

Article

The Influence of the Fire Point on the Thermal Dynamic Disaster in the Goaf

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Abstract: A thermal dynamic disaster in the goaf is one of the most serious coal mine disasters formed by coal spontaneous combustion and gas interweaving. However, the influence of the high-temperature hidden fire source formed in the goaf on the evolution law of thermal dynamic disasters is not clear, and effective prevention and control measures cannot be taken. Therefore, this paper uses the experimental platform of thermal dynamic disaster in the goaf to study the influence of different fire point positions on the development of thermal dynamic disaster in the goaf through a similar simulation experiment of thermal dynamic disaster evolution in the goaf and analyzes the corresponding relationship between temperature and CO concentration in the upper corner. The results show that under different locations of heat source, the high-temperature heat source of coal spontaneous combustion migrates to the air leakage side with sufficient oxygen supply, and an oxygen-poor circle is formed near the ignition point. Under the action of air leakage flow, CH₄ accumulates in the deep part of the goaf on the return air side. Due to the increase in coal, part of CH₄ is produced, which leads to the increase in concentration of CH₄ at the ignition point. Under the action of different heat sources, the changing trend of concentration of CO and temperature in the return air corner is the same, but the temperature change in the return air corner shows a lag compared with the change in the concentration of CO, so concentration monitoring of CO can reflect the evolution process of the fire field in the goaf more quickly than temperature monitoring.

Keywords: thermal dynamic disaster; coal spontaneous combustion; CO; CH₄



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1. Introduction

In the past 20 years, China's energy structure has gradually diversified, and the proportion of coal consumption has declined. However, its position as the main body and basic energy is difficult to change in a short period, and it will still play a critical role in ensuring national energy security and sustained and healthy economic development [1]. With the increase in mining depth, the complex mining environment such as high ground temperature, high ground stress, high gas, and low permeability is becoming more and more prominent. The risk of thermal dynamic disasters, exemplified by coal spontaneous combustion and gas-related calamities, is escalating. The superposition of multiple factors threatens the safety production of coal mines seriously [2]. Thermal dynamic disasters in coal mine goaves are primarily caused by the interaction over time and space of coal spontaneous combustion, gas, and coal dust, among which the coupling of gas and coal spontaneous combustion is the most serious. In recent years, thermal power disasters in the goaf have occurred from time to time and caused serious casualties. At present, there is still a risk of thermal power disasters in coal mines, and no effective containment measures have been put forward. It can be seen that the prevention and control of thermal dynamic disasters in the goaf is particularly important in the process of coal seam mining.

The gas flow field in the goaf determines the distribution characteristics of oxygen and gas, which in turn affects the formation of coal spontaneous combustion and gas

compound disasters [3]. Because the mine goaf is filled with collapsed coal gangue, the on-site personnel cannot enter, which leads to people's inability to understand the actual situation in the goaf. The numerical simulation method can make up for the monitoring problems in the coal mine site and can help to understand the characteristics of gas flow and temperature distribution in the goaf [4–6]. Ma et al. [7] simulated the air leakage intensity and coal spontaneous combustion risk in an adjacent goaf through gas monitoring and numerical simulation. Xia et al. [8] extended the coal spontaneous combustion model to a symbiotic model between gas and coal spontaneous combustion and pointed out that increasing the air volume can dilute the gas concentration in the return airway and the working face, but it will increase the risk of coal spontaneous combustion in the goaf. Considering the coupling mechanism of coal oxidation and gas flow, Cheng et al. [9] studied the distribution law of gas explosion danger zones in the goaf under different air volumes and gas emission rates and found that the large-scale void space of the roof is the main area of gas accumulation and explosion. Xia et al. [10] constructed a gas–solid coupling model of the goaf and quantitatively studied the gas migration law in the process of coal spontaneous combustion in the goaf. Based on the established division method of the risk area for coal spontaneous combustion and gas compound disasters, the influence of gas extraction in the goaf on the risk area was studied. The results show that gas extraction increases the risk of compound disaster in the goaf and expands the distribution range of risk areas. Lei et al. [11] constructed a dynamic model of oxidation heating of coal spontaneous combustion in the goaf based on deformation geometry through numerical simulation and obtained the evolution and migration law of the seepage field, oxygen concentration field, temperature field, and high-temperature zone of coal spontaneous combustion in the goaf during the advancing process of the working face. During the process of coal spontaneous combustion, heat is transferred to the surrounding gases, and forms a density difference between the coal spontaneous combustion fire area and the surrounding environment, which eventually affects the gas migration near the coal spontaneous combustion in the goaf [12].

Gas migration is the key process leading to gas explosion. When the gas in the goaf migrates to the location of the coal spontaneous combustion point and reaches its flammable limit, it can be ignited by the high temperature of the fire source of coal spontaneous combustion [13–17]. Therefore, it is necessary to study the law of gas migration in a coal spontaneous combustion environment to reveal the formation mechanism of compound disasters [18]. Shi et al. [19] revealed the mechanism of a gas explosion caused by fire zone closure through numerical simulation. In the process of fire zone closure, the airflow in the fire zone gradually decreases, and the air flows out through the air inlet in the later stage. The return air side of the coal spontaneous combustion fire zone is prone to gas explosion accidents. In addition, gas extraction is considered to be an effective method to control high-concentration gas in the goaf. Although the numerical simulation method can be used to study the gas distribution characteristics in the goaf, it is difficult to analyze the gas migration process in the coal spontaneous combustion environment. The physical similarity simulation experiment can restore the actual conditions of the coal mine goaf to a certain extent and provide a new way of analyzing the gas migration process in the goaf [20–22]. Li et al. [23] built a simulation test bench for a fully mechanized caving goaf and found that gas accumulation easily occurs near the high-temperature fire source in the goaf. Zheng et al. [24] analyzed the coupling evolution law of air and temperature fields in the goaf by building a similar simulation experiment platform in the goaf. Influenced by a high-temperature heat source, oxygen in the air is affected by the chimney effect, which accelerates the mixing with accumulated gas. Su et al. [25,26] built a three-dimensional physical model of the goaf and tested the influence of air volume on the oxygen concentration in the goaf. The above physical similarity experiment has mastered the law of gas flow in the goaf to a certain extent. However, the influence of the coal spontaneous combustion fire zone is not considered, so it is difficult to study the law of gas migration in a coal spontaneous combustion environment.

With the deepening of the research on the compound disaster of coal spontaneous combustion and gas, the mechanism and conditions of the formation of various disasters have been gradually clarified. However, given the specific environment of the goaf, the existing research on coupling disasters is mostly based on numerical simulation and theoretical analysis. At the same time, it is restricted by field conditions and lacks practical verification. Therefore, it is the key to further improve the relevant research content to study the evolution process of thermal dynamic disasters using experimental testing and to quantitatively characterize the critical conditions of thermal dynamic disasters in the goaf based on the evolution process.

In this paper, by using the evolution experiment of thermal dynamic disasters, the evolution law of the gas field and temperature field in the development process of thermal dynamic disasters is studied, the evolution characteristics of the temperature field and gas concentration field in the goaf after the formation of high temperature is obtained, and the corresponding relationship with the upper corner temperature and CO concentration is analyzed. The evolution process of thermal dynamic disasters in the goaf is deduced. Based on the air leakage rate and heat loss rate in the goaf, the criterion of gas explosion disasters induced by coal spontaneous combustion in the goaf is proposed.

2. Experiments and Methods

2.1. Experimental System

A self-designed experimental platform for thermal dynamic disasters in the goaf is used in this paper, as shown in Figure 1. This platform can be used to simulate the evolution process of coal spontaneous combustion and gas composite disasters in the goaf and for multi-parameter measurement. The experimental platform of the thermal dynamic disaster is mainly composed of the ventilation system, gas supply system, heating system, temperature acquisition system, gas sample collection and analysis, and pressure and pressure difference monitoring. The gas supply system is composed of a gas cylinder, a flow controller, a gas mixing tank, a one-way valve, and a gas purifier. Nitrogen, air, and methane are used as gas sources, and a high-precision gas flow controller is used to adjust the input flow of each gas. By changing the inlet flow ratio, each component gas is fully mixed in the gas mixing tank to obtain a gas supply source with different concentration ratios, and the gas explosion test induced by coal spontaneous combustion under different gas concentration conditions is realized. The heating control system can simulate the heating process of coal spontaneous combustion in the goaf (Figure 2). The heating control system is mainly composed of a heating rod and a temperature control cabinet. The heating rod simulates the heating process of coal in the form of a point heat source, and the superheated thermocouples and power supply line are connected to the temperature control cabinet to realize the heat release control of different heating rates, temperature ranges, and power. The temperature acquisition system is realized by arranging temperature sensors in the coal seam. The temperature measuring points include K-type thermocouples and protective casings, which can be connected to the temperature acquisition instrument through the bottom connection port to realize automatic temperature field acquisition. The gas acquisition module analyzes the gas samples at the measuring points. During the experiment, the syringe is used to collect the gas samples in the goaf at regular intervals, and the gas samples are analyzed by gas chromatography to realize the collection of the gas distribution law in the goaf during the experiment.



Figure 1. Experimental platform of thermal dynamic disaster in the goaf.

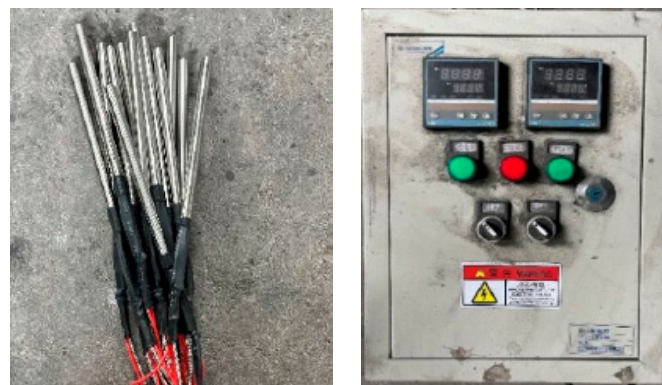


Figure 2. Control heating system.

2.2. Experimental Methods

2.2.1. Experimental Samples

The strike length of the 40204 working face in Dafosi Coal Mine is 1871 m, the inclined length is 220 m, and the average recoverable thickness is 10 m. The backward longwall comprehensive mechanized top coal caving mining method is adopted. The coal cutting height of the working face is 3.5 m, the coal caving height is 6.75 m, and the roof is managed by the whole caving method. The coal spontaneous combustion tendency grade is class I easy spontaneous combustion coal seam, and the spontaneous combustion period is from March to May. At the same time, coal dust has the risk of explosion. The fresh massive coal samples from the 40204 working face of the Dafosi Coal Mine were sealed with woven bags and sent to the laboratory. The broken coal tools were used for crushing, 0.5~1 cm, 1~2 cm, and 2~3 cm particle sizes were selected by different aperture sieves into woven bags, and the labels were affixed for backup. The industrial analysis data of coal samples in the 40204 working face of Dafosi Coal Mine are shown in Table 1.

Table 1. Industrial analysis data of coal samples.

Coal Samples	M_{ad} (%)	A_{ad} (%)	V_{daf} (%)	C (%)
40204 working face of Dafosi Coal Mine	4.37	16.78	23.55	55.3

2.2.2. Goaf Model

The overall size of the goaf model is set as $1.2 \text{ m} \times 1.2 \text{ m} \times 0.6 \text{ m}$. To be similar to the actual situation in terms of the similarity of geometrics and dynamics, the geometric similarity ratio between the model and the actual working face is 1:150. To prevent the heat loss of coal spontaneous combustion caused by direct contact heat transfer between the bottom of the model and the coal body, a porous insulation partition made of aluminum

silicate ceramic fiber is embedded at the bottom of each frame unit as the floor of the goaf. The caving zone is composed of broken coal and rock mass. To simulate the multi-void space in the goaf, according to Equations (1) and (2), the height of the filling caving zone required by the model is 12 cm and the height of the fracture zone is 36 cm [27].

$$H_k = \frac{100 \times M_1}{5.45 \times M_1 + 5.82} \pm 3.15 \quad (1)$$

$$H_1 = \frac{100 \times M_1}{2.32 \times M_1 + 0.8} \pm 2.35 \quad (2)$$

where H_k is the height of the caving zone; H_1 is the height of the fracture zone; and M_1 is the height of the working face. According to the distribution characteristics of an “O”-type circle of caving coal and rock in the goaf, the porosity of coal and rock accumulation is related to the expansion coefficient, which is

$$K_p(x, y) = k_{p,min} + (K_{p,max} - K_{p,min}) \exp\{-a_1 d_1 \times [1 - \exp(-\zeta_1 a_0 d_0)]\} \quad (3)$$

$$\varepsilon_p = 1 - \frac{1}{K_p(x, y)} \quad (4)$$

$$H = \frac{M_1 \times K_p(x, y)}{K_{p,max} - 1} \quad (5)$$

where ε_p is the caving coal rock porosity of goaf caving; H is the height of caving space in the goaf; $K_p(x, y)$ is the expansion coefficient of the caving coal and rock mass in the goaf; $K_{p,max}$ is the initial value of the bulking coefficient of the caving coal rock mass; and the value is 1.68. $k_{p,min}$ is the broken expansion coefficient of caving coal and rock mass after compaction, take 1.25; M_1 is the mining height of the working face; a_0 and a_1 are the attenuation rate of the broken expansion coefficient of the caving coal and rock mass from the two sides of the roadway and the working face, respectively; d_0 and d_1 are the distance from any point in the goaf to the two sides of the roadway and the working face, respectively; and ζ_1 is the adjustment coefficient that controls the distribution pattern of the “O” ring model.

The model cavity is divided into three regions: A, B, and C (Figure 3). Different porosity is simulated by laying coal and rock particles with different particle sizes. After the coal sample is taken back from the site, the crushing and screening are carried out. Three coal blocks with different diameters of 0.5~1 cm, 1~2 cm, and 2~3 cm are taken, and the goaf caving zone is filled according to the gradual increase in the particle size from the inside to the outside, as shown in Figure 3.

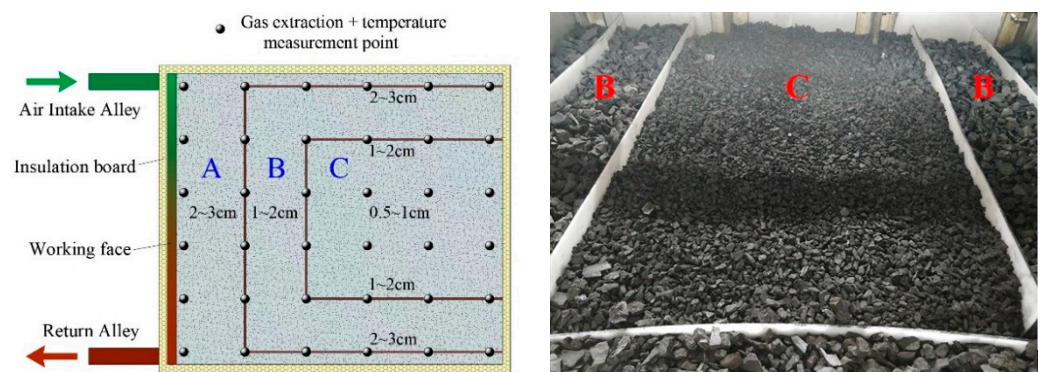


Figure 3. Filling diagram of the goaf model.

Zone A: the coal with a thickness of 10 cm at the bottom and stones with a thickness of 20 cm at the top, with a particle size of 2~3 cm;

Zone B: the coal with a thickness of 10 cm at the bottom and stones with a thickness of 20 cm at the top, with a particle size of 1~2 cm;

Zone C: the coal with a thickness of 10 cm at the bottom and stones with a thickness of 20 cm at the top, with a particle size of 0.5~1 cm.

2.2.3. High-Temperature Heat Source Arrangement

By changing the location of the heat source, the heat source is set in the shallow part of the inlet side, the deep part of the inlet side, the rear of the working face, the shallow part of the return air side, and the deep part of the return air side. The influence of coal spontaneous combustion at different positions on the temperature field and gas concentration field in the goaf is simulated and tested. The diameter of the heating rod is 2 cm, the length is 5 cm, and the heating power is 250 W. The internal temperature of the goaf is collected by thermocouples. The specific arrangement of thermocouples is shown in Figure 3, which realizes the measurement of temperature at different heights inside the goaf.

2.2.4. Experimental Steps

(1) Inserting by N₂ injection: N₂ was injected into the model cavity to reduce the O₂ concentration in the model to less than 3%. (2) Ventilation and gas injection: open the fan and adjust the air volume, adjust the air volume, and inject CH₄ and N₂ into the model cavity at 1 L/min and 2 L/min until the O₂ concentration in the return air corner is stable at about 20%. (3) Open the temperature measurement system: after ventilation for 2 h, the gas concentration reaches the temperature constant state, and the temperature data of the goaf, the inlet, and return air corners are collected in real time. (4) Open the heat source: open the specified heat source, set the heating rate to 1 °C/min, heat up to the design temperature, and simulate the high-temperature point of the goaf. (5) Collect gas samples: collect gas samples from the bottom measuring points of the goaf, the gas collection interval is 30 min, and the extracted gas is analyzed by a gas chromatograph until the high-temperature heat source temperature reaches 430 °C. (6) Cooling by nitrogen injection: after the end of the experiment, the high-temperature heat source and ventilation system were closed, and N₂ was injected into the goaf at a flow rate of 80 L/min. After continuous injection for 30 min, the inlet and outlet of the return air roadway, the high extraction roadway, and the extraction pipe were blocked, and the internal temperature of the goaf was cooled by nitrogen injection to ensure the safety of the experiment.

3. Results

3.1. Influence of Ignition Position on the Temperature Field of Goaf

When the ignition point is in the shallow part of the intake side, the evolution of the temperature field with time is shown in Figure 4. It can be seen that the high-temperature point gradually migrates to the direction of the intake lane, that is, the fire area spreads to the direction of sufficient oxygen supply; with the spread of the fire area, there is a strip temperature rise zone along the inclined direction behind the working face. At 4 h, the maximum temperature reaches 730 °C, while the temperature rise is not obvious at the beginning of the experiment.

When the ignition point is in the deep part of the inlet side, the evolution of temperature field is shown in Figure 5. At the beginning of the experiment, the evolution of temperature and the ignition point has the same trend when the ignition point is in the shallow part of the inlet side, the high-temperature point gradually migrates to the inlet side, and the temperature shows an increasing trend. The temperature rise behind the air inlet side is not obvious in the shallow part, which proves that the location of the fire source affects the temperature change in the stope monitoring, that is, different stope temperature information corresponds to different fire source locations.

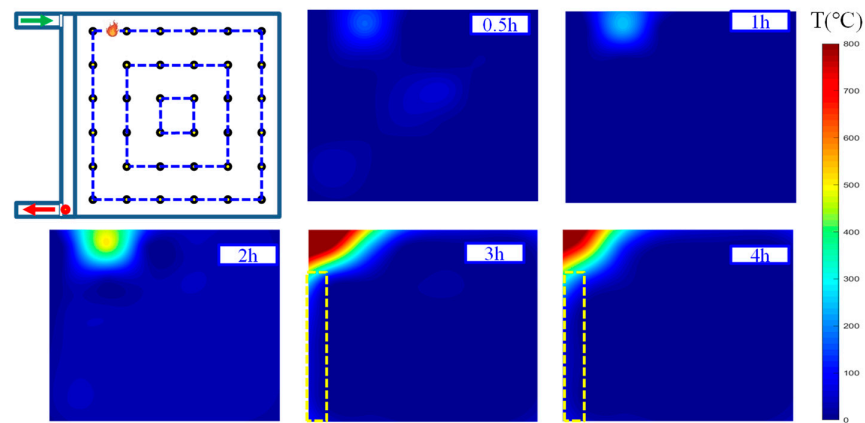


Figure 4. The temperature field when the ignition point is in the shallow part of the inlet side. (the yellow dotted box is a strip temperature rise zone).

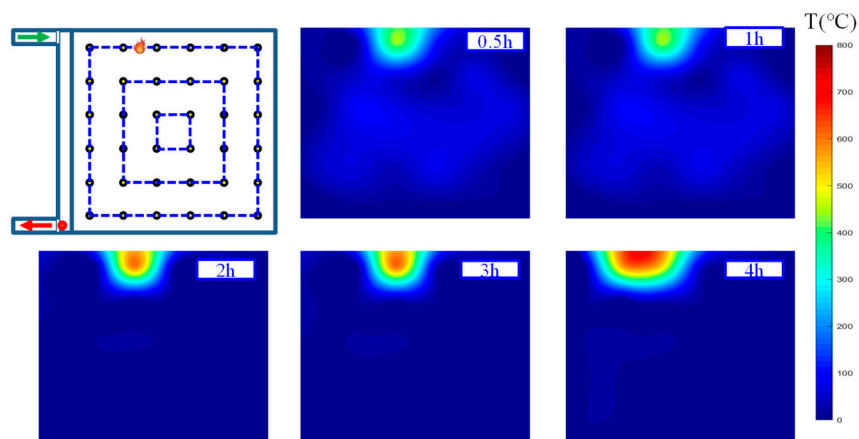


Figure 5. The temperature field when the ignition point is deep in the inlet side.

When the ignition point is behind the working face, the evolution of the temperature field is shown in Figure 6. The temperature of the fire area rises rapidly, and the maximum temperature reaches 500°C at the beginning of the experiment 1 h, and it spreads rapidly to the intake side. The duration of high temperature is the longest of each ignition point, due to the continuous and sufficient support conditions along the working face direction. At this time, O_2 is no longer the key to determining the spread of the fire area. Adequate fuel has become the main factor affecting the spread of the fire area.

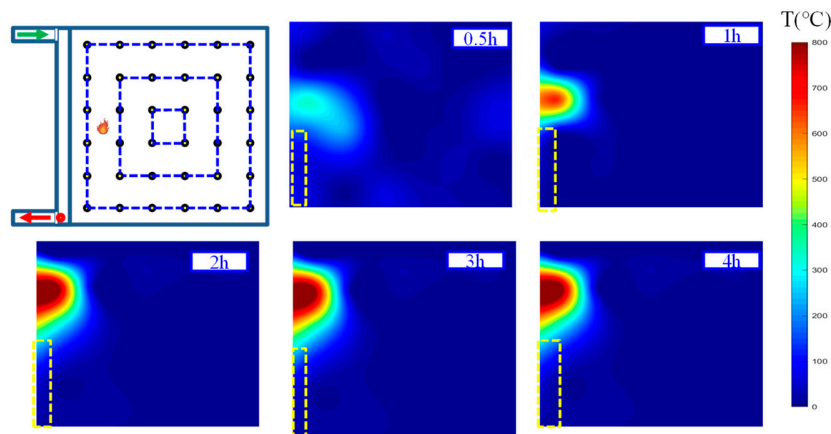


Figure 6. The temperature field when the ignition point is behind the working face. (the yellow dotted box is a strip temperature rise zone).

When the ignition point is in the shallow part of the return air side, the evolution of the temperature field is shown in Figure 7. Compared with the fire in the shallow part of the intake air side, the high-temperature point on the return air side moves faster because the oxygen concentration near the working face is sufficient. On the other hand, the airflow direction of the point is blown to the working face, and the high-temperature flue gas quickly spreads to the working face, resulting in the coal near the working face being more flammable.

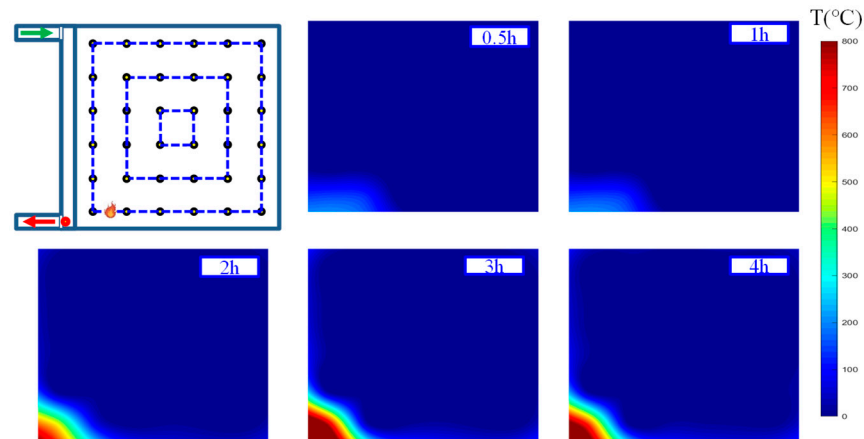


Figure 7. The temperature field when the ignition point is in the shallow part of the return air side.

When the ignition point is in the deep part of the return air side, the evolution of the temperature field is shown in Figure 8. There is no large-scale fire spread in the early stage. As the high-temperature point moves to the shallow part, the temperature of the fire source begins to gradually increase. Compared with the fire source on the intake side of the same position, the temperature rise and migration speed of this point are relatively slow. During the whole process, the maximum temperature is only about 480 °C, which is caused by the characteristics of air leakage in the goaf. The concentration of O₂ on the return air side is lower, the oxygen supply near the high-temperature fire source point is more inadequate, and the combustion of residual coal is slow, resulting in a decrease in the spread speed of the fire area.

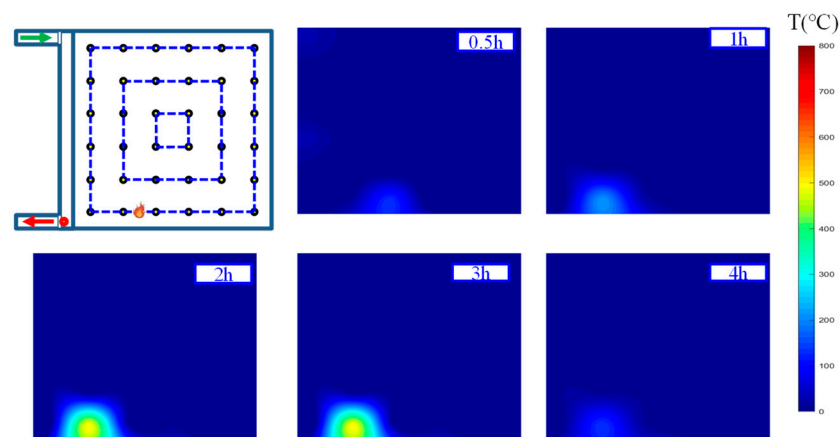


Figure 8. The temperature field when the ignition point is in the deep part of the return air side.

3.2. Influence of Ignition Position on Gas Concentration Field in the Goaf

3.2.1. Concentration Field of O₂

When the ignition point is in the shallow part of the inlet side, the evolution of the concentration field of O₂ is shown in Figure 9. The coal near the ignition point is oxidized under the action of high temperature, which consumes a large amount of O₂, resulting in a low concentration of O₂ and forming an oxygen-lean circle. The concentration of O₂ in the

oxygen-lean circle is always lower than 5%. Due to the existence of a high-temperature fire source, it is difficult for air leakage to enter the goaf along the gap near the roadway side, resulting in a low concentration of O_2 in the goaf on the intake side.

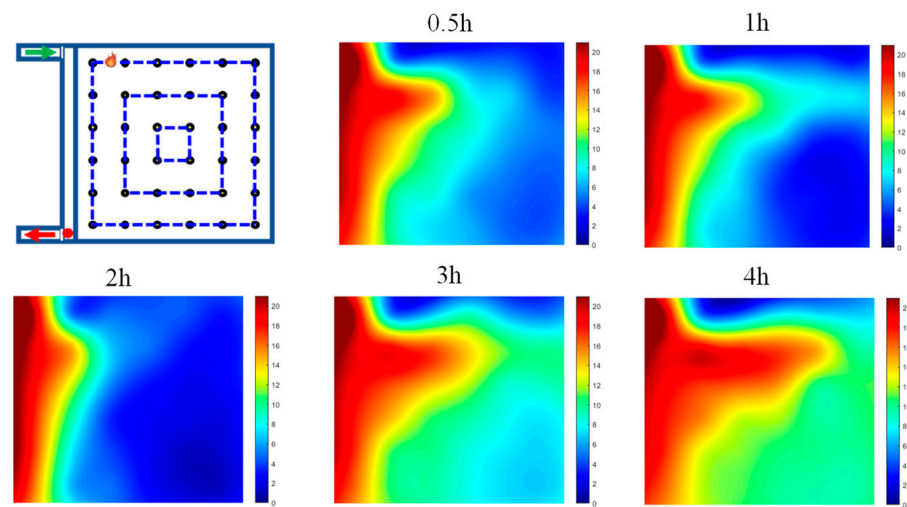


Figure 9. The concentration field of O_2 when the ignition point is in the shallow part of the inlet side.

When the ignition point is in the deep part of the intake side, the evolution of the concentration field of O_2 is shown in Figure 10. An oxygen-lean circle is still formed near the fire source point, and the concentration of O_2 behind the goaf is low. With time, the air leakage enters the goaf, which increases the concentration of O_2 in the goaf.

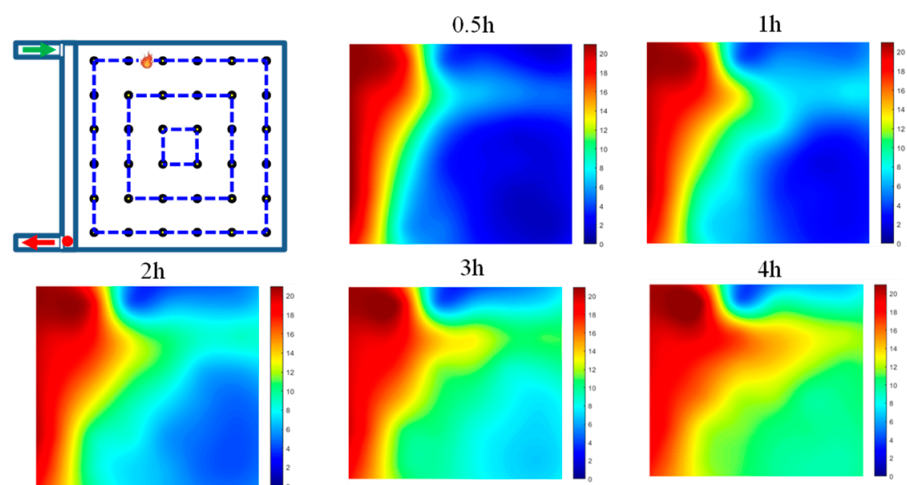


Figure 10. The concentration field of O_2 when the ignition point is in the depth of the inlet air.

When the ignition point is behind the working face, the evolution of the concentration field of O_2 is shown in Figure 11. A semi-circular oxygen-lean area facing the return airway is first formed near the fire source. With the spread of the fire, the oxygen-poor area gradually closes to form a ring.

When the ignition point is in the shallow part of the return air side, the evolution of the concentration field of O_2 is shown in Figure 12. At the initial stage of ignition, the fire source has little effect on the concentration of O_2 . With the combustion of the fire area, the oxygen-lean circle similar to the ignition of the inlet side is also formed near the fire area.

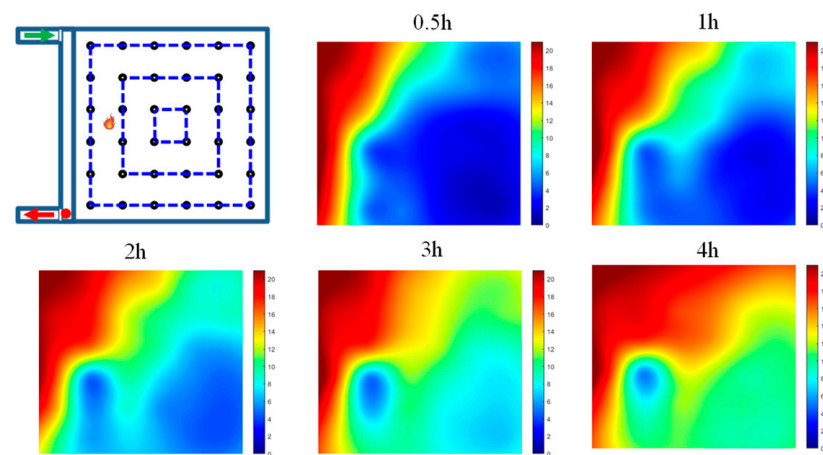


Figure 11. The concentration field of O_2 when the ignition point is behind the working face.

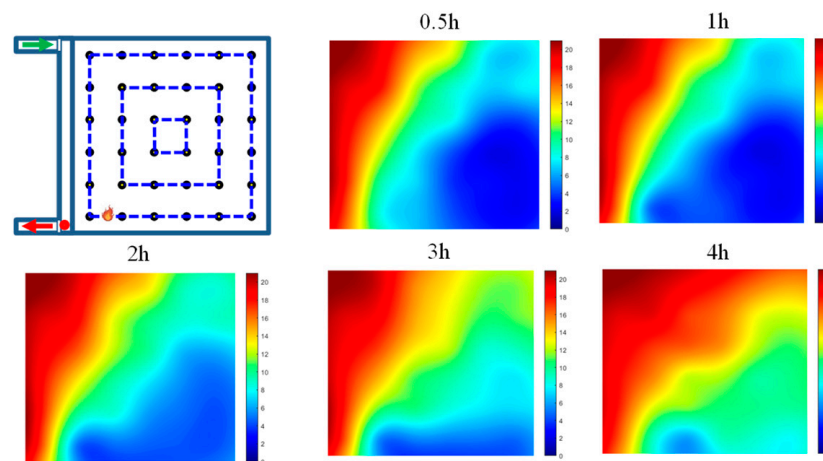


Figure 12. The concentration field of O_2 when the ignition point is in the shallow part of the return air side.

When the ignition point is in the deep part of the return air side, the evolution of the concentration field of O_2 is shown in Figure 13, the concentration of O_2 on the inlet side is greater than that on the return air side. Over time, O_2 gradually diffuses into the goaf, and O_2 near the fire source point is consumed in large quantities, forming an oxygen-lean circle near the fire source point.

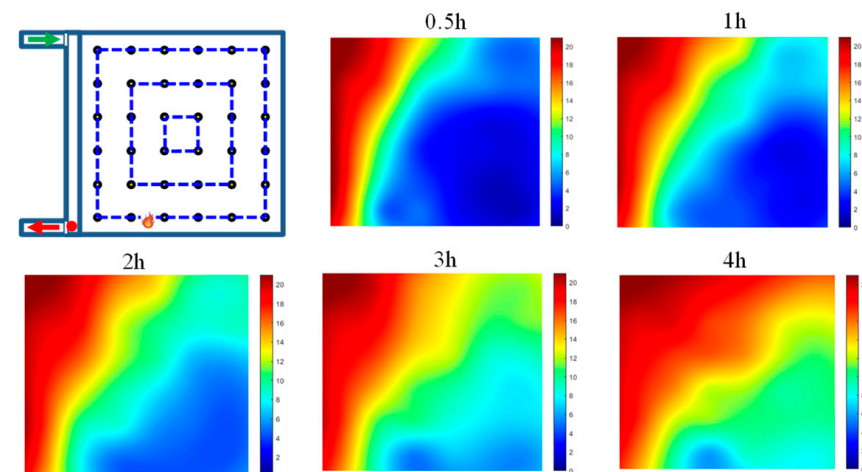


Figure 13. The concentration field of O_2 when the ignition point is deep in the return air side.

3.2.2. Concentration Field of CH₄

When the ignition point is in the shallow part of the inlet side, the evolution of the concentration field of CH₄ is shown in Figure 14. At the beginning of the experiment, CH₄ began to accumulate in the deep part of the goaf on the return air side at 1 h. The highest concentration of CH₄ reached 10.3% at 4 h, which is due to the movement of CH₄ to the deep return air side driven by the wind flow, resulting in the accumulation of CH₄ in the interior. The concentration of CH₄ at the ignition point increases, which is since the high temperature causes the coal to release a part of CH₄.

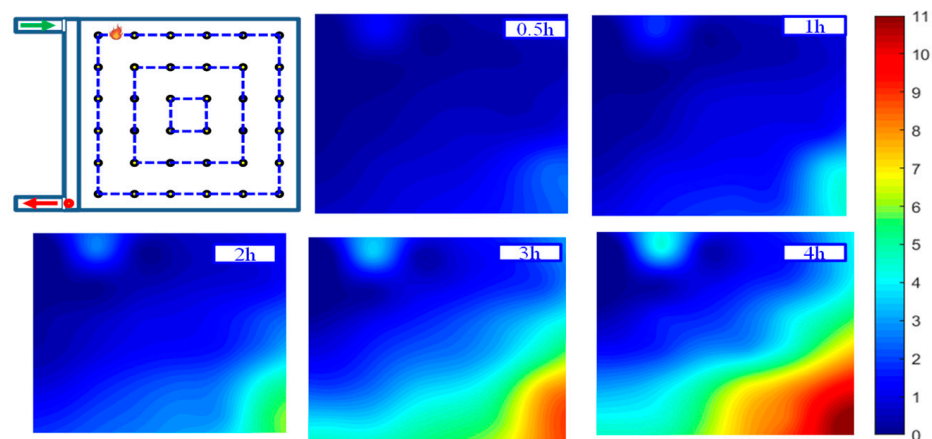


Figure 14. The concentration field of CH₄ when the ignition point is in the shallow part of the inlet side.

When the ignition point is in the deep part of the inlet side, the evolution of the concentration field of CH₄ is shown in Figure 15. The changing trend in the concentration of CH₄ is the same as that of the ignition point in the shallow part of the inlet side. The concentration of CH₄ shows that the return air side is higher than that of the inlet side and accumulates in the deep part of the return air side. The concentration of CH₄ at the ignition point increases, but the increase is less than that when the fire source is located in the shallow part.

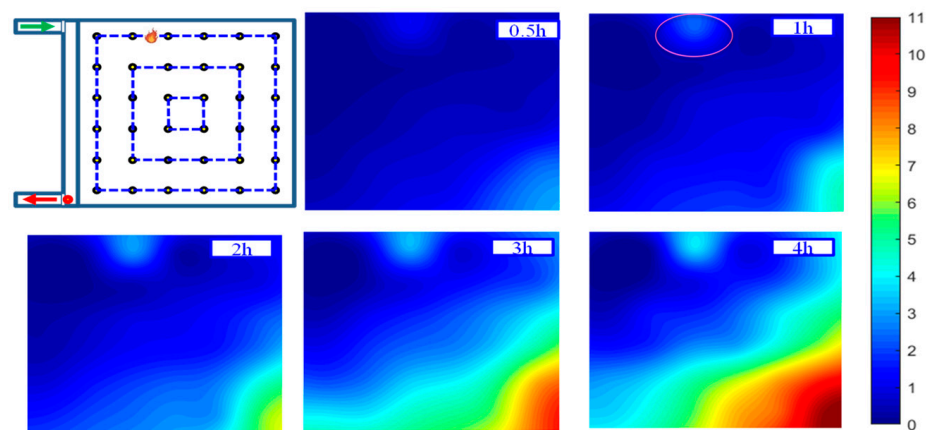


Figure 15. The concentration field of CH₄ when the ignition point is deep in the inlet side.

When the ignition point is behind the working face, the evolution of the concentration field of CH₄ is shown in Figure 16. The concentration of CH₄ at the fire source position still shows an increasing phenomenon, and it communicates with the CH₄ in the deep part of the goaf on the return air side.

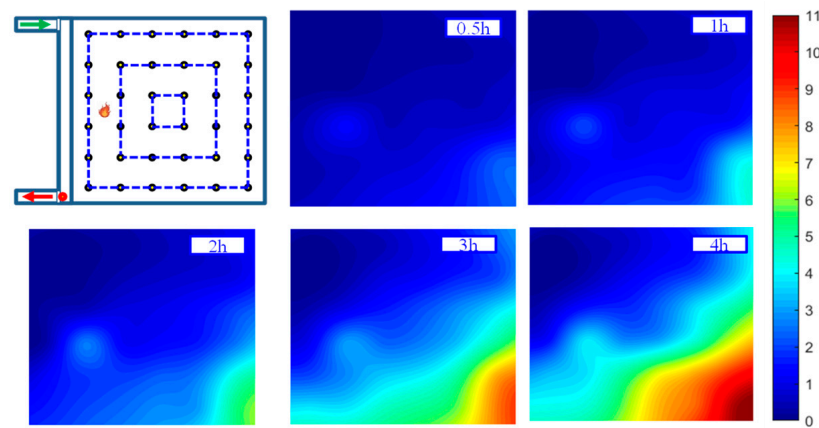


Figure 16. The concentration field of CH_4 when the ignition point is behind the working face.

When the ignition point is in the shallow part of the return air side, the evolution of the concentration field of CH_4 is shown in Figure 17. The concentration of CH_4 at the ignition point appears a protruding point, increasing the concentration of CH_4 .

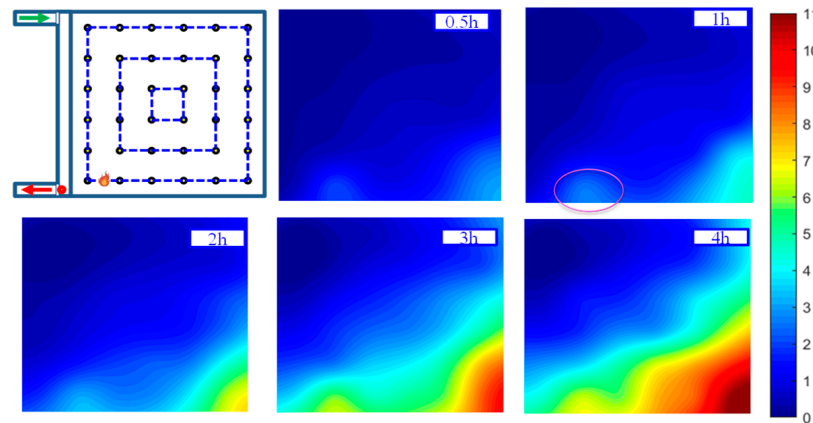


Figure 17. The concentration field of CH_4 when the ignition point is in the shallow part of the return air side. (the circle is a protruding point).

When the ignition point is in the deep part of the return air side, the evolution of the concentration field of CH_4 is shown in Figure 18. In the shallower part, the increase in concentration of CH_4 at the ignition point is smaller, and no concentration of CH_4 bump is formed.

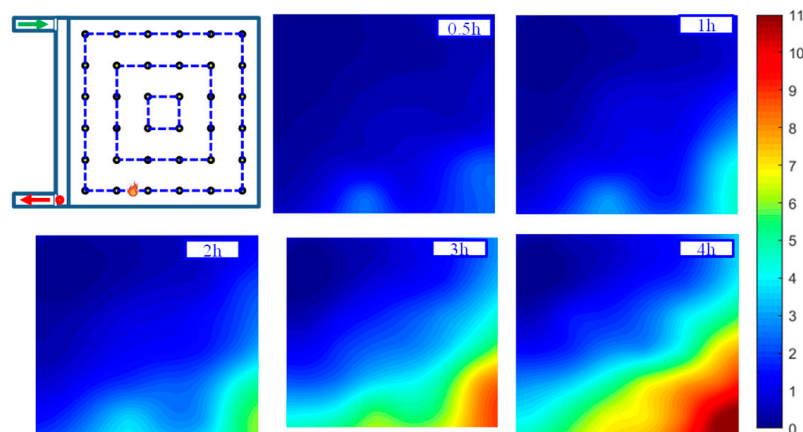


Figure 18. The concentration field of CH_4 when the ignition point is deep in the return air side.

3.3. Influence of Temperature and CO Concentration at the Corner of the Return Air

The concentration of CO in the return air corner and the temperature difference between the inlet and return air corners change with time under different heat source conditions as shown in Figure 19. The changing trend in the concentration of CO in the return air corner under different heat source conditions is consistent, showing three stages of rising, stability, and falling. In the beginning, CO gas was first detected in the return air corner, indicating that the oxidation and heating of residual coal occurred in the goaf with the rapid increase in CO concentration, the rapid heating of residual coal in the goaf, and the continuous expansion of the high-temperature area. At this stage, the fire is gradually formed, the scale of the fire area is still in the expansion stage, and fire extinguishing measures must be implemented in time. Subsequently, the concentration of CO in the return air corner reaches the maximum value and tends to be stable. At this time, the fire area has reached the largest scale and has been gradually spread within a limited range. The high-temperature point at this stage continues to migrate to the working face with higher oxygen concentration. Once the gas explosion condition is reached, it is very easy to induce serious gas explosion accidents. Finally, as the fire area is extinguished, the concentration of CO in the return air corner shows a downward trend. It can be seen that the change in the concentration of CO in the return air corner corresponds to the formation and migration stages of the fire area in the goaf, which can fully reflect the evolution process of the fire area. The continuous monitoring of CO in the return air corner can provide a basis for the judgment of the disaster process in the disaster relief process.

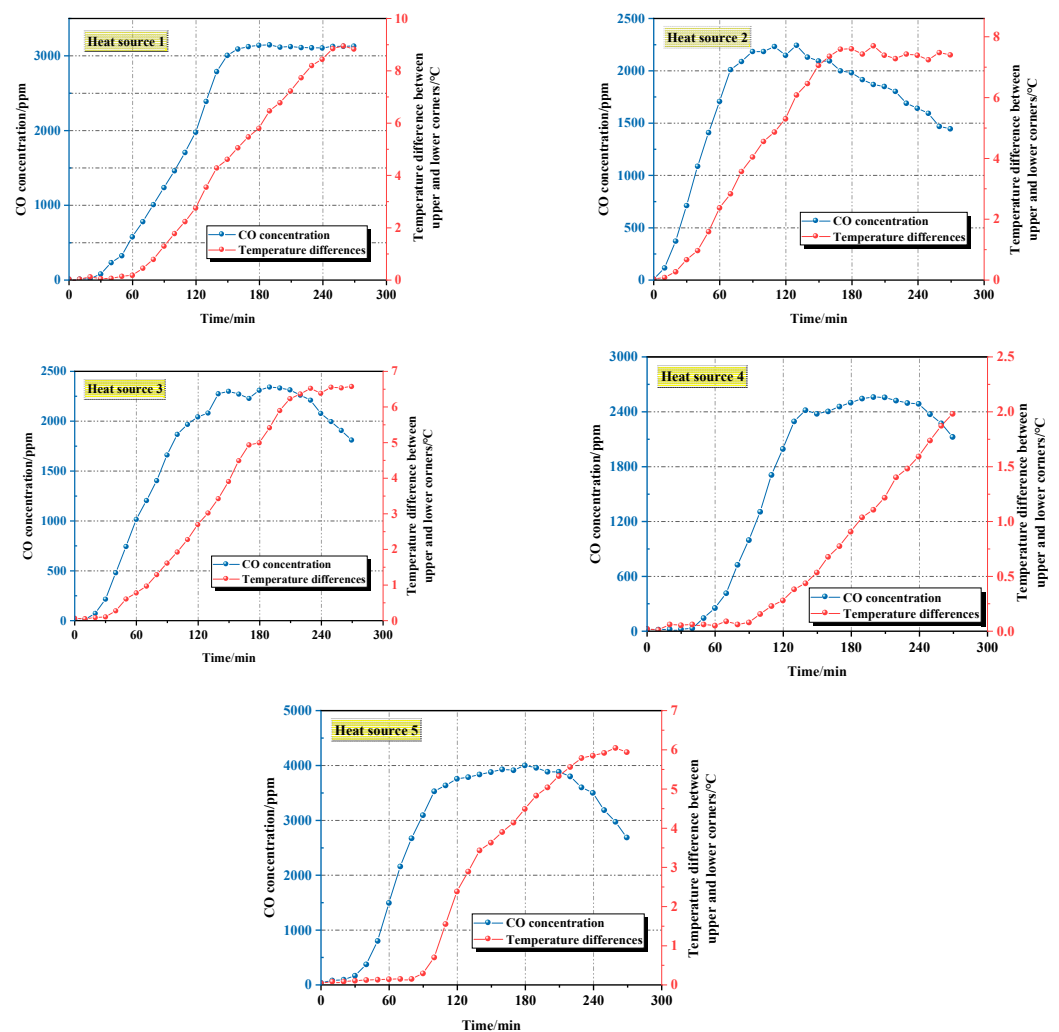


Figure 19. The concentration of CO and the temperature under different heat source conditions.

The temperature of the return air corner also shows the characteristics of periodic change. Different from the change in CO, the increase in temperature is relatively slow. For each heat source point, the time of temperature rise monitored in the return air corner is later than that of the rise of CO. This is mainly because the CO produced by the heating of the coal body can be transferred to the return air corner with the airflow, and the smoke flow after the heating of the heat source will be lost due to the heat absorption of the coal and rock along the way, resulting in the slow heating of the airflow in the early stage of spontaneous combustion. Only when the airflow reaches a certain temperature can the return air corner be heated. Although the temperature has a consistent trend with the change in the concentration of CO, it always lags behind the change in the concentration of CO over time. Therefore, concentration monitoring of CO can reflect the evolution process of the fire field in the goaf more quickly than temperature monitoring.

The lag time is defined as the time difference between the initial rise temperature and the CO concentration of the return air corner, and the curves of the lag time with the position of the heat source are shown in Figure 20. It is found that the farther the wind flow line is, the greater the lag time is. This is because in the process of high-temperature smoke flow to the return air corner, the heat loss is positively correlated with the distance of the line. The farther the line is, the more heat loss there is along the way. The time that the return air corner captures the temperature change is later than that of CO.

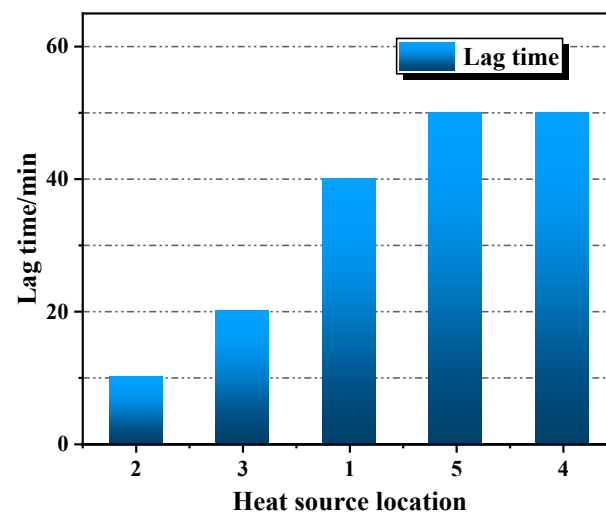


Figure 20. The lag time with the position of the heat source.

4. Analysis and Discussion

4.1. Evolution Process Deduction of Thermal Dynamic Disaster

(1) Energy conservation

When spontaneous combustion occurs in the goaf, the low-temperature airflow in the air intake roadway enters the goaf through the air leakage inflow section of the working face, and after absorbing the effective heat of the goaf fire area (the heat loss), it flows into the working face through the air leakage outflow section of the goaf, resulting in the temperature rise of the airflow in the goaf. The heat balance of the process, namely,

$$\varphi \dot{m}_i c_p T_i + \chi \dot{Q}_{sc} = \int_0^L \dot{m}(x) c_p T(x) dx \quad (6)$$

where φ is the goaf air leakage rate, $\dot{m}_i$ is the working face inlet air volume, c_p is the specific heat capacity of airflow in the working face, and χ is the rate of gob heat loss, $\dot{Q}_{sc}$ is the oxidation heat release of coal in the goaf.

(2) Mass conservation

Assuming that the form of air leakage in the goaf is “one source and one sink”, the air volume flowing out of the goaf on the return side is approximately equal to the air volume leaking into the goaf on the intake side, that is,

$$\int_0^L \dot{m}(x) dx = \varphi \dot{m}_i, \quad \dot{m}(L) = 0 \quad (7)$$

(3) Energy conservation in intake and return airways

After the air leakage in the working face and the goaf, the air in the intake roadway flows into the return air roadway through the return air corner. In this process, the temperature rises after the low-temperature inlet air flow absorbs the heat loss in the goaf, then,

$$\dot{m}_i c_p T_i + \chi \dot{Q}_{sc} = \dot{m}_R c_p T_R \quad (8)$$

where $\dot{m}_i$ is the working face inlet air volume, and T_R is the workplace return air temperature.

(4) Remaining coal oxidation exothermic equation

There is a certain quantitative relationship between the oxidation heat release of residual coal in the goaf and the production of CO and CO₂. By monitoring the increment of CO and CO₂ gas in the return airflow relative to the intake airflow, the oxidation heat release of residual coal in the goaf can be quantitatively described, that is,

$$\dot{Q}_{sc} = K_1 \dot{m}_{CO} + K_2 \dot{m}_{CO_2} \quad (9)$$

where K_1 and K_2 are experimental coefficients, $\dot{m}_{CO}$ is an increment of CO mass flow in return air of mining face, and $\dot{m}_{CO_2}$ is an increment of CO₂ mass flow in return air of mining face.

(5) Due to the different air leakage at different positions of the air leakage outflow section in the goaf, and the closer to the return air lane, the greater the air leakage. The closer to the static section, the smaller the air leakage. When the air leakage at the junction of the air leakage inflow section and the static section is 0, assuming that the air leakage at different positions of the air leakage outflow section changes linearly, then,

$$\dot{m}'(x) = \dot{m}'(1 - \frac{x}{L}), \quad x \in [0, L] \quad (10)$$

where $\dot{m}'(x)$ is the air leakage mass flow per unit length at the x position of the outflow section, x is the coordinates pointing to the inlet corner with the vertex of the return corner as the origin, L is the length of the outflow section of the airflow in the goaf of L-working face, and $\dot{m}'(0)$ is the air leakage mass flow rate per unit length at $x = 0$ in the outflow section.

When coal spontaneous combustion occurs in the goaf, the temperature of the air leakage flow in the goaf rises through the heating of the high-temperature fire zone. Because the air leakage volume at each position of the air leakage outflow section is different, the temperature distribution of each point is also different. The temperature of the return air corner is relatively high, and the temperature of the airflow is relatively low in the place where the air leakage volume is small. The temperature at the junction of the outflow section and the stationary section of the working face is the lowest, which is the temperature of the inlet airflow. Assuming that the temperature at different positions of the air leakage outflow section changes linearly, then,

$$T(x) = T_g - (T_g - T_i) \frac{x}{L}, \quad x \in [0, L] \quad (11)$$

where $T(x)$ is the temperature at the x position of the outflow section, T_g is the temperature at the return air corner, and T is the temperature at the inlet air of the working face.

(6) Goaf air leakage rate and heat loss rate

By solving the simultaneous Equations (6)–(11), the expressions of air leakage rate and heat loss rate in the goaf can be obtained:

$$\begin{cases} \chi = \frac{\dot{m}_R c_p T_R - \dot{m}_i c_p T_i}{K_1 \dot{m}_{CO} + K_2 \dot{m}_{CO_2}} \\ \varphi = \frac{3}{2} \frac{\dot{m}_R T_R - \dot{m}_i T_i}{\dot{m}_i (T_g - T_i)} \end{cases} \quad (12)$$

4.2. Analysis of Thermal Dynamic Disaster Evolution Process

From Equation (12) of air leakage rate and heat loss rate in the goaf, the following can be obtained:

(1) When the value of χ decreases significantly, it is determined that the spread of the high-temperature area is mainly to the inlet side.

After the air leakage flow of the working face passes through the high-temperature zone, the heat is absorbed and finally incorporated into the return air corner. The heat taken away by the airflow is the heat loss rate of the goaf. The longer the airflow path between the high-temperature zone and the return air corner is, the more the heat carried by the air leakage flow is absorbed by the coal rock along the way, and the lower the proportion of heat carried out by the airflow out of the goaf is. Therefore, when the heat loss rate decreases significantly, it indicates that the airflow path between the high-temperature zone and the return air corner becomes longer, that is, it can be determined that the high-temperature zone spreads to the inlet side.

(2) When the value of χ increases significantly, it is determined that the spread of the high-temperature area is mainly to the return air side.

Contrary to the significant decrease in the value χ above, when the value of χ increases significantly, the airflow path between the high-temperature zone and the return air corner becomes shorter, that is, it can be determined that the fire zone spreads to the intake side.

(3) When the value of φ does not decrease significantly with the increase in $\dot{Q}_{sc}$, the range of the high-temperature zone is expanded, but it is still limited to the possible spontaneous combustion zone.

The increase in the value of $\dot{Q}_{sc}$ means that the heat release rate in the high-temperature area increases. When there is a continuous residual coal distribution around the high-temperature area, the range of the high-temperature area will inevitably expand. The φ value did not decrease significantly, indicating that the high-temperature area did not affect the main air leakage channel in the goaf, so it was judged that the high-temperature area was still limited to the possible spontaneous combustion zone.

(4) When the value of $\dot{Q}_{sc}$ increases and the value of φ decreases significantly, it is determined that the range of the high-temperature area is expanded, and the high-temperature area has spread to the cooling zone, and the risk of gas explosion induced by coal spontaneous combustion increases.

The significant decrease in the value of φ indicates that the wind resistance of the main air leakage passage in the goaf increases, and one of the main reasons that may lead to this result is the thermal resistance formed in the high-temperature area. Therefore, it can be determined that the high-temperature area has spread to the cooling zone. Due to the large gap between coal and rock blocks in the cooling zone, there is a large space for gas accumulation and sufficient oxygen supply. However, when the high-temperature area spreads to this area, the risk of gas explosion will increase significantly.

5. Conclusions

In this paper, through the coupling detection experiment of a goaf thermal dynamic disaster, the coupling law of temperature field and gas concentration field in the goaf during coal spontaneous combustion was obtained. The main conclusion is as follows:

(1) Under the condition of different heat source positions, the high-temperature heat source of coal spontaneous combustion in the goaf migrates to the air leakage side with

sufficient oxygen supply, and an oxygen-lean circle is formed near the ignition point. Under the action of air leakage flow, CH_4 accumulates in the deep part of the goaf on the return air side. Due to the increase in the coal body, part of CH_4 is produced, which leads to the increase in the concentration of CH_4 at the ignition point.

(2) Under the action of different heat sources, the changing trend of the concentration of CO and temperature in the return air corner is the same, but the temperature change in the return air corner lags behind the change in the concentration of CO. Therefore, concentration monitoring of CO can reflect the evolution process of the fire field in the goaf more quickly than temperature monitoring.

(3) The evolution process deduction model of thermal dynamic disaster in the goaf is established. According to the relationship between air leakage rate and heat loss rate in the goaf, the migration direction of the high-temperature area of coal spontaneous combustion under the condition of air leakage in the goaf and the criterion of gas combustion and explosion risk induced by coal spontaneous combustion are obtained.

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