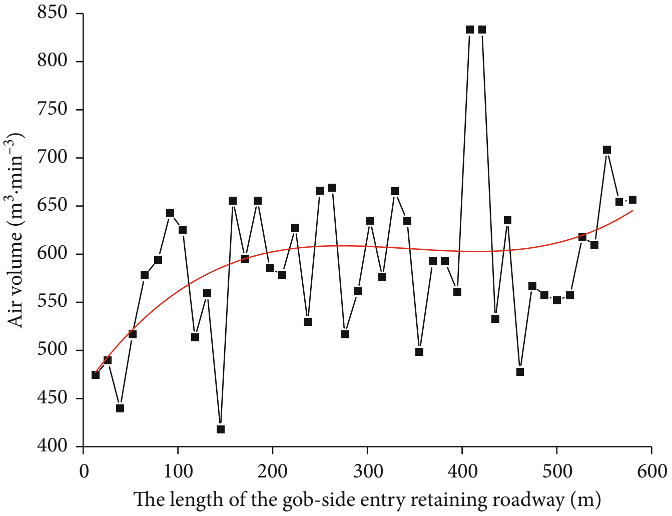


Figure 6: Air volume along the RCGSER roadway.

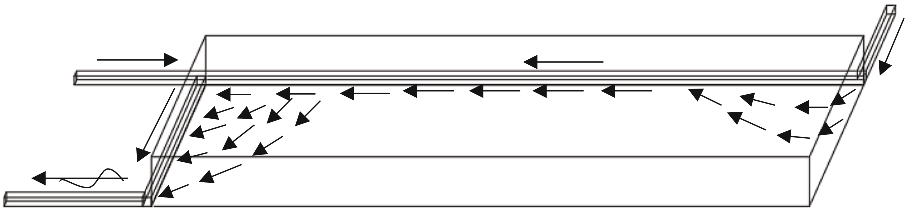


Figure 7: Track chart of air leakage airflow in the goaf.

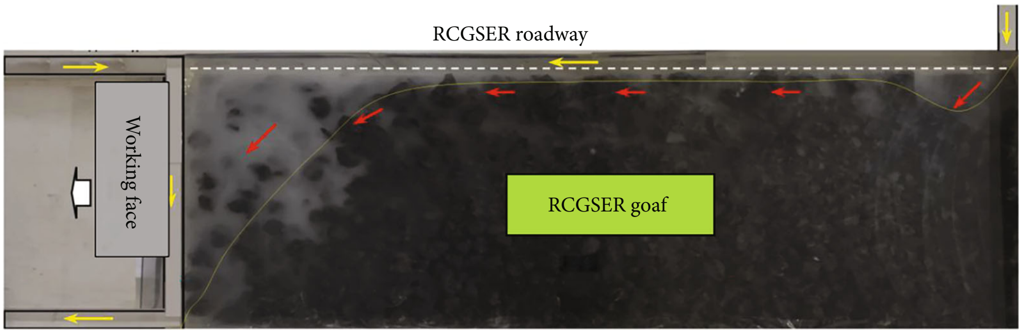
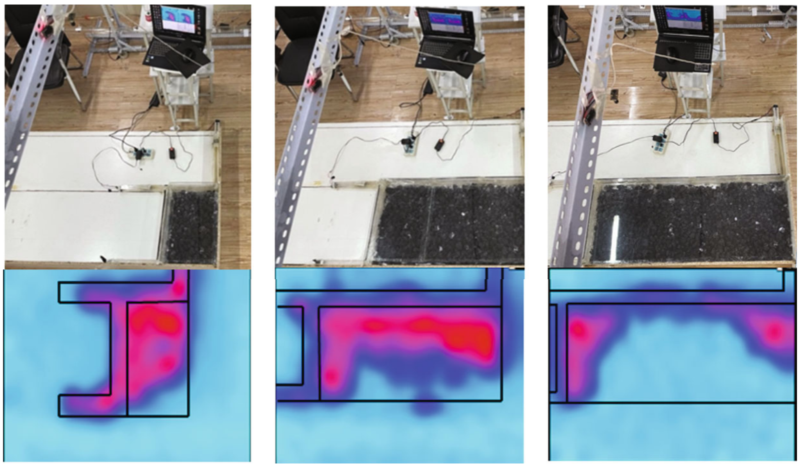


Figure 8: Experimental results of smoke flow in goaf.

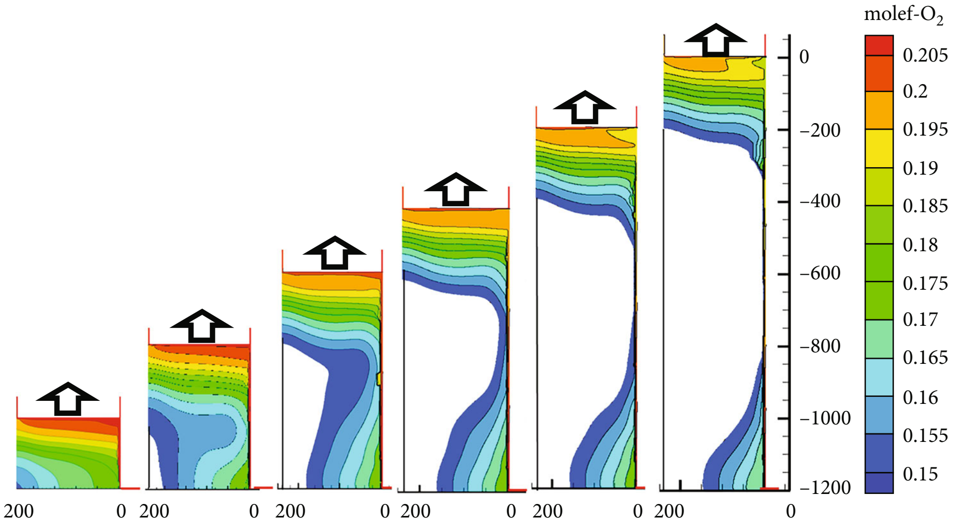
A comparison of Figures 7 and 8 shows that the distribution of the oxygen flow field simulated by the models at 200 m, 600 m, and 800 m is consistent with the measured air leakage and distribution behaviors of temperature-increase areas of the solid similarity model. Moreover, the three distributions confirm the air leakage behavior of the I2101 first mining face RCGSER goaf in the Qipanjing Mine. The CFD simulation results illustrated in Figure 10 show that the goaf behind the U + L ventilation working face conformed to the principle of oxygen consumption nonuniformity, and the oxygen concentration distribution on the inlet side was greater than that on the return side.

The following conclusions are based on the mentioned analysis. (1) Three areas may spontaneously ignite in the RCGSER goaf of the first face: near the open-off cut, within 5–10 m near the RCGSER roadway, and behind the working face. The distribution morphology and three areas change as the working face advances. The dangerous areas of the two parts behind the working face and near the open-off cut tend to be fixed after the working face advances beyond 800 m. (2) The air flow velocity of the working face leaking into the goaf is greater than that infiltrated by the RCGSER roadway. The pressure difference generated by air leakage during the working face affects the air flow infiltrated into the goaf by the RCGSER roadway, and its scope of action is 200–300 m near the working face. (3) Air leakage at the air inlet end of the RCGSER roadway (near the open-off cut) is the main factor affecting the safety of the RCGSER goaf of the



200 m 600 m 800 m

Figure 9: Experimental results at working face advancement positions.



(a) 200 m (b) 400 m (c) 600 m (d) 800 m (e) 1000 m (f) 1200 m

Figure 10: Goaf spontaneous combustion risk areas at different working face advancement positions.

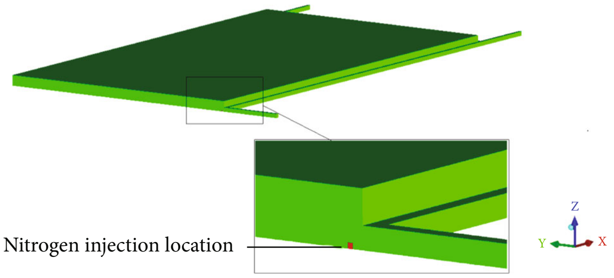
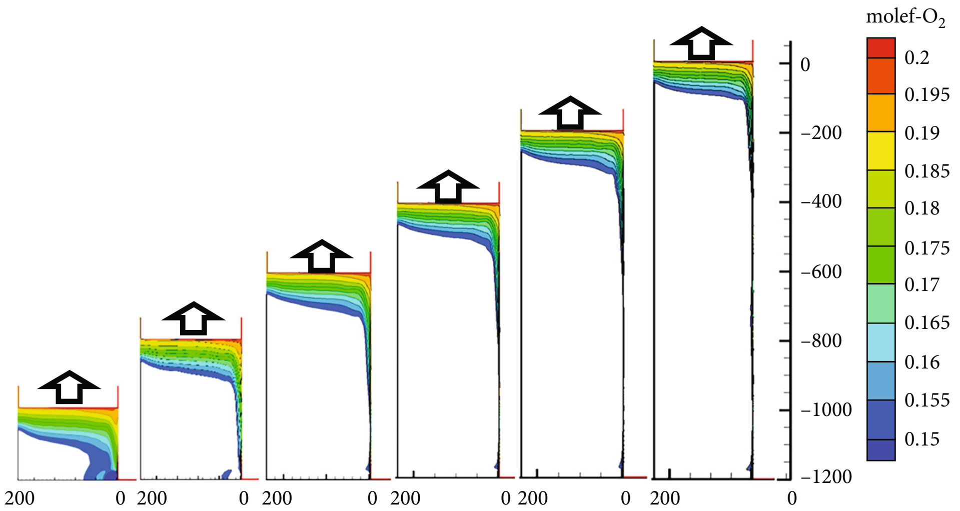


Figure 11: Location of nitrogen injection port.

first mining face. As the length of the RCGSER goaf increases, the spontaneous combustion and oxidation time of the residual coal near the open-off cut gradually increases and the likelihood of combustion in the goaf also gradually increases. (4) The oxygen volume fraction of the goaf near the RCGSER roadway is always high, the width of the zone narrows gradually during the working face advancement and eventually maintains a range of 5–10 m; according to the “three spontaneous combustion zones” division principle of spontaneous combustion in the goaf with a U-shaped ventilation retaining coal pillar, this part of the area should belong to the oxidation spontaneous combustion zone. While the working face advances, the length of the goaf area extends, thereby making it difficult to use the original method to determine the risk of spontaneous combustion in the RCGSER goaf of the first mining face.

The I2101 working face of the Qipanjing Mine was fully exploited, so the residual coal was minimal, and the mine water inflow was large, isolating the residual coal from oxygen through air leakage and airflow. Therefore, no signs of spontaneous combustion were found in the goaf when the working face advanced to 600 m, which was a peculiar case. According to the oxidation duration of the residual coal, the most likely area for spontaneous combustion in the aforementioned goaf was near the open-off cut. Therefore,



(a) 200 m (b) 400 m (c) 600 m (d) 800 m (e) 1000 m (f) 1200 m

Figure 12: Distribution of dangerous areas in the goaf after nitrogen injection.

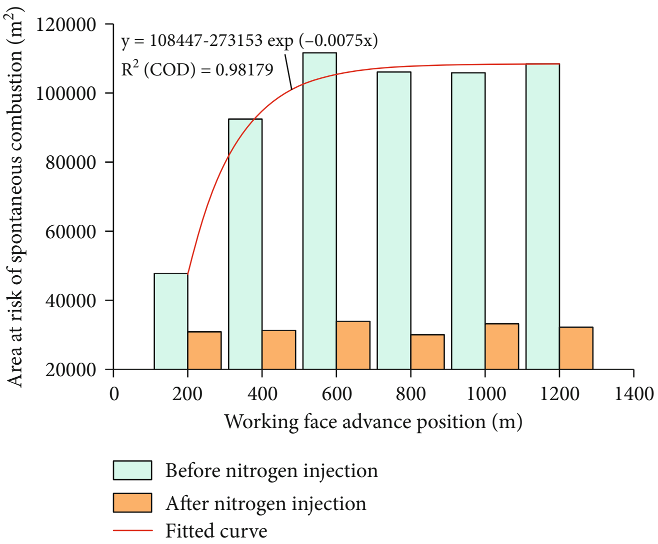


Figure 13: Changes in area of spontaneous combustion risk areas in the goaf.

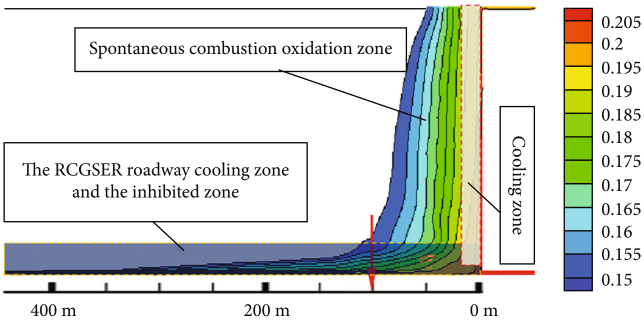


Figure 14: Determination of the spontaneous combustion oxidation zone and scale behind the working surface.

reducing the oxygen content in this goaf area will be insignificant for preventing and controlling spontaneous combustion in the RCGSER goaf of the first mining face. Therefore, a fire prevention measure of nitrogen injection into the air inlet end of the RCGSER roadway was considered, and its effect was verified by fluid simulation software.

5.2.2. Measures of Nitrogen Injection. Air leakage at the air inlet end of the RCGSER roadway affects the goaf near the open-off cut of the first mining face. The likelihood of spontaneous combustion in the goaf is very high because of continuous residual coal oxidation. To attempt to solve the problem of reducing the oxygen amount in this area and address the possibility of spontaneous combustion in the goaf, a method of nitrogen injection was introduced at the air inlet end of the RCGSER roadway. The effect of this measure was simulated and verified by a fluid simulation software. Figure 11 illustrates the position of the nitrogen injection port.

The simulation of the proposed nitrogen injection was only used to verify the feasibility of the injection in reducing the risk distribution of spontaneous combustion in the RCGSER goaf of the first mining face. Hence, the nitrogen injection is not extensively described in this paper. According to the formula in the MT/T701-1997 Technical Specification for Nitrogen Fire Prevention and Control in Coal Mines, the nitrogen injection rate was 21 m^3/min. Similarly, the distribution slice cloud diagram of the spontaneous combustion risk area in the goaf after nitrogen injection was obtained from a simulation, as shown in Figure 12. After the nitrogen injection, the possible spontaneous combustion risk areas in the RCGSER goaf of the first mining face reduced from three to two parts; 5–10 m near the RCGSER roadway and behind the working face, that is, the oxygen volume fraction in the goaf near the open-off cut decreased, and the risk of spontaneous combustion reduced.

To quantitatively analyze the results shown in Figures 10 and 12, the simulation software was used to calculate the area of the dangerous goaf areas before and after the nitrogen injection. Figure 13 shows the histogram of the relationship between the hazardous areas and the position of the working face, and the simulation results data before nitrogen injection were fitted.

Figure 13 shows that the area of the spontaneous combustion risk area rises before the working face advances to 600 m. At this stage, the ratio of the spontaneous combustion risk area to the total area of the goaf is large. As the working face advances, the dangerous areas expand, exhibiting a trend of gradual stability when the length of the goaf exceeds approximately 600 m. The relationship between the area (S_f) of the dangerous range and the advancing distance (x) of the working face is expressed by the exponential function $S_f = a + b \cdot \exp\,(c \cdot x)(b < 0, c < 0)$.After nitrogen injection, the size of the spontaneous combustion risk areas of the goaf slightly changes in several model groups; the areas decrease by approximately 30% from the initial size before nitrogen injection.

5.2.3. Measures of Spraying Inhibitor. The oxygen volume fraction in some areas near the RCGSER roadway remains extremely high, but the tendency range is small. Hence, measures such as spraying inhibitor, grouting, and gel plugging can serve as effective controls. The area cannot be considered in the analysis of spontaneous combustion of residual coal. Therefore, the analysis of spontaneous combustion in the goaf can be interpreted according to the method of setting three zones of spontaneous combustion in the U-shaped ventilation goaf. Taking the working face advancing 800 m as an example, the risk analysis of spontaneous combustion was performed, as illustrated in Figure 14.

As shown in Figure 10, the position of the 15% oxygen volume fraction on the air inlet side in the gob is approximately 100 m away from the working face. The width of the cooling zone behind the working face is 20 m, as measured by the Chongqing Research Institute, and the width of the cooling zone along the RCGSER roadway was calculated as 15 m. The maximum width of the spontaneous combustion oxidation zone behind the working face is $L_m = 101 - 21 = 80$ m. Thus, the conditions for determining the risk of spontaneous combustion in the goaf are obtained as follows:

$$\tau_1 = \frac{L_m}{v_1} < \tau^*{}_1, \tag{6}$$

where L_m is the width of the spontaneous combustion oxidation heating zone in the goaf, m; v_1 is the propulsion degree of the working face, m/d; τ_1 is the oxidation time of the remaining coal in the goaf, d; τ_1^* is the shortest spontaneous ignition period, d.

According to Equation (6), the minimum safe propulsion speed (v_1^*) of coal face 9-1 is obtained as

$$v_1^* = \frac{L_m}{\tau_1^*} = 80/66 \approx 1.21. \tag{7}$$

Evidently, at the current daily advancement speed of 4 m on the working face, the goaf will not spontaneously ignite. However, when the working face encounters a fractured zone of a geological structure, such as a fault, the remaining amount of coal seam in the goaf will increase substantially, leading to a risk of spontaneous combustion. Hence, this value provides scientific guidance for preventing and controlling spontaneous combustion.

6. Conclusion

(1) The results of the closed oxygen consumption experiment are of great significance to determining the danger of spontaneous combustion in a goaf more accurately. The measured mine data as well as the results of the solid similarity model experiments and simulation were consistent. The distribution behavior of air leakage in the RCGSER goaf of the first mining face of Qipanjing Mine was also explored

(2) The areas with a spontaneous combustion tendency in the RCGSER goaf are mainly near the open-off cut, near the RCGSER roadway area, and a part behind the working face. The distribution form of the three parts changes dynamically as the working face advances. The prediction model of the dangerous area (S_f) of the gob and the advancing distance (x) of the working face is obtained as $S_f = a + b \cdot \exp\,(c \cdot x)(b < 0, c < 0)$

(3) The measures of nitrogen injection in the open-off cut and inhibitor injection along the RCGSER roadway are proposed and can transform the spontaneous combustion mode of a U + L ventilation goaf into a U ventilation spontaneous combustion mode.

In this case, the danger zone of spontaneous combustion in the RCGSER goaf remains in the natural oxidation zone behind the working face. According to the theory of three zones of spontaneous combustion in a goaf, the minimum daily safe propulsion degree of the mine is 1.2 m, which is less than the current daily propulsion speed by 4 m, and spontaneous combustion will not occur in the goaf

(4) Through a preliminary exploration of the new field of the RCGSER goaf coal spontaneous combustion prevention and control, this study establishes the distribution behavior of the spontaneous combustion danger area of the RCGSER goaf, and corresponding measures are proposed. However, proof of field practicability is lacking. In addition, U + L ventilation has various combinations of inlet and return air as well as different air inlet volume ratios, which should be explored soon

Data Availability

The data that support the findings of this study are available within the article. All data generated or analysed during this study are included in this published article [DOI: 10.6084/m9.figshare.19612983.v3].

Conflicts of Interest

Authors have no conflicts of interest to declare.

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