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Xiaowen Zhang (✉ [zxw502943580@163.com](mailto:zxw502943580@163.com))

Liaoning Technical University

Xihua Zhou

Liaoning Technical University

Gang Bai

Liaoning Technical University

Cheng Wang

Guoneng Ningxia Coal Mine Group Co., Ltd. Yangchangwan Coal Mine Yinchuan

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## Research Article

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# Influence of Air Supply on Coal Spontaneous Combustion During Support Withdrawal in Fully Mechanized Coal Mining and its Prevention

Xiaowen Zhang<sup>1,2</sup>, Xihua Zhou<sup>1,2</sup>, Gang Bai<sup>1,2</sup>, Cheng Wang<sup>3</sup>

<sup>1</sup>College of Safety Science & Engineering, Liaoning Technical University, Fuxin, Liaoning 123000, China. <sup>2</sup>Key Laboratory of Mine Thermodynamic Disasters & Control of Ministry of Education, Fuxin, Liaoning 123000, China. <sup>3</sup>Guoneng Ningxia Coal Mine Group Co., Ltd. Yangchangwan Coal Mine Yinchuan Ningxia 751409, China. email: zwx502943580@163.com

**Abstract:** It is important to study the oxidation characteristics of coal samples under different air supply rates to prevent spontaneous combustion of coal, particularly when the air supply rate at the working face needs to be changed during support withdrawal. In this work a self-designed temperature-programmed experimental device was used to study the change laws of various index gases released during the spontaneous combustion of coal under various air supply conditions. The study focused on the analysis of the low-temperature (30–200 °C) oxidation stage, the increase in air supply, and the concentration change process of four hydrocarbon gases (C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>2</sub>H<sub>2</sub>) generated by the coal sample. The change law of the CO generation rate under the combined effect of temperature and air supply was analyzed, and surface fitting was performed to determine the characteristics of phased changes. Based on the working face parameters of the Yangchangwan Coal Mine, this study predicted the CO concentration at the upper corner of the working face at the characteristic temperature of coal spontaneous combustion during the withdrawal period. The paper summarizes comprehensive safety measures that can help prevent spontaneous combustion during the withdrawal period.

## 1. Introduction

The spontaneous combustion of coal is detrimental to the safe operation of coal mines. This phenomenon not only causes wastage of resources and equipment damage, but can also lead to gas and coal dust explosions, induce secondary disasters, and cause serious casualties and property losses<sup>1–4</sup>. The goaf area is most prone to spontaneous combustion<sup>5</sup>. Particularly when mining is stopped during the support withdrawal period, a reduction in air supply exacerbates the heat dissipation condition behind the hydraulic support, easily leading to heat accumulation, which is a fundamental cause of fires in fully mechanized caving faces<sup>6,7</sup>. Because of the long working face and the large number of supports, the withdrawal period is too long. This provides sufficient time for the coal that remains in the goaf to fully oxidize and undergo spontaneous combustion. Therefore, an early prediction of spontaneous combustion during the withdrawal period, analysis of the influence of air supply on the combustion process, and effective measures are of great significance to the prevention and control of fires in coal mines.

Currently, the most effective and widely used measure to predict and prevent spontaneous combustions in the goaf is to predict the temperature of the goaf and the index gases accompanying the spontaneous combustion<sup>8–10</sup>. The combustion of coal is accompanied by the release of gases under the conditions of heat storage oxidation and high temperatures. The temperature-programmed experiment is an effective method to study the spontaneous combustion characteristics of coal. Related studies on the thermal oxidation of coal have shown that the concentration of the combustion products increases with the increase in the coal temperature<sup>11–13</sup>. Lu et al.<sup>14</sup>, Wu<sup>15</sup>, and Dong et al.<sup>16</sup>

found that as the oxidation temperature of coal samples increases in the experiment, the CO concentration exhibits an exponential increase trend with the increase in the coal temperature. In the initial stages of oxidation, the CO concentration increases gradually; however, when the coal temperature exceeds a certain critical temperature, the gas concentration rises rapidly.

Scholars have conducted related research on the influence of air supply on the spontaneous combustion of coal. Yuan and Smith<sup>17</sup> studied the effects of oxygen concentration in the air and the air supply rate on the spontaneous combustion of coal. They showed that under an initial temperature of 70 °C, changing the ventilation rate has no evident effect on CO production. Xu et al.<sup>18</sup> tested the spontaneous combustion characteristics of bituminous coal under different oxygen concentrations. As the oxygen concentration decreased, the temperature corresponding to four stages slightly increased. Rambha and Ren<sup>19</sup> conducted adiabatic oxidation experiments on dry coal samples at air inflow rates of 150, 200, and 250 mL/min. The coal sample was found to have a maximum oxidation potential at an airflow velocity of 200 mL/min. Więckowski et al.<sup>20</sup> showed that with the increase in the air flow, the ratio of CO/CO<sub>2</sub> produced by the spontaneous combustion of coal samples increases with temperature and that the flow rate has an impact on the index value.

However, the above studies mainly focused on the spontaneous combustion characteristics of coal under the condition of stable air supply in conventional mining, and the analyses were performed under the effects of temperature and air supply on the CO generation rate. In practice, the spontaneous combustion process of coal is affected by the coupling of temperature and air supply.

In this work, experimental coal samples were obtained from the Yangchangwan Coal Mine, which belongs to the Eastern Ningxia Mining Area, a billion-ton coal base in China accounting for a significant proportion of coal power supply. The natural fires in the goaf induced during the withdrawal of fully mechanized mining are a safety hazard. Therefore, this study developed a temperature-programmed experimental device to oxidize the coal sample, analyze the influence of the gas product concentration on the temperature under different air volume rates. Based on a prediction model for the upper-corner CO concentration combined with the actual site parameters, the paper summarizes effective measures that can be taken to prevent spontaneous combustion during the withdrawal period.

## 2. Analysis of CO concentration at upper corner when coal mining is halted

The source of CO at the corners of the fully mechanized mining face is analyzed. Most of the CO comes from the oxidation of leftover coal in the goaf, while a small amount comes from the release of broken coal bodies due to the advance of the working face, blasting, and influx of adjacent working areas<sup>21</sup>. Therefore, the CO concentration at the upper corner can be expressed as:

$$C_{co} = (W_1 + W_2)/Q_L \quad (1)$$

where  $C_{co}$  is the CO concentration at the upper corner of the working face (mol/m<sup>3</sup>),  $Q_L$  is the air leakage volume in the goaf (m<sup>3</sup>/s),  $W_1$  is the amount of CO released by the oxidation of the residual coal in the goaf per unit time (mol/s),  $W_2$  is the amount of CO produced by other factors (mol/s). When the working face is no longer advancing, the amount of  $W_2$  can be ignored. Therefore, the CO concentration expression for the upper corner can be written as follows:

$$C_{co} = W_1/Q_L \quad (2)$$

According to the theory of spontaneous combustion in three zones of the goaf<sup>22,23</sup>, the amount of CO produced by the oxidation of the residual coal in the goaf  $W_1$  is expressed as:

$$W = 10^6(\alpha X_1 + \beta X_2)S(1 - \eta)\varphi_{CO} \quad (3)$$

where  $\alpha$  is the oxidation correction coefficient of the leftover coal in the heat dissipation zone, which is typically in the range of 0.3–0.5 for fully mechanized mining faces;  $X_1$  is the width of the heat dissipation zone, m;  $\beta$  is the oxidation correction coefficient of the leftover coal in the oxidation zone, which is in the range of 0.8–1.0 under normal air leakage conditions (when the air leakage rate is <1%,  $\beta$  is <0.5);  $X_2$  is the width of the oxidation zone, in m;  $S$  is the cross-sectional area of the coal seam in the working face, m<sup>2</sup>;  $\eta$  is the recovery rate of the coal seam in the working face, %.  $\varphi_{CO}$  is the release rate of CO, mol/(cm<sup>3</sup>·s).

The expression for the CO concentration at the upper corner of the working surface when mining is halted and supports are being withdrawn is:

$$C_{CO} = 10^6(\alpha X_1 + \beta X_2)S(1 - \eta)\varphi_{CO}/Q_L \quad (4)$$

where  $\varphi_{CO}$  can be measured from the coal oxidation temperature experiment, based on the CO generation rate model of the temperature-programmed experiment<sup>5</sup>:

$$\varphi_{CO} = \frac{C_{CO}^2 q \ln a}{AL \left[ 1 - a^{-\frac{1}{a}} \right]} \quad (5)$$

where  $\varphi_{CO}$  is the CO production rate, mol/(cm<sup>3</sup>·s);  $a$  is the ratio of the oxygen concentration at the entrance  $C_{O_2}^1$  to the oxygen concentration at the outlet  $C_{O_2}^2$ ;  $C_{CO}^2$  is the outlet CO concentration, mol/cm<sup>3</sup>;  $A$  is the cross-sectional area of the coal sample tank, cm<sup>2</sup>;  $q$  is the air supply rate of the experimental system, mL/s;  $L$  is the height of the coal in the coal sample tank, cm;

The volume concentration of  $O_2$  and CO at the inlet and outlet of the coal sample tank measured in the experiment is converted to the mass concentration by molar mass and substituted into the formula. The CO generation rate  $\varphi_{CO}$  of the coal at different oxidation temperatures can be obtained. Combined with the actual parameters of the working face at the site<sup>24</sup>, the predicted value of the CO concentration at the upper corner corresponding to different characteristic temperatures during the withdrawal period of fully mechanized mining can be derived. Therefore, a coal temperature program test was implemented to analyze the gas release law of the coal samples at different characteristic temperatures.

### 3. Coal oxidation temperature-programmed experiment

#### 3.1 Experimental system and method

To analyze the influence of air supply on the process of coal carbon oxidation, an oxidation temperature-programmed chromatographic analysis test was conducted using the developed temperature-programmed experimental device. Fig 1 shows the experimental system comprising four parts: gas circuit, coal sample, heating temperature control, and data collection. The experimental coal samples were obtained from the 20606 working face of Yangchangwan Coal Mine. After being packaged and transported to a laboratory peeling surface, they were crushed using a jaw crusher. The samples were then sieved to sizes of 0–0.5, 0.5–0.9, 0.9–3, 3–5, and 5–8 mm using a vibrating sieve machine, and a total of 1 kg was mixed based on the mass ratio and loaded into the coal sample tank which has a diameter of 9.2 cm and a height of 25 cm.

The coal sample tank was placed in an insulating sleeve, and the heating tube in the cylinder surrounded the coal sample tank body for heating. Rock wool was attached to the inner wall of the

sleeve to reduce the heat exchange between the internal heating tube and the external environment. The coiled arrangement of the intake copper pipe on the outside of the coal sample tank ensured that the intake air fully preheated the upper end of the coal sample tank and the lower end exhausted to the external chromatograph. The heating tube was controlled using an external XMTD temperature control module to control the heating temperature and heating rate. A K-type armored thermocouple was inserted in the tank to monitor the temperature of the coal sample, and the software recorded the temperature data in real time.

From the similarity theory, the temperature-programmed experiment can produce a law similar to that of the actual coal spontaneous combustion point gas release in the goaf<sup>25</sup> before the experiment, ventilate the air, and check the air tightness of the device. According to literature<sup>26</sup>, the upper and lower limits of the air supply flow rate for the oxidation temperature test should be set to 40 and 200 mL/min, respectively. At the beginning of the experiment, the pressure reducing valve of the high-purity air cylinder was opened, and the air pressure was adjusted to 0.1 MPa. The flow rate of the rotameter in each experiment was set to 40, 80, 120, 160, and 200 mL/min. The heating rate of the heating device was set to 1 °C/min. After the air was heated and reacted with the coal sample through the coal sample tank, the gas sample was collected through the drying tube and placed in a GC4000A chromatograph for analysis. The gas products were recorded once every at 5 °C from 30 to 200 °C and every 50 °C from 200 to 600 °C.



**Figure 1** Temperature-programmed experimental system for coal oxidation

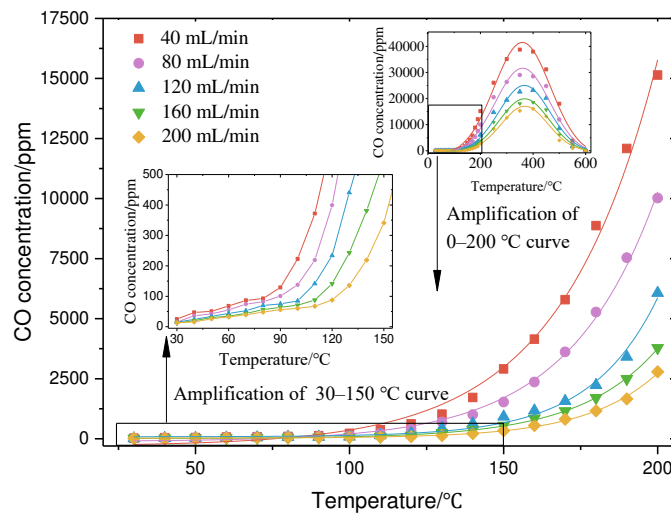
### 3.2 Experimental results

#### (1) CO concentration

The CO concentration was detected by the chromatographic TCD detector. From the result, the CO volume concentration data generated by each coal sample during the spontaneous combustion process were curve-fitted, and the CO concentration released by the coal samples under different air supply conditions was obtained, as shown in Fig 2. The figure shows that the entire oxidation process exhibits a Gaussian function distribution under different air supply conditions

For the early warning of coal spontaneous combustion, the focus should be on the analysis in the low-temperature (30–200 °C) oxidation stage. In this stage, the distribution of the CO concentration  $C_{CO}$  can be fitted using an exponential function  $C_{CO} = a + be^{-T/c}$  with

temperature  $T$ , where  $C_{CO}$  is in ppm, and  $T$  is in  $^{\circ}\text{C}$ . Table 1 lists the parameter values. From the concentration change curve, the low-temperature oxidation and heating process of the coal sample can be divided into two stages: a stable heat storage stage and an accelerated oxidation stage. The critical temperature of CO release is typically used to divide the two stages<sup>27</sup>. Fig 2 shows a comparison of the CO concentration release laws of the same coal sample under air volume rates of 40, 80, 120, 160, and 200 mL/min. CO gas can be detected at a low temperature of 30  $^{\circ}\text{C}$ , and it is inferred that a part of the CO gas adsorbed inside the coal body is released. It is verified that even a small amount of CO gas can be detected under normal conditions where spontaneous combustion does not occur at the site. When the air supply rate is set to 40, 120, and 200 mL/min, the CO concentration released by the coal sample increases significantly after 90, 100, and 120  $^{\circ}\text{C}$ , respectively. After this temperature, the rate of increase in the CO concentration increases sharply, and it develops toward deep oxidation. This shows that the critical temperature of CO release increases with the increase in the air volume.



**Figure 2** Variation curve of the CO concentration in the spontaneous combustion process of coal samples under different air volume rates

**Table 1** Curve parameters of CO concentration varying with temperature under an air volume rate of 40–200 mL/min

Parameters	Air volume rate (mL/min)				
	40	80	120	160	200
a	-308.37	-112.89	83.94	12.65	24.55
b	28.17	9.74	0.59	1.40	0.45
c	-31.51	-28.68	-21.78	-25.35	-22.99

## (2) Hydrocarbon gas concentration

The concentration of the hydrocarbon gases was detected using a chromatographic flame ionization detector. Four types of typical hydrocarbon gases were selected: saturated hydrocarbon  $\text{C}_2\text{H}_6$ ,  $\text{C}_3\text{H}_8$ , unsaturated hydrocarbon  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_2$ . An analysis of the concentration test results shows that the gas concentration changes with the coal temperature

under different air supply conditions, as shown in Fig 3. The release concentrations of the four hydrocarbon gases decrease with increasing air volume rate. Fig 4 shows the relationship between the initial temperature of the four hydrocarbon gases and the air volume rate.

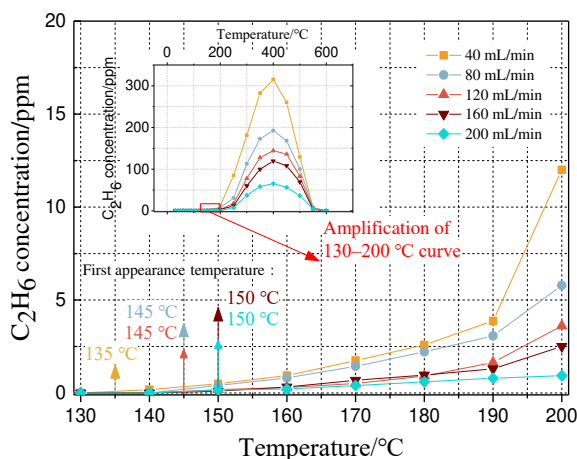
The initial temperatures of  $C_2H_6$  and  $C_3H_8$  under different air volume rates are relatively close, at  $135\text{ }^\circ\text{C}$ , under the minimum air supply condition of  $40\text{ mL/min}$ . When the air supply is increased to a maximum of  $200\text{ mL/min}$ , the initial temperatures of  $C_2H_6$  and  $C_3H_8$  increase to  $150\text{ }^\circ\text{C}$  and  $160\text{ }^\circ\text{C}$ , respectively.

In the low-temperature oxidation stage, the critical temperature for the accelerated release of the  $C_2H_6$  and  $C_3H_8$  gases under different air volume rates is in the range of  $180\text{--}200\text{ }^\circ\text{C}$ . Above this temperature, the coal oxidation reaction intensifies, and the concentrations of the  $C_2H_6$  and  $C_3H_8$  gases produced increase sharply. Above  $400\text{ }^\circ\text{C}$ , the  $C_2H_6$  and  $C_3H_8$  gas produced by the coal drops sharply after reaching the peak value. At this stage, the combustion state of the coal sample begins to weaken.

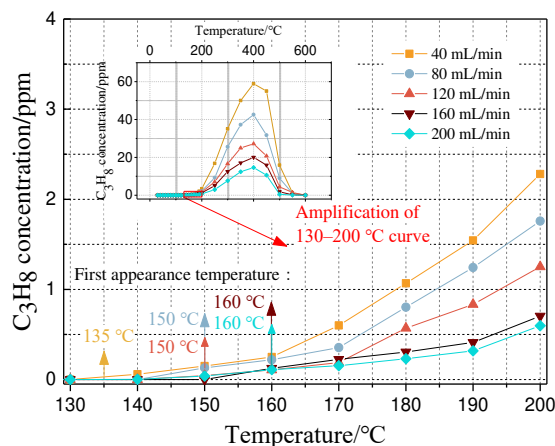
Fig 3(c) shows that the initial temperature of  $C_2H_4$  is the lowest,  $120\text{ }^\circ\text{C}$  at  $40\text{ mL/min}$ . When the air volume rate increases to  $120\text{ mL/min}$ , the initial temperature rises to  $140\text{ }^\circ\text{C}$ . The initial temperature of  $C_2H_4$  remains unchanged at  $140\text{ }^\circ\text{C}$  when the experimental air supply continues to increase; The initial temperature of the  $C_2H_4$  gas under different air volume rates is the lowest, making it a suitable index gas to judge the combustion temperature status in advance.

Fig 3(d) shows that the concentration of the  $C_2H_2$  gas produced is much lower than those of the other hydrocarbon gases. When  $C_2H_2$  gas is detected, the coal temperature is over  $220\text{ }^\circ\text{C}$ , which makes it unsuitable as an indicator gas for the early prevention of coal spontaneous combustion.

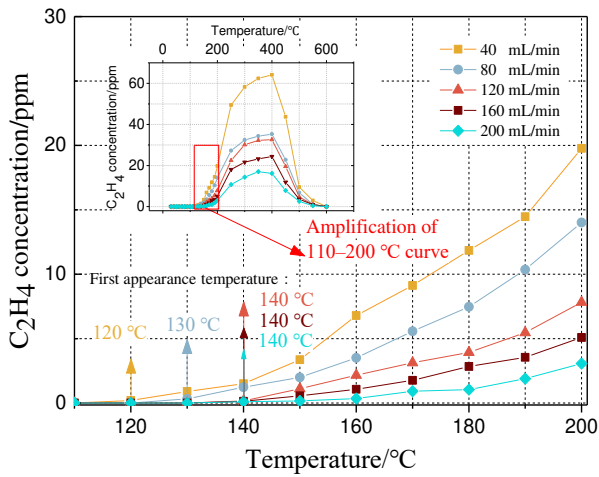
In summary, at higher air volumes, the heat generated by coal combustion is dissipated more easily, and the coal–oxygen recombination reaction rate decreases. As a result, as the air volume rate increases at the same temperature, the release concentrations of the four hydrocarbon gases decrease. The initial temperatures of these gases lag due to the increase in the air volume rate.



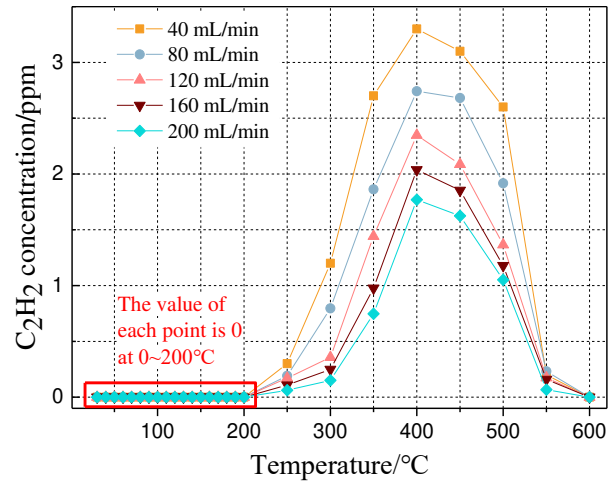
(a) Relationship between  $C_2H_6$  concentration and temperature



(b) Relationship between  $C_3H_8$  concentration and temperature

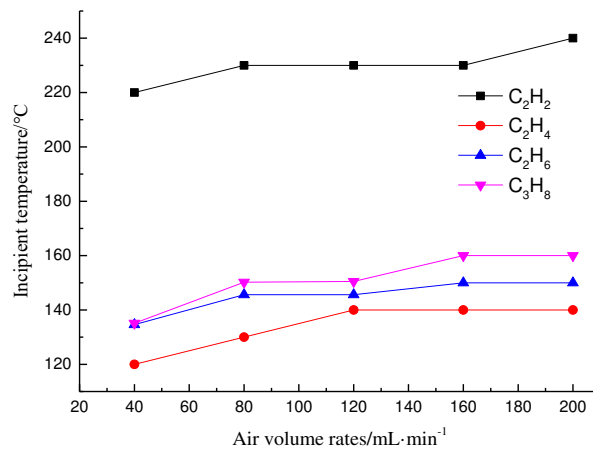


(c) Relationship between  $C_2H_4$  concentration and temperature



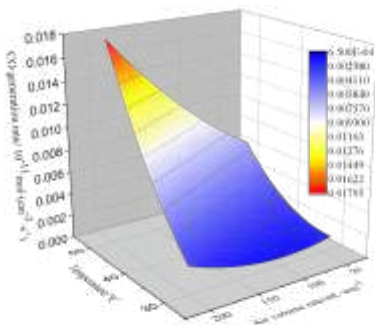
(d) Relationship between  $C_2H_2$  concentration and temperature

**Figure 3** Relationship between gas concentration and temperature under an air volume rate range of 40–200 mL/min

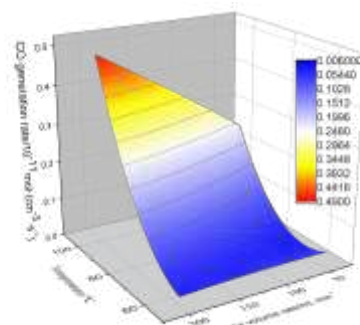


**Figure 4** Variation in the first appearance temperatures of  $C_2H_6$ ,  $C_3H_8$ ,  $C_2H_4$ , and  $C_2H_2$  under different air volume rates

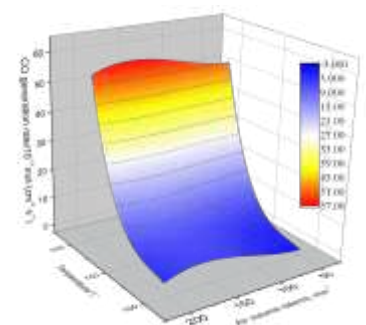
(3) CO generation rate



(a) Stage 1: Temperature range 30–50 °C, air volume rate 40–200 mL/min



(b) Stage 2: Temperature range 50–100 °C, air volume rate 40–200 mL/min



(c) Stage 3: Temperature range 100–200 °C, air volume rate 40–200 mL/min

**Figure 5** Variation in the CO production rate of the coal samples with temperature and air volume



The measured CO generation rate varies with the temperature and air supply. The experimental results have the characteristics of stages. Based on the magnitude and change law of the CO generation rate, it can be divided into three stages. Fig 5 shows the 3D surface of the air volume rate and temperature on the combined effect of  $\varphi_{CO}$ .

The temperature range corresponding to the first stage is 30–50 °C, as shown in Fig 5(a). The CO production rate in this stage shows a gradual upward trend with the increase in the temperature and air volume rate. At 40 mL/min, the CO production rate increases with temperature from  $0.00106 \times 10^{-11}$  mol/(cm<sup>3</sup>·s) to  $0.00681 \times 10^{-11}$  mol/(cm<sup>3</sup>·s). At 200 mL/min, the CO production rate increases with temperature from  $0.00155 \times 10^{-11}$  mol/(cm<sup>3</sup>·s) to  $0.01674 \times 10^{-11}$  mol/(cm<sup>3</sup>·s). Increasing the air supply will increase the CO generation rate at the same temperature. In this stage, the CO production rate is low and unstable. The main source of CO production is that coal molecules produce a large number of bond breaks due to external forces, which react with oxygen. The regular change in the CO gas produced obeys a binary quadratic polynomial distribution. At this stage, the quantitative relationship equation for the CO production rate  $\varphi_{CO}$ , temperature  $T$ , and air supply  $Q$  can be fitted as follows:  $\varphi_{CO} = 1.93e-2-9.85e-4T-1.29e-4Q+1.39e-5T^2+1.65e-7Q^2+3.25e-6TQ$ .

The temperature in the second stage corresponding to the relationship between the CO generation rate and the combined effect of air volume rate and temperature is between 50 and 100 °C, and the rate of change in the CO generation rate in this stage is significantly higher than that in the first stage. The influence law of the temperature and air volume rate on the generation rate is consistent and positively correlated with the first stage. When the air volume rate is 40 mL/min, the CO generation rate increases with the temperature, from  $0.0082 \times 10^{-11}$  mol/(cm<sup>3</sup>·s) to  $0.22683 \times 10^{-11}$  mol/(cm<sup>3</sup>·s). At 200 mL/min, the CO generation rate increases from  $0.0266 \times 10^{-11}$  mol/(cm<sup>3</sup>·s) to  $0.48343 \times 10^{-11}$  mol/(cm<sup>3</sup>·s). This shows that the source of CO production in this stage is affected by coal–oxygen recombination, exhibiting an accelerated reaction trend. This inference is mainly due to the cleavage of the surface functional groups of the coal molecules and the recombination of oxygen to produce CO gas. The entire curve change in this stage also obeys the binary quadratic polynomial equation, and the quantitative relationship equation can be fitted as:  $V_{CO} = 8.97e-1-2.64e-2T-1.84e-3Q+1.92e-4T^2-6.37e-7Q^2+3.56e-5TQ$ .

The third stage of the change in the CO generation rate of the coal samples corresponds to a temperature between 100 and 200 °C, as shown in Fig 5(c). Under the same temperature conditions, when the air volume rate increases from 40 mL/min to 120 mL/min, the CO generation rate increases with the increase in the air volume rate. When the air volume rate is increased from 120 mL/min to 160 mL/min, the CO generation rate remains largely unchanged. Under the same conditions of 200 °C and air volume rates of 120, 160, and 200 mL/min, the  $\varphi_{CO}$  values are 58.50042, 60.24115, and 54.45101 mol/(cm<sup>3</sup>·s), respectively. At this time, the air supply is increased, and the air leakage is close to the upper limit. A state of inhibited oxidation can be observed, which decreases the oxidation rate. This shows that the inhibitory effect of air supply on the CO generation rate is mainly reflected in the accelerated CO release stage. The data in this stage obey the binary cubic surface equation, which can be fitted as:  $\varphi_{CO} = -137.55+3.41T-2.87e-2T^2+8.21e-5T^3-0.13Q+2.07e-3Q^2-7.08e-6Q^3$ .

## 4. Application and countermeasures

### 4.1 Overview of working face

The average coal seam thickness of the 20606 working face is 3.48 m, and the design

mining height is 2.9 m. A fully mechanized mining method is adopted, and the roof is managed using caving methods. The inclined length of the working face is 247.3 m, and the length of the working face can be 1570 m. A U-shaped full air pressure upward ventilation is adopted during the working face. The actual air distribution rate is approximately 897 m<sup>3</sup>/min, and the air leakage rate of the goaf is measured to be 32 m<sup>3</sup>/min.

#### 4.2 Three-zone observation and prediction calculation

To study the distribution of the oxygen concentration in the goaf of the 20606 working face, monitoring points were pre-arranged at the inlet and return air sides of the goaf in the initial stage of the working face. As the working face advances, a downhole special suction pump is used to pass through the embedded bundle pipe. The gas is collected, and the oxygen concentration at different distances from the measuring point in the goaf to the working surface is analyzed. Based on the judgment theory for areas prone to spontaneous combustion [5,23], the oxygen volume fraction in the heat dissipation zone is greater than or equal to 18%; the oxygen volume fraction in the oxidation heating zone is 18% to 8%; the oxygen volume fraction in the asphyxiation zone is <8%. The measured O<sub>2</sub> volume fraction varies with the advancing distance of the working surface, as shown in Fig 6.

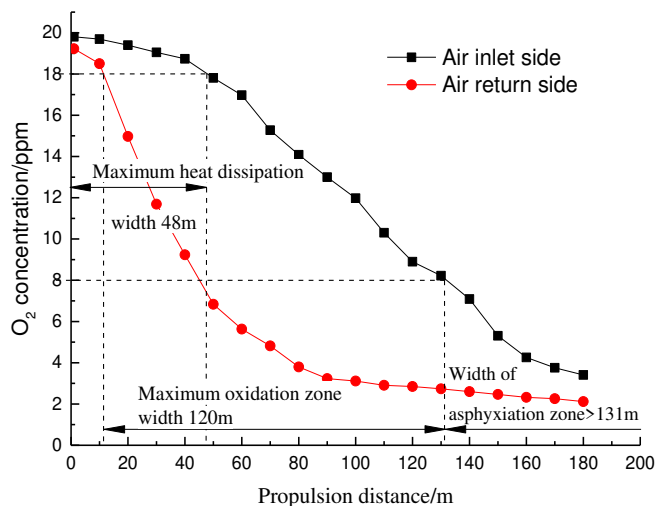


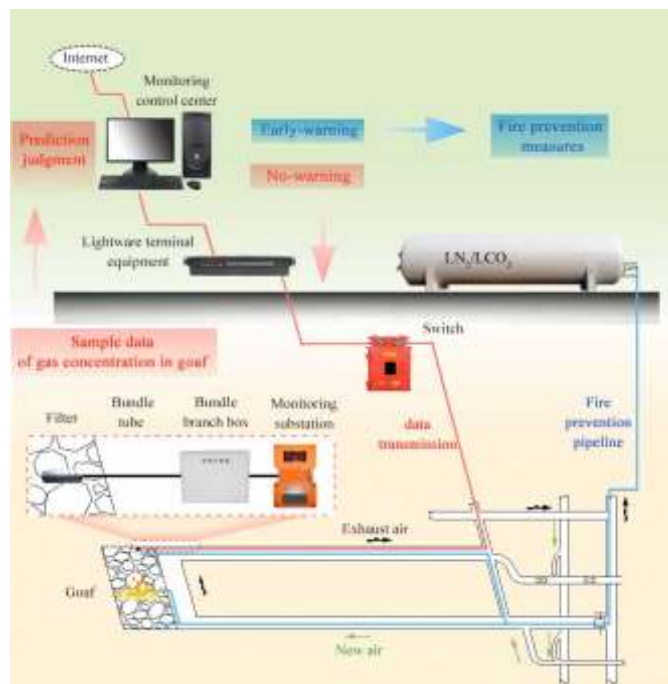
Figure 6 Three-zone division of the goaf in the 20606 working face

The measured oxygen concentration index at the 20606 working face is divided into a “three zone” range of the goaf spontaneous combustion: the maximum width of the heat dissipation zone is 48 m on the inlet side; the width of the heat dissipation zone on the inlet side is 48–131 m, and the width of the oxidation zone is 48–131 m on the return side. The width of the oxidation zone is 11–45 m, and the maximum width of the oxidation zone is 120 m. Based on the actual measured oxygen concentration and air leakage conditions, the CO concentration at the upper corner of the working face calculated using Equation (4) should be lower than 44.6 ppm for a coal temperature of 30 °C when mining is stopped at the 20606 working face. The lowest critical temperature of accelerated oxidation is 90 °C. The upper-corner CO concentration should be lower than 873.5 ppm.

### 4.3. On-site response measures

The experimental results of this study show that, in the low-temperature heat storage stage of coal spontaneous combustion, reducing the air volume rate can help reduce the rate of CO generation and decelerate the combustion process. To reduce the spread of air leakage to the goaf during the suspension and withdrawal period, the air volume supply can be reduced under the condition of meeting the minimum air volume of the working face, and a wind screen can be installed in the auxiliary lane.

When mining at the working face is close to the stop line, the working face should be recovered along the roof as much as possible to minimize the amount of floating coal in the goaf and reduce the risk of spontaneous combustion.



**Figure 7** Monitoring linkage system for fire prevention and extinguishing at the working face

Using a laser beam tube monitoring system, the gas analysis and calibration can be controlled via a computer, and the analysis results can be transmitted to the ground through an optical fiber to realize the automation of the monitoring and analysis and display the real-time changes in the data. Currently, inert gas fire extinguishing has been widely used in the field of mine fire prevention. Injecting low-temperature inert liquid can effectively reduce the oxygen concentration and temperature in the goaf, which significantly delays the oxidation process of the remaining coal and provides sufficient time for the withdrawal of the rack. As shown in Fig 7, inerting firefighting pipelines are pre-embedded from the final mining line to the goaf to prevent and control areas prone to spontaneous combustion during the withdrawal period. The inertia injection firefighting system is linked through the ground dispatch center. Underground real-time monitoring and monitoring data analysis, which has the highest efficiency for controlling any fire situations in the goaf, can improve the safety of the final mining and reduce the need to take drastic prevention measures during the suspension and withdrawal period.

## 5. Conclusions

This study conducted temperature-programmed experiments on coal samples collected from the Yangchangwan Coal Mine. The results showed that changing the air supply conditions has a significant impact on the development of coal spontaneous combustion. An analysis of the experimental results in the low-temperature (30–200 °C) oxidation stage under different air volume rates showed that, under the same air supply conditions, the generated CO concentration increases with the increase in the coal temperature, following a power-exponential function. With the increase in the experimental air volume rate, the concentrations of the released hydrocarbon gases decreased, and their initial temperatures showed a hysteresis phenomenon. Under the influence of different air volume rates, the lowest initial temperature of C<sub>2</sub>H<sub>4</sub> was found to be 120–140 °C, and the highest initial temperature of the C<sub>2</sub>H<sub>2</sub> gas was in the range of 220–240 °C. The C<sub>2</sub>H<sub>4</sub> gas was most suitable as the indicator gas for the early warning of coal spontaneous combustion.

The change law of the CO generation rate under the combined effect of air volume rate and temperature could be divided into three stages based on the change magnitude and law. The corresponding temperature ranges are 30–50, 50–100, and 100–200 °C. In the first and second stages, the CO production rate showed a gradual upward trend with the increase in the temperature and air volume rate. In the third stage, the CO production rate increased with increasing temperature; however, at the same temperature, with the increase in the air volume, it first increased and then decreased. The inhibitory effect of increasing the air volume rate on CO release from coal oxidation is mainly reflected in the third stage of accelerated CO release.

The paper summarized comprehensive measures that can help prevent spontaneous combustion during the support withdrawal period, reduce the air leakage in the goaf during this period, reduce the amount of remnant coal, and enable real-time monitoring. Pre-arranged measures, such as a linkage system for firefighting, can help prevent/extinguish fires in a timely manner. Put together, these measures can ensure a smooth progress of the support withdrawal operation in coal mines.

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## Author contributions

X.Z: experiment, analysis, writing. X H: guidance, providing fund support. G.B: guidance. C.W: field data collection

## Competing interests

The authors declare no competing interests.

Correspondence and requests for materials should be addressed to X.Z.