Measurement and Numerical Simulation of Coal Spontaneous Combustion in Goaf under Y-type Ventilation Mode

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ABSTRACT: In the process of advancing the working face, the temperature rise and oxidation characteristics of residual coal in goaf and the prediction of index gas are of great significance to mine fire prevention and safety production. Based on the coal spontaneous combustion test, the oxygen consumption and heat release characteristics of coal spontaneous combustion were analyzed by taking coal samples at the working face and carrying out temperature-programmed experiments in the laboratory. The characteristic temperature and index gas of coal spontaneous combustion were determined as the judgment bases of “three zones” of spontaneous combustion in goaf, and the influencing factors of coal spontaneous combustion in goaf under Y-type ventilation were analyzed. Based on the test results, the changes of gas composition in goaf during the advancing of the W1310 working face were monitored. According to the actual situation of the W1310 working face in the Gaohe energy mine of Lu’an group, the multifield three-dimensional numerical simulation calculation and analysis of gas composition in goaf were carried out, and the distribution of oxygen concentration field in goaf under different air volume ratios of machine roadway and air roadway was studied. Through the analysis of the parameters of porous media in the goaf, combined with the actual situation, the user-defined function was compiled for the key parameters such as porosity, viscous resistance coefficient, and inertial resistance coefficient of porous media in the goaf. The three-dimensional seepage field, gas concentration field, oxygen concentration field, and pressure field of the gas components in goaf during the advancement of the goaf working face were simulated. The comparison of the numerical simulation results with the field-measured results shows good agreement. In order to consider safety, the numerical simulation results with a wide oxidation temperature rise zone are used for linear regression, and the regression equation is used to dynamically determine the O2 concentration at a point away from the goaf and to determine the “three-zone” state of the point, which is of great significance to guide the progress of the working face and safe production.

INTRODUCTION

Due to the energy situation of more coal, less gas, and less oil, coal has long been China’s leading energy structure. However, with the depletion of shallow resources and the rapid development of the country, the demand for energy surges. The exploitation of deep coal resources has become the main development direction in the future. The increase of coal seam mining depth will inevitably lead to the rise of ground temperature, which is the main factor inducing the spontaneous combustion of residual coal in goaf. Therefore, it is of great significance to study the characteristics of gas released by coal combustion in the process of heating up and optimize the index gas of coal spontaneous combustion.

In the study of coal spontaneous combustion, experimental research is the most direct means to explore the essence of coal spontaneous combustion. Domestic and foreign scholars have successively designed many experimental devices for the study of the influencing factors of coal spontaneous combustion. Fan et al.1 studied the macro and micro characteristics of raw coal and oxidized coal in the combustion stage by thermogravi-

metric analysis and in situ Fourier transform infrared spectroscopy. The results show that preoxidation treatment can promote and inhibit the weight loss characteristics of oxidized coal. Xu et al.2 established an experimental platform to measure the spontaneous combustion characteristics of large pressure coal. The thermal analysis experiment and microscopic analysis of briquette under different axial pressures were carried out. The results show that when the axial pressure is 4 MPa, the heating rate of coal oxidation combustion accelerates, the intersection temperature is reduced by 71.09 °C, the activation energy is reduced (the second stage is decreased by 21.3 kJ/mol), and the oxidation combustion is more intense.
Chen et al. studied the distribution of CO in the goaf during the advance of the "roof cutting and pressure relief" mining face by installing CO sensors in the air intake lanes and gob-side entry retaining in goaf. Comparative analysis of CO concentration methods in the upper corner of the working face under traditional mining method and roof cutting pressure relief mining method was performed. The results show that CO in the test face mainly comes from the oxidation of residual coal. Through analysis, it is observed that the CO concentration in the goaf is divided into three areas: slow increase area, rapid increase area, and attenuation area. The CO concentration in the upper corner of the Y-shaped ventilation face in roof cutting and pressure relief mining is much lower than that in the upper corner of U-shaped ventilation face in traditional mining. In order to prevent the oxidation and heating of residual coal in goaf from producing CO, comprehensive prevention and control measures for CO escape from the goaf are taken. Jia et al. studied the effect of water content on the coal spontaneous combustion process by experiments. Zhou et al. carried out coal spontaneous combustion with different oxygen concentrations, analyzed the product composition, and explained the characteristics of coal spontaneous combustion. Cui et al. analyzed the difference of gas products in raw coal and samples treated with ionic solution and then studied their mechanism of inhibiting coal spontaneous combustion by calculating the inhibition rate and apparent activation energy of samples. Lu et al. used a large-scale experimental bench with a coal loading of 5 tons to study the law of coal spontaneous combustion. Fierro et al. established five coal loading (2000–3000 tons) test piles to simulate the problem of coal spontaneous combustion and proposed a method to directly determine the total heat loss coefficient. Chen et al. studied the spontaneous combustion of bituminous coal by thermogravimetric analysis and in situ Fourier transform infrared spectroscopy. Yuan and Alex studied the heat transfer law of coal in goaf through similar simulation experiments and put forward the coupling model of gas flow and heat transfer in the goaf. Liu et al. studied the formation relationship between the standard oxygen consumption rate and the standard CO formation rate of coal samples by low-temperature experiments, theoretically deduced the empirical formula, and proved the elementary reaction. Wang et al. verified the adsorption of CO₂, N₂, and O₂ by coal through isothermal adsorption experiments. Ma et al. experimentally studied the spontaneous combustion tendency of high-volatile mixed coal. Li et al. combined the internal structures of coal to make model compounds to simulate the oxidation of functional groups to generate gas. Deng et al. studied the spontaneous combustion characteristics of water content on coal secondary oxidation.

Because experimental simulations can only reflect the spontaneous combustion of coal under laboratory conditions, but cannot intuitively reflect the spontaneous combustion of goaf, and the goaf is a closed area, and personnel are basically unable to enter, scholars from various countries have started the exploration of numerical simulation on the basis of experiments. Numerical simulation has become a research hotspot in the prevention and control of spontaneous combustion at this stage because of its convenience, rapidity, and predictability. Numerical simulation has also developed from the initial simple steady-state one-dimensional non-reaction simulation to today’s three-dimensional, unsteady, and multifield coupling simulation. Numerical simulation plays an important role in mine fire prevention. Si et al. uses the three-dimensional physical model of stope to analyze the law of CO₂ gas migration, the relationship between gas injection rate and oxidation zone area, and the safety of CO₂ inerting technology. The results show that the oxygen concentration is diluted between the working face and the injection port, especially on the inlet side. In addition, CO₂ injection rate is an important parameter of fire prevention and extinguishing technology. Gou and Han theoretically analyzed the gas migration in goaf, established the mathematical control equation of gas migration, and numerically simulated the effect of different technical means on gas control in goaf. Jiang and Zhang established the three-dimensional flow-field mathematical model of the goaf, regarded the goaf as a uniform porous medium, carried out computer numerical simulation of the goaf, corrected the simulation results by using the experimental data, and achieved good simulation results. Li et al. first introduced the heat transfer equation to solve multifield coupling problems such as seepage field, temperature field, and gas concentration field and numerically simulated the influence of gas drainage in goaf and nitrogen injection in goaf on residual coal spontaneous combustion. Liu et al. established a mathematical model after the theoretical analysis of air leakage in goaf and numerically simulated the relationship between air leakage intensity and coal pillar buried depth. Zhu et al. and Liu combined the characteristics of goaf, established a three-dimensional multiphysical field goaf natural ignition model based on moving coordinates, and carried out numerical calculations. Liu et al. proved the characteristics of "U" and "Y" ventilation based on the discrete model solution of the finite volume method. Qin et al. studied the coupling of airflow, oxygen concentration field, and temperature field in goaf based on non-Darcy seepage by using the numerical simulation method on the basis of experiment and similar simulation. Zhai et al. carried out temperature-programming experiments to simulate the low-temperature oxidation of CSC at different heating rates.

With the deepening of the research on coal spontaneous combustion in goaf, in order to prevent coal spontaneous combustion in goaf, scholars put forward the theory of "three zones" of spontaneous combustion. The theory holds that the goaf can be divided into three zones (i.e., divergent zone, oxidation temperature rise zone, and asphyxia zone) from the working face to the deep part of goaf. As long as the residual coal enters the asphyxia zone before reaching the full oxidation reaction, it is considered that the combustion conditions are insufficient and the residual coal cannot spontaneously ignite. However, there are many views on the division of "three zones" of spontaneous combustion, different standards are adopted, there is no unified consensus, and a complete theoretical system is not formed. Early scholars mainly observed and analyzed the oxygen concentration and temperature in the goaf according to the on-site measurement in the goaf, which was used as the basis for the division of "three zones" of spontaneous combustion in the goaf. In recent years, with the popularization and wide application of computers, computer simulation has become an important means of goaf spontaneous combustion, and scholars have also made great achievements. Li et al. proposed the combined oxygen concentration method and temperature method to divide the "three zones" of goaf under the condition of continuous nitrogen injection. Xie and Xue proposed to divide the "three zones" of spontaneous combustion in goaf by comprehensively...
Considering the oxygen concentration and floating coal thickness in goaf as judgment indexes. Aiming at the uncertainty of coal spontaneous combustion in goaf, Cheng et al.26 added fuzzy clustering method to determine the “three zone” range of spontaneous combustion in goaf. Based on the factors affecting coal spontaneous combustion, Sun et al.30 proposed to divide the “three zones” of spontaneous combustion in goaf by using the minimum residual coal thickness, limited air leakage wind speed, and critical oxygen concentration as the main indexes and the temperature rise speed as the auxiliary index. Lu et al.31 and Xie et al.32 pointed out that the method of combining oxygen concentration and CO concentration was used to divide the “three zones” of spontaneous combustion. Wang et al.33 divided the “three zones” of spontaneous combustion by combining the air leakage wind speed and oxygen concentration in the goaf through numerical simulation. Li34 predicted the risk of spontaneous combustion of residual coal in goaf by monitoring the temperature change of the working face.

Through the investigation of the research status of the theory, experiment, numerical simulation, and the division of “three zones” of residual coal spontaneous combustion at home and abroad, it can be seen that scholars at home and abroad have adopted a variety of methods and means to conduct a large number of detailed research studies on coal spontaneous combustion from multiple angles, but there are also some problems. When identifying the risk area of residual coal spontaneous combustion in goaf, most of the existing methods are based on the general methods of current research to identify the residual coal spontaneous combustion and development in goaf, without considering the characteristics of coal in different regions, and the external factors of spontaneous combustion have not been accurately quantified. For example, compared with U-type ventilation, the air supply volume and air pressure of Y-type ventilation are significantly increased, resulting in strengthened airflow disturbance in the working face and increased air leakage in the goaf, increasing the risk of spontaneous combustion of residual coal in the goaf. Therefore, the law of coal spontaneous combustion obtained under the condition of U-type ventilation will not be suitable for mines with Y-type ventilation. In the numerical simulation of residual coal spontaneous combustion in goaf, considering the actual situation of goaf, the three-dimensional mathematical model is very complex. Therefore, most researchers approximately simplify the three-dimensional goaf into two-dimensional goaf. Even if some scholars have established a three-dimensional model, they also use commercial software such as FLUENT to simulate, and regard the goaf porous media area as a unified area, which is lack of calculation accuracy and applicability. At present, in the study of residual coal spontaneous combustion in goaf, scholars either use the single-field measurement method to study the “three areas” of spontaneous combustion or use the simple two-dimensional or three-dimensional numerical simulation method to simulate multifield spontaneous combustion in goaf. The actual observation in the goaf is less, the combination of theoretical research and production practice is not close enough, and there is a lack of necessary connection.

Based on the coal spontaneous combustion index gas optimization experimental system, the coal spontaneous combustion characteristic test is carried out to study the corresponding relationship between the temperature and the gas released by coal oxidation in the process of coal heating, so as to determine the index gas of coal spontaneous combustion. Based on the index gas determined by the test, a beam tube monitoring system is arranged in the W1310 working face of Gaohe coal mine to monitor the change of gas concentration in goaf with the advancing distance of the working face. The oxygen concentration is used as the standard of measured “three zones” of spontaneous combustion in goaf and divided into “three zones”. Through the theoretical analysis of the influencing factors and seepage characteristics of residual coal spontaneous combustion under the condition of Y-type ventilation, the characteristic parameters of the coal sample of the working face are analyzed in the laboratory, the “three zones” of on-site spontaneous combustion are measured, and the multifield change law of goaf is simulated by the ANSYS FLUENT software. The three-dimensional seepage field, gas concentration field, oxygen concentration field, and pressure field of gas components in goaf during the advancement of the goaf working face are simulated. Based on the analysis of the parameters of porous media in goaf, combined with the actual situation, the user-defined function (UDF) of key parameters such as porosity, viscous resistance coefficient, and inertial resistance coefficient of porous media in goaf is compiled. The distribution law of “three zones” of residual coal spontaneous combustion in goaf is deeply studied. According to the actual situation of the W1310 working face in the Gaohe coal mine of Lu’an group, the numerical simulation calculation is carried out for the goaf of the mine, the distribution of oxygen concentration field of different sizes in the goaf under different air volume ratios of machine roadway and air roadway is studied, and the accuracy of the numerical simulation results can be verified by the field test.

### EXPERIMENTAL STUDY ON COAL SPONTANEOUS COMBUSTION INDEX SYSTEM IN GOAF

#### Experimental Coal Sample

The experimental coal samples are taken from the W1310 coal face of Shaxi Gaohe coal mine 3# seam. In the laboratory, the surface of large coal samples is stripped, and the internal coal core is taken and broken into particles of a certain size. Then, the broken coal particles are screened by a sieve, and four coal particles with particle sizes of 0–1, 1–3, 3–5, and 5–10 mm are selected and sealed for storage. In order to comprehensively reflect the influence of different particle sizes on coal spontaneous combustion, four mixed coal samples with the particle size mass ratio of 1:1:1:1 were selected as the experimental coal samples of the temperature-programmed experiment. The gas composition, concentration, and generation rate produced by coal samples with the increase of temperature and the characteristic parameters of CO, CO₂,

| coal sample                     | average particle size/mm | test tube coal height/cm | coal weight/g | coal volume/cm³ | weight/g·cm⁻³ | void ratio/% | air flow/mL·min⁻¹ | heating rate/°C·min⁻¹ |
|---------------------------------|--------------------------|--------------------------|---------------|-----------------|---------------|--------------|-------------------|----------------------|
| W1310 working face             | 5.0                      | 17.33                    | 1000          | 1228.11         | 0.81          | 43.06        | 130               | 0.50                 |

Table 1. Temperature-Programmed Experimental Conditions
CH₄, C₂H₆, C₂H₄, C₂H₂, and other gases produced and changed with temperature were determined, so as to optimize the gas index of the Gaohao coal mine 3# coal seam. The temperature-programmed experimental conditions are shown in Table 1.

**Test Equipment.** The test instrument of the coal sample temperature-programmed gas optimization system is mainly composed of three parts: gas supply system, temperature-programmed system, and gas analysis system. The air supply system mainly includes an air pump, float flowmeter, 5 m preheating copper pipe, and several high-temperature-resistant gas pipes. The automatic temperature-programmed system is mainly composed of a temperature-programmed furnace, a coal sample tank, and a thermometer for measuring temperature. The gas analysis system is mainly composed of a GC-4008B gas chromatograph, a drying tube, and several gas-taking needle tubes. The experimental system is shown in Figure 1.

The coal spontaneous combustion-programmed temperature rise experimental furnace is equipped with a canned cavity containing coal samples. The height of the canned cavity is 260 mm, the inner diameter is 95 mm, the outer diameter is 105 mm, and the mass of coal samples that can be loaded is about 1.0 kg. During the temperature-programmed experiment, in order to ensure the uniform gas distribution and smooth ventilation of the cavity containing coal samples, a height of 2 cm is reserved at the upper and lower ends of the cavity of the coal sample tank as the free space for movement; the free space ensures that the gas preheated into the cavity can be in uniform contact with the coal sample, so that the gas sensitivity produced by the coal sample in the heating process is higher. Then, it is heated in a temperature-programmed furnace with controllable temperature, and the gas preheated to a certain temperature in the copper pipe is continuously transmitted to the coal sample tank cavity. The gas generated in the process of coal sample oxidation is taken, and its composition is analyzed until the coal sample temperature reaches the expected temperature in the experiment. The basic principle of the spontaneous combustion experimental device is shown in Figure 2.

**Experimental Steps.** The temperature-programmed experiment is mainly divided into four steps:

1. Check the air tightness of the coal sample tank, ventilation pipeline, and the joint between the pipeline and the tank in the programmed temperature rise furnace.
2. Fully mix the processed coal particles of 0−1, 1−3, 3−5, and 5−10 mm according to the mass ratio of 1:1:1:1, weigh 1 kg of the evenly mixed coal sample by balance, and put it into the coal sample tank.
3. After putting the coal sample into the coal tank cavity for leveling, recheck the air tightness of the tank and its gas pipe connector, check the air tightness of the experimental device, and calibrate the gas analysis device.
4. Turn on the gas, and use the flow control device to control the gas injected into the coal sample tank to flow into the cavity at a flow rate of 130 mL/min. First, after dry air is introduced, the temperature-programmed experiment is carried out. After the experiment, the coal particles in the tank are heated at a heating rate of 0.5 °C/min by the sampling method; when the temperature rises to the design sampling temperature, the temperature is kept constant for 2 min and then the gas is sampled and analyzed in the gas analysis system.

**RESULTS AND DISCUSSION**

**Production Law of CO and CO₂.** It can be seen from Figure 3 that with the increase of the coal sample temperature, the production of CO gradually increases, and the change trend is first gentle and then exponential. When the coal is at 20 °C, the presence of CO gas is detected. With the continuous increase of the coal sample temperature, the production rate of CO increases gradually. When the coal temperature exceeds 160 °C, the production rate of the coal sample takes a qualitative leap, the coal sample enters the full oxidation reaction stage, and the production amount and production rate of CO increase rapidly. It can also be seen from Figure 3 that the variation curve of CO concentration with temperature conforms to the laws of sensitivity, regularity,
measurability, and monotonicity; therefore, it can be considered that CO can reflect the characteristics of coal spontaneous combustion in the Gaohe coal mine 3# coal W1310 face and can be used as the landmark gas for judging coal spontaneous combustion in the Gaohe coal mine 3# coal W1310 face.

It can be seen from Figure 4 that CO$_2$ production increases nonlinearly with the increase of the coal sample temperature.

When the coal temperature is gradually heated from 20 °C to about 150 °C, the production of CO$_2$ gradually increases, but there is a certain fluctuation in the production of CO$_2$ gas in this process, indicating that CO$_2$ gas is not completely generated by coal spontaneous combustion and oxidation, and a small amount of it belongs to coal adsorption gas. Thus, from the perspective that the selection index principle does not comply with the principle of uniqueness and monotonic change, CO$_2$ should not be used as the landmark gas of coal spontaneous combustion in the W1310 face of Gaohe coal mine.

**Generation Law of CH$_4$ Gas.** It can be seen from Figure 5 that the CH$_4$ gas concentration gradually increases with the increase of the coal sample temperature. When the coal sample temperature is 20 °C, the existence of CH$_4$ gas has been detected; at this time, methane gas mainly exists on the coal sample surface in free form. With the increase of coal temperature, the gas concentration increases gradually, the rising rate remains basically unchanged, and the adsorbed methane desorption is free. After the temperature reaches 140 °C, the CH$_4$ gas concentration basically changes little, indicating that the methane gas in the coal sample is basically desorbed. Although the variation law of CH$_4$ gas concentration meets the principle of gas index optimization, CH$_4$ is generally not selected as the judgment index of coal seam spontaneous combustion risk because there is always gas in coal samples.

**Generation Law of C$_2$H$_4$ and C$_2$H$_2$ Gases.** The generation of C$_2$H$_2$ gas is very rare and has strong temperature range characteristics. Even if it occurs, it also occurs in the violent oxidation stage of coal; at this time, the coal temperature exceeds 200 °C. As long as the existence of C$_2$H$_2$ gas is detected, it can be considered that the residual coal in the goaf has the risk of spontaneous combustion, which is in line with the optimization principle of coal spontaneous combustion gas prediction. Therefore, C$_2$H$_2$ gas is used as the prediction index to judge coal spontaneous combustion.

As can be seen from Figure 6, the generation of C$_2$H$_4$ has obvious temperature range characteristics. No C$_2$H$_4$ gas is produced at the temperature of 0–140 °C. When the temperature reaches 140 °C, C$_2$H$_4$ begins to appear, and its gas production and production rate increase rapidly with the increase of temperature, but the total production is also relatively small. When the temperature reaches 200 °C, the C$_2$H$_4$ gas concentration is only 10.34 × 10$^{-6}$ ppm. When the temperature is 140 °C, C$_2$H$_4$ gas is generated, indicating that the coal sample has entered the rapid oxidation stage, and the
generation of the gas meets the gas optimization principle of the prediction index of residual coal spontaneous combustion. Therefore, the generation of C₂H₆ can be used as one of the gas indexes for judging the prediction of residual coal spontaneous combustion in goaf.

Generation Law of C₂H₆ and C₃H₈ Gases. As can be seen from Figure 7, C₂H₆ gas concentration gradually increases with the increase of the coal sample temperature, but C₂H₆ gas concentration fluctuates up and down in the range of 70−150 °C. When the temperature is 40 °C, C₂H₆ gas begins to be detected. The generation temperature and variation law of C₂H₆ gas are in line with the optimization principle of gas spontaneous combustion prediction; in view of the poor regularity of C₂H₆ concentration variation with temperature, the occurrence temperature of C₂H₆ is selected as the auxiliary index of coal seam spontaneous combustion in the W1310 coal face.

As can be seen from Figure 8, C₃H₈ gas concentration shows strong temperature characteristics. The presence of C₃H₈ gas was detected when the coal sample temperature was 140 °C; then, the C₃H₈ gas concentration increased nonlinearly with the increase of temperature. When the temperature reaches 200 °C, the concentration of C₃H₈ gas is detected to be 5.57 × 10⁻⁶ ppm. According to the variation law of C₃H₈ gas concentration with temperature, the occurrence temperature of C₃H₈ gas can be used as an auxiliary index of coal seam spontaneous combustion in the W1310 coal face. Once C₃H₈ is detected underground, it indicates that the coal temperature has exceeded 150 °C and the residual coal has undergone severe oxidation.

Optimization of Coal Spontaneous Combustion Marker Gas. By analyzing the gas generation law and ratio of coal spontaneous combustion marker gas optimization test, the characteristic temperature and index gas of coal spontaneous combustion can be obtained. The characteristic temperature and gas characterization of coal seam spontaneous combustion marker gas optimization test in the W1310 coal face are shown in Table 2. Based on Table 2, the coal seam spontaneous combustion marker gas of the W1310 coal face is optimized, and the results are shown in Table 3.

FIELD MEASUREMENT OF “THREE ZONES” OF SPONTANEOUS COMBUSTION IN GOAF

Engineering Background. W1310 working face is the working face of Gaomeng energy West panel 1 of Lu’an group, with an average distance of 65.4 m from the upper 9# coal seam, the goaf of W1309 working face in the north, and w1311 working face (undrawn area) in the south. The strike length of the working face is 320 m, the dip length is 1872 m, the dip angle of the coal seam is 5°, the average buried depth of the coal seam is 450 m, the thickness of the coal seam is 6.57 m, the mining height of the working face is 3.5 ± 0.1 m, the caving height is 3.07 m, the mining and caving ratio is 1:0.87, the coal cutting recovery rate is 98%, the top coal recovery rate is 88%, and the comprehensive recovery rate is 93.1%. The basic parameters of the roof and roadway section of the working face are shown in Table 4. The coal in 3# coal seam is lean, and the coal dust is explosive. There is no risk of coal (rock) and gas (carbon dioxide) outburst, and there is no spontaneous combustion. It is a coal seam, the spontaneous combustion of which is not easy. The average ground temperature is about 23 °C, and the ground pressure is normal. The shortest spontaneous combustion period is 80 days, the oxygen consumption rate in fresh airflow at 23 °C is 1.472 × 10⁻⁵ mol/(m²·s), the measured pressure of coal seam gas is 0.3−2.2 MPa, and the permeability is less than 0.5 × 10⁻¹⁵ m². The coal seam has spontaneous combustion tendency and belongs to class I coal seam prone to spontaneous combustion. Coal seam 3# is identified as a high gas mine. The working face adopts two inlet and one return Y-type ventilation modes. During the normal production of the working face, the air volume of adhesive tape roadway is 3210 m³/min, the air volume of track roadway is 795.6 m³/min, the coal seam gas emission of the working face is 0.11 kg/s, and the gas emission of the goaf is 0.247 kg/s (see Table 4 for the occurrence of the working face).

Experimental Equipment. The “three zones” of spontaneous combustion in the goaf of W1310 working face of Gaomeng coal mine mainly show the gas and temperature data in the goaf and analyze the changes of gas composition and concentration in the goaf with the advance of the working face. 500 m flame-retardant polyethylene bundle pipes with an inner diameter of 8 mm and 6 in. a cluster, 50 steel pipes with a length of 6 m (standby), 7 T-flanges, 50 pipe joints, two 2×4 mining intrinsically safe vacuum negative pressure air pumps, 10 air bags, 1 GC-2010 gas chromatograph, one computer, two bundles of ties, three bags of wrenches, pliers, yellow mud, and so forth are taken. The main gas production device and gas sample analysis system are shown in Figure 9.
Table 2. Characteristic Temperature and Gas Characterization of Coal Seam Spontaneous Combustion Marker Gas Optimization Test in the W1310 Working Face

| characteristic temperature | characterization parameters | temperature/°C | remarks |
|---------------------------|----------------------------|----------------|---------|
| critical temperature      | the decrease of oxygen concentration increased | 50–60          | small molecular substances are easy to oxidize, chemical bonds are easy to break, and a few functional groups are easy to react in coal |
| dry crack temperature     | produce ethane, ethylene, and other gases; release a large amount of volatile matter | 150            | the molecular structure of coal has changed greatly, resulting in free radicals, and the fracture and cracking of side chains and bridge bonds are accelerated |

Table 3. Spontaneous Combustion Sign Gas of Coal Seam in W1310 Coal Mine Face

| index classification | indicator name | occurrence temperature/°C | concentration (ratio)/10⁻⁶ |
|----------------------|----------------|---------------------------|---------------------------|
| main indicators      | CO             | 25                        | 6.87–15.10                | 5160 |
| auxiliary index      | C₂H₄           | 150                       | 0                         | 10.34 |
|                      | C₂H₆           | 50                        | 2.77–6.07                 | 49.83 |
|                      | C₃H₈           | 150                       | 0                         | 5.57  |
|                      | CO/CO₂         |                           | 0.01                      | 0.38  |

Table 4. Occurrence Characteristics of Coal Seams in Working Face

| name          | rock name                  | thickness/m | proctor hardness/f | lithologic characteristics                                      |
|---------------|----------------------------|-------------|--------------------|----------------------------------------------------------------|
| main roof     | fine-grained sandstone–medium-grained sandstone–sandy mudstone | 18.55–25.9 | 4.04               | gray, medium thick, mainly sandstone, locally intercalated with sandy mudstone and carbonaceous debris |
| direct roof   | sandy mudstone–fine sandstone | 2.30–3.35  | 2.70               | dark gray, mainly quartz, thin layer, parallel bedding, siliceous cementation, and poor sorting |
| false roof    | mudstone                   | 0.20–0.50   | 1.22               | dark gray, thick-layered, semi-hard, rich in incomplete plant root, and leaf fossils |
| 3# coal seam  | coal seam                  | 5.60–7.10   | 0.70               | black, massive, mainly bright coal, followed by dark coal |
| direct        | sandy mudstone–fine sandstone | 1.01–1.40  | 2.08               | grayish green, thin layer, horizontal bedding, containing argillaceous strips; vertical fractures are developed and filled with calcite |
| bottom old    | fine-grained sandstone–medium sandstone–sandy mudstone | 21.00–27.39 | 3.00               | grayish white, mainly quartz, containing rock debris, with horizontal bedding and mica flakes on the layer |

Figure 9. Field experimental equipment. (a) Automatic negative pressure gas sampler. (b) Gas chromatography system.

Experimental Scheme. In order to accurately observe and study the gas distribution law in the goaf of W1310 general mining face, seven measuring points are arranged in the working face. Measuring points 1, 2, and 3 are laid along the W1310 transport channel, and the measuring points are arranged at an interval of 27 m according to the scheme. In the back side of the working face, the measuring points 4, 5, and 6 are adjusted to be 14, 27.5, and 46 m away from the flexible membrane wall according to the site conditions. Two bundle pipes are used as a group and placed at one measuring point, and 1 m bundle pipes are reserved outside the flexible membrane wall of the roadway along the goaf. The plane layout of the buried pipe observation probe in the W1310 working face is shown in Figure 10. According to Section 3.2.4, the experiment optimized the results of the spontaneous combustion indicator gas in the coal seam of the W1310 coal mining face. The main gases measured in the field experiment are: O₂, CO, CO₂, CH₄, and C₃H₈. According to the above arrangement scheme of the beam tube detection system, the statistics of point numbers and laying positions of the beam tube monitoring system are shown in Table 5.

Experimental Results and Analysis. O₂ Concentration Measurement Results and Analysis. The oxygen concentration in goaf is of great significance to analyze the “three zones” of spontaneous combustion in goaf, and it is also the most commonly used index in the division of “three zones” of spontaneous combustion in goaf. O₂ concentration is closely related to the oxidation capacity of residual coal, coal rock collapse density in goaf, air leakage in goaf, and so forth. According to the field-measured data, the variation of O₂ concentration at the inlet and return air sides of the working face with the advancing distance is drawn, as shown in Figure 11.

It can be seen from Figure 11 that with the advancement of the working face, the O₂ concentration shows a downward trend and finally tends to 6%. It can be seen from the change rate that the O₂ concentration at the return side decreases faster than that at the inlet side of the adhesive tape roadway. The O₂ concentration decreased to 18%, the working face of the air inlet side was pushed forward by 50 m, the return side was pushed forward by 10 m, and the return side entered the
oxidation zone 40 m in advance than the air inlet side. The O₂ concentration decreased to 8%, the working face on the inlet side was advanced by 13 m, the return side was advanced by 43 m, and the return side entered the asphyxia zone 92 m in advance than the inlet side. This is mainly because the air inlet side is close to the protective coal pillar, the roof collapse is relatively slow, the pores are relatively large, the air flow has a strong ability to penetrate the goaf, the heat dissipation conditions are good, the heat is not easy to accumulate, and the oxidation intensity of residual coal is relatively low. In the return air roadway, the roof collapses rapidly, the overlying strata collapse and compact quickly, and the O₂ concentration decreases rapidly due to the influx of gas released from the goaf and the oxidation of residual coal. It can be seen from point 3 that the O₂ concentration cannot be monitored when the working face advances about 70 m. It is speculated that point 3 is flooded because the terrain of point 3 is low and water in the working face and goaf flows to the low terrain, so it is impossible to collect gas samples, and the layout of point 3 fails. The O₂ concentration at point 4 has been relatively high, and the decline rate is slow. It is speculated that there may be air leakage in the flexible membrane wall along the goaf retaining roadway or an air leakage channel is formed between the high extraction roadway and the goaf.

**Figure 11.** Variation curve of O₂ concentration with advancing distance. (a) Air inlet side. (b) Return air side.

**Table 5. Layout of Measuring Points**

| place                      | measuring point number | layout position     | layout mode                                                                 |
|----------------------------|------------------------|---------------------|-----------------------------------------------------------------------------|
| W1310 working face belt     | 1                      | 15 m from the goaf  | the bundle pipe is laid along the bottom plate of the adhesive tape roadway |
| W1310 working face belt     | 2                      | 42 m from the goaf  |                                                                              |
| W1310 working face belt     | 3                      | 69 m from the goaf  |                                                                              |
| W1310 rear slide (group 1) | 4                      | 45 m from the return wind tunnel | the bundle pipe is laid along the outer edge of the scraper conveyor at the tail of the hydraulic support |
| W1310 rear slide (group 1) | 5                      | 27 m from the return wind tunnel |                                                                              |
| W1310 rear slide (group 2) | 6                      | 14 m from the return wind tunnel |                                                                              |
| W1310 rear slide (group 2) | 7                      | 45 m from the return wind tunnel | the bundle pipe is laid along the outer edge of the scraper conveyor at the tail of the hydraulic support |

**Measurement Results and Analysis of CO Concentration.**

CO concentration can be used as a sign of the oxidation degree of residual coal in the initial goaf. The appearance of CO concentration indicates that the residual coal in goaf has been
oxidized. The higher the CO concentration, the more intense is the oxidation degree of residual coal. The variation relationship between the CO concentration in the goaf and the advancing of working face is shown in Figure 12.

The CO concentration in the goaf generally increases first and then decreases, and the CO concentration at the return side is higher than that at the inlet side. At the air inlet side, the CO concentration is almost 0 at about 40 m away from the working face, and the CO rate rises rapidly at 40−120 m, reaching the maximum value of 311 ppm at about 120 m, indicating that there is a loose zone within 40 m away from the working face. At a distance of 40 m away from the working face, it enters the oxidation temperature rise zone, the residual coal begins to oxidize, and the oxidation process increases. The return side reaches the peak at 80 m and then enters the asphyxia zone. The coal oxidation is inhibited, and the CO concentration decreases gradually. The CO concentration at point 4 has been relatively low. Although coal oxidation has been occurring near the flexible membrane wall, due to the air leakage of the flexible membrane wall or the formation of air leakage channel with the high extraction roadway, the return airflow takes away part of CO, resulting in the concentration fluctuation in the range of 50 ppm.

Figure 12. Variation curve of CO concentration with advancing distance. (a) Air inlet side. (b) Return air side.

Figure 13. Variation curve of CO2 concentration with propulsion distance. (a) Air inlet side. (b) Return air side.

Figure 14. Variation curve of CH4 concentration with advancing distance. (a) Air inlet side. (b) Return air side.
Measurement Results and Analysis of CO₂ Concentration. The peak CO₂ concentration can be used to judge whether the goaf enters the asphyxia zone or not, and the severity of residual coal oxidation reaction can also be judged according to the CO₂ generation rate. The variation relationship between the CO₂ concentration in goaf and the advancing of working face is shown in Figure 13. As can be seen from Figure 13, the CO₂ concentration at each measuring point shows a continuous increasing trend and finally reaches the peak value of 1%, which tends to be stable. The air inlet side reaches the peak at about 160 m, and the return side reaches the peak at about 80 m and then tends to be stable. It shows that when the CO₂ concentration reaches the peak, the overlying roof of the goaf basically collapses and enters the suffocation zone. The CO₂ concentration tends to be stable, indicating that the overburden collapse is backward, the compaction degree is good, the air leakage wind speed in the goaf is small, and the CO₂ produced by oxidation is not easy to diffuse to other areas. The CO₂ concentration near the flexible membrane wall has been relatively low and has a slow increasing trend, indicating that the residual coal near the return air roadway has been oxidized and the rate is accelerating.

Determination Results and Analysis of CH₄ Concentration. As shown in Figure 14, the overall gas concentration distribution shows that the return air side is always higher than the inlet air side, and with the advancement of the working face, the gas concentration shows a change trend of first rising and then falling, and there is a gas jump in some parts, indicating that there is gas accumulation in some parts. It can be seen from the data of measuring point no. 6 that as the residual coal has just been scattered in the goaf, the gas in the coal has not been completely desorbed. With the advance of the working face, the gas in the residual coal is gradually desorbed under the action of airflow, resulting in the increase of gas concentration. With the action of airflow, the gas in floating coal is continuously diluted, and the gas concentration decreases.

To sum up, in the whole monitoring process, the variation laws of O₂, CO, CO₂, and CH₄ gas concentrations with the advance of the working face were monitored, and there were no C₂H₂ and C₂H₄ gases. By testing the gas production of CO, CO₂, CH₄, C₂H₆, C₂H₅, and C₃H₈ during the programmed temperature rise of coal samples, it can be seen that C₂H₆ and C₃H₈ gases will be generated when the temperature reaches more than 150 °C, and the temperature is much higher than the coal seam temperature. Therefore, C₂H₂ and C₂H₄ gases will not be generated during the advancement of the working face. At the same time, because the goaf is a closed area, it is impossible to measure the air leakage wind speed in the goaf on-site. Therefore, the “three zones” of goaf spontaneous combustion are divided according to the oxygen supply environment of coal spontaneous combustion: heat dissipation zone (oxygen concentration > 18%), oxidation temperature rise zone (8% < oxygen concentration ≤ 18%), and suffocation zone (oxygen concentration ≤ 8%). Finally, the range of “three zones” is determined as follows: heat dissipation zone: 0–60 m; oxidation temperature rise zone: 60–200 m; and suffocation zone: >200 m.

Numerical Simulation of the Three Zones of Spontaneous Combustion in Y-Ventilation Goaf

Physical Model. The strike length of the W1310 working face in Gaohe coal mine is 310 m. According to the scholars’ experience in numerical simulation of Y-type ventilation and on-site actual production experience, the depth of goaf is taken as 400 m.³⁵ The average thickness of coal seams available for mining in the working face is 6.71 m. After surface exploration, the influence area is formed after coal seam mining, that is, the vertical height of “three zones” formed is 40 m. Therefore, the 1:1 size simulation is adopted. The longitudinal height of the model is 40 m, the working face is 5 m wide and 5 m high, the adhesive tape roadway is 5 m wide and 5 m high, the track roadway is 5.2 m wide and 5 m high, and the roadway reserved along the goaf is 5.2 m wide and 5 m high. The conclusion of the influence of roadway length on the simulation results in references is quoted.³⁶ The simulation effect is the best when the length of track roadway and adhesive tape roadway is 20 m. Therefore, the length of track roadway and adhesive tape roadway in this model is 20 m. According to the above parameters, the established physical model is shown in Figure 15.

Grid Division. Due to the good regularity of the physical model of goaf, in order to improve the calculation accuracy and efficiency, the structural grid (quad method) is used to mesh the model in this paper. The airflow around the roadway will produce turbulence under the action of the wall. In order to capture more wall surface airflow disturbance, the model sets four layers of boundary layer grid and encrypts the working face grid, roadway grid, and airflow concentration. Finally, 3375411 grids are obtained. The detected grid quality is more than 0.9, and the quality is good. The divided grid and model grid are shown in Figure 16.

Boundary Conditions. According to the field measurements, the air volume of adhesive tape roadway and track roadway in the normal production process of the working face is Q_{adhesive tape} = 3210 m³/min and Q_{track} = 795.6 m³/min; the air volume of adhesive tape roadway and track roadway in the working face is calculated as 3:1 and 2:1, that is, Q_{adhesive tape} = 3Q_{track} and Q_{adhesive tape} = 2Q_{track}. The model in this paper uses the condition that the airflow concentration is the best when the airflow concentration is the best when the airflow concentration is the best when the airflow concentration.
3210 m³/min: \( Q_{\text{track}} = 1070 \) m³/min and \( Q_{\text{adhesive tape}} = 3210 \) m³/min: \( Q_{\text{track}} = 1605 \) m³/min. The wind speed at each point on the roadway section is considered to be approximately equal, and the calculated wind speeds of the adhesive tape roadway and track roadway are 2.41 and 0.52 m/s, respectively. The section entrance of adhesive tape roadway and track roadway is set as the velocity inlet, the outlet of gob retaining roadway is set as the outflow, the hydraulic support at the junction of the working face and goaf is set as the interior, and the wall of gob retaining roadway and goaf are set as the internal boundary. The goaf is set as porous media, except that all boundaries are set as wall boundaries. The settings of boundary conditions for different partitions are shown in Table 6. With the advancement of the working face, the compaction speed is very low, the difficulty of oxygen diffusion gradually increases, and the oxygen is gradually consumed and reduced in the diffusion process, showing a linear downward trend.

(2) In the Y direction, the oxygen concentration near the gob retaining roadway in the goaf keeps a high level from the working face to the depth of the goaf, the oxygen concentration near the working face is high, the oxygen concentration gradient at the intersection of the working face and the track roadway is wide, the range is large, and the oxygen concentration distribution law presents a semi “t” shape. It is mainly because the air leakage wind speed near the working face in the goaf is large, and the heat generated by residual coal oxidation is not easy to accumulate, which inhibits the oxygen consumption of coal oxidation. Therefore, the oxygen concentration near the working face is high. The high oxygen concentration near the gob retaining roadway is due to the lax sealing of the flexible membrane wall and the airflow in the return roadway leaks into the goaf through the flexible membrane wall.

(3) In the Z direction, the airflow forms a three-dimensional flow field due to buoyancy, resulting in the irregular distribution of oxygen affected by the airflow in the Z direction. At the same height as the working face (within 0~5 m), the distribution law of oxygen concentration is basically the same. On the plane higher than the working face \((Z > 5 \) m), due to the reduction of air leakage flow in goaf, oxygen will be reduced accordingly, and the width of oxygen concentration will be narrowed accordingly.

(4) When the air volume proportion \( (Q_{\text{adhesive tape}}/Q_{\text{track}}) \) gradually increases (i.e., the air volume of adhesive tape roadway increases and the air volume of track roadway remains unchanged), the wider the width of oxygen concentration zone near the return air side, the greater is the change gradient.

### Influence of Air Volume Ratio between Adhesive Tape Roadway and Track Roadway on “Three Belts” of Spontaneous Combustion

In order to study the influence of the air volume ratio of adhesive tape roadway and track roadway on the “three belts” of spontaneous combustion in goaf, based on the above analysis, two typical representative points are selected, which are 30 m away from the adhesive tape roadway and 30 m away from the return air roadway, after the postprocessing analysis of the oxygen concentration distribution obtained from the numerical simulation under the three working conditions that the air volume ratio of adhesive tape roadway and track roadway is \( Q_{\text{adhesive tape}}/Q_{\text{track}} = 4:1, Q_{\text{adhesive tape}}/Q_{\text{track}} = 3:1, \) and \( Q_{\text{adhesive tape}}/Q_{\text{track}} = 2:1 \). As can be seen from Figure 17:

1. In the X direction, the distribution of oxygen concentration shows obvious regionality. The deep color from the working face to the goaf shows red/green/blue changes. The oxygen concentration is high near the working face and gob retaining roadway; as the distance between the residual coal in the goaf and the working face becomes farther, the oxygen concentration gradually decreases until the oxygen concentration at 400 m from the working face reaches 2%. This is mainly because the airflow enters the goaf from the working face, the resistance effect of the goaf exists, the wind

| partition | settings of boundary conditions |
|-----------|-------------------------------|
| section entrance of adhesive tape roadway | velocity inlet |
| section entrance of track roadway | velocity inlet |
| gob-side entry exit | outflow |
| hydraulic support at the junction of the working face and goaf | interior |
| goaf | porous |
| other walls | wall |

characteristics of the goaf are constantly changing, and various parameters in the porous media area have great differences in their impact on the flow field. On the premise of the rational use of the theory of horizontal “three zones” and vertical “three zones” in the goaf space, the basic parameters are obtained by field measurement through mathematical analysis and user-defined methods. The porosity, viscous resistance coefficient, and inertial resistance coefficient of porous media are written into UDF by C++ language.

**Numerical Method.** The software ANSYS FLUENT is used for numerical simulations. The state parameter is set to steady, the type is set to pressure-based, the standard k-epsilon double-equation model is selected, and the SIMPLEC pressure velocity correlation algorithm is adopted. The second order upwind algorithm is used to discretize the convection term of the momentum equation. After 500 steps of iteration, the calculated residuals of velocity and \( O_2 \) concentration are less than \( 10^{-6} \), reaching convergence and meeting the requirements of “three zones”.

**Numerical Simulation Results.** Figure 17 shows the simulation results of \( O_2 \) concentration distribution in goaf with different air volumes of adhesive tape roadway and track roadway, \( Q_{\text{adhesive tape}}/Q_{\text{track}} = 4:1, Q_{\text{adhesive tape}}/Q_{\text{track}} = 3:1, \) and \( Q_{\text{adhesive tape}}/Q_{\text{track}} = 2:1 \). As can be seen from Figure 17:

1. In the Y direction, the distribution of oxygen concentration shows obvious regionality. The deep color from the working face to the goaf shows red/green/blue changes. The oxygen concentration is high near the working face and gob retaining roadway; as the distance between the residual coal in the goaf and the working face becomes farther, the oxygen concentration gradually decreases until the oxygen concentration at 400 m from the working face reaches 2%. This is mainly because the airflow enters the goaf from the working face, the resistance effect of the goaf exists, the wind

2. In the X direction, the oxygen concentration near the gob retaining roadway in the goaf keeps a high level from the working face to the depth of the goaf, the oxygen concentration near the working face is high, the oxygen concentration gradient at the intersection of the working face and the track roadway is wide, the range is large, and the oxygen concentration distribution law presents a semi “t” shape. It is mainly because the air leakage wind speed near the working face in the goaf is large, and the heat generated by residual coal oxidation is not easy to accumulate, which inhibits the oxygen consumption of coal oxidation. Therefore, the oxygen concentration near the working face is high. The high oxygen concentration near the gob retaining roadway is due to the lax sealing of the flexible membrane wall and the airflow in the return roadway leaks into the goaf through the flexible membrane wall.

3. In the Z direction, the airflow forms a three-dimensional flow field due to buoyancy, resulting in the irregular distribution of oxygen affected by the airflow in the Z direction. At the same height as the working face (within 0~5 m), the distribution law of oxygen concentration is basically the same. On the plane higher than the working face \((Z > 5 \) m), due to the reduction of air leakage flow in goaf, oxygen will be reduced accordingly, and the width of oxygen concentration will be narrowed accordingly.

4. When the air volume proportion \( (Q_{\text{adhesive tape}}/Q_{\text{track}}) \) gradually increases (i.e., the air volume of adhesive tape roadway increases and the air volume of track roadway remains unchanged), the wider the width of oxygen concentration zone near the return air side, the greater is the change gradient.

Table 6. Settings of Boundary Conditions for Different Partitions

| partition | settings of boundary conditions |
|-----------|-------------------------------|
| section entrance of adhesive tape roadway | velocity inlet |
| section entrance of track roadway | velocity inlet |
| gob-side entry exit | outflow |
| hydraulic support at the junction of the working face and goaf | interior |
| goaf | porous |
| other walls | wall |
range of oxygen concentration in the heat dissipation belt is smaller, indicating that the increase of air volume has less impact on the heat dissipation belt.

**Comparative Analysis of Field-Measured Data and Simulation Results.** By arranging the beam tube monitoring system in the W1310 working face of Gaohe coal mine for 3 months, the gas in the goaf was extracted and analyzed by a GC-2010 gas chromatograph, and 31 groups of oxygen concentration change data at the air inlet side were obtained. The comparison between the field-measured data and the simulated data at the same position is shown in Figure 19.

It can be seen from Figure 19 that the measured value in the heat dissipation zone is greater than the simulated value, and the simulated value in the oxidation temperature rise zone is greater than the measured value first. As the working face advances to 95 m, the measured O₂ concentration is equal to the simulated result, indicating that the simulated oxygen consumption and the actual oxygen consumption reach a dynamic balance at this point, and the simulated value after this point is greater than the actual value. At a distance of 200 m from the working face, the actual measured oxygen concentration on-site is lower than 8%, entering the asphyxia...
zone, while the simulated measured oxygen concentration is still in the oxidation temperature rise zone. This is mainly because in the process of numerical simulation, the goaf is only divided into three sections of porous media with different properties, and O2 dissipation is also set to the error caused by the fixed value. However, from the perspective of safety, this result increases the safety factor of spontaneous combustion in the goaf, and the simulation results are basically consistent with the overall trend of measured O2 concentration, which can better guide the safe production of the working face.

Linear Regression Analysis of Oxygen Consumption Rate. Due to the large air volume at the inlet side and small air volume at the return side of the goaf, the width of the oxidation temperature rise zone at the inlet side is greater than that at the return side. Therefore, theoretically, as long as the safety of the air inlet side is ensured, the spontaneous combustion of residual coal will not occur at the air return side. At the same time, in order to guide the mine safety production and dynamically determine the goaf state, the O2 concentration measured by numerical simulation in Figure 18 is selected for regression analysis. It can be seen from Figure 18 that the oxygen content in the goaf shows a linear downward trend with the increase of the distance from the working face, so the linear regression method is used to carry out the regression analysis of O2 concentration with the distance from the working face, as shown in Figure 20.

Figure 20 shows that there is a good linear relationship between the oxygen concentration obtained by numerical simulation and the field-measured O2 concentration and the advancing distance of the working face, and the fitting accuracy of the two is high. Therefore, the linear equation after regression can be used to dynamically determine the O2 concentration at a point away from the goaf and roughly determine the “three zones” state of the point. At the same time, according to the regression equation between the numerical simulation results and the measured values, it can be seen that there is little difference between the slope and intercept values of the regression equation between the numerical simulation results and the measured values, which further verifies the accuracy of the numerical simulation results.
CONCLUSIONS

Taking the W1310 working face of Gaohe coal mine as an example, through the theoretical analysis of the influencing factors and seepage characteristics of residual coal spontaneous combustion under the condition of Y-type ventilation, the characteristic parameters of the coal sample of the working face are analyzed in the laboratory, the “three zones” of on-site spontaneous combustion are measured, and the three-dimensional numerical simulation of the multifield change law of goaf is carried out by using ANSYS FLUENT software. The three-dimensional seepage field, gas concentration field, oxygen concentration field, and pressure field of gas components in goaf during the advancement of the goaf working face are simulated. Based on the analysis of the parameters of porous media in goaf and combined with the actual situation, the UDF of key parameters such as porosity, viscous resistance coefficient, and inertial resistance coefficient of porous media in goaf is compiled. The distribution law of “three zones” of residual coal spontaneous combustion in goaf is deeply studied. The following conclusions are drawn:

(1) The characteristic parameters of coal spontaneous combustion are measured experimentally. Through the standardized treatment of coal samples in the W1310 working face of Gaohe coal mine, the temperature-programmed test of 20–200 °C is carried out in the temperature-programmed experimental system, the relationship between the gas composition produced by coal oxidation and temperature is obtained, and the oxygen consumption and heat release characteristics of coal samples are analyzed. The prediction gas index of coal spontaneous combustion in the W1310 face of Gaohe coal mine is optimized.

(2) Through the analysis of the influencing factors of spontaneous combustion in goaf and the seepage characteristics of goaf under Y-type ventilation mode, combined with the horizontal “three zones” and vertical “three zones” theory of goaf, it is considered that the media in goaf are regional, and the factors affecting residual coal spontaneous combustion in the working face, ventilation mode, and coal seam geological structure are comprehensively considered. A “two-way and one vertical” goaf index gas and temperature monitoring system is designed to obtain the gas composition and temperature data of goaf, so as to distinguish the residual coal state of goaf and provide data support for the verification of numerical simulation results.

(3) A three-dimensional physical model of goaf proportional to the actual production of Gaohe coal mine is established. Based on the analysis of the parameters of porous media in goaf and combined with the actual situation, the UDF of key parameters such as porosity, viscous resistance coefficient, and inertial resistance coefficient of porous media in goaf is compiled. The three-dimensional seepage field, gas concentration field, oxygen concentration field, and pressure field of gas components in goaf during the advancement of the goaf working face are simulated and calculated by using ANSYS FLUENT software. The simulation results are in good agreement with the field-measured results of the W1310 working face. By changing the air volume ratio between adhesive tape roadway and track roadway (i.e., the air volume of adhesive tape roadway remains unchanged, and the air volume of track roadway increases), it is proved that the scope and location of goaf near the oxidation natural zone on one side of the adhesive tape roadway increase, but the increase is not obvious. Near the track carriageway, with the increase of the airflow ratio, the airflow resistance between the belt carriageway and the track carriageway increases. The more disordered the gas flow is, the more gas enters the goaf, and the width of the oxidation temperature rise zone in the goaf increases significantly and moves to the deep.

(4) The oxygen consumption rate of coal samples in Gaohe coal mine increases with the increase of coal temperature. Below 50 °C, the oxygen consumption rate increases slowly with the linear law. After exceeding 50 °C, the oxygen consumption increases rapidly, according to the linear law. According to the measured results of coal spontaneous combustion prediction index gas experiment, it is determined to take CO as the main coal spontaneous combustion prediction index gas and the production of C2H4, C3H8, and C2H6 as the auxiliary coal spontaneous combustion prediction index gases to comprehensively judge the state of residual coal in goaf.

(5) Based on the type of spontaneous combustion sign gas determined by the experiment, a beam tube monitoring system is arranged in the W1310 working face of Gaohe coal mine to monitor the gas composition in goaf. The O2 concentration shows a decreasing trend, and the decreasing speed of O2 concentration on the return side is greater than that on the inlet side of adhesive tape roadway. The CO concentration in the goaf generally increases first and then decreases, and the CO concentration on the return side is higher than that on the inlet side. The CO2 concentration of each measuring point shows a continuous increasing trend and finally reaches the peak value of 1%, which tends to be stable. The gas concentration distribution as a whole shows that the return air side is always higher than the inlet air side, and with the advancement of the working face, the gas concentration as a whole shows a change trend of first rising and then falling, with gas jump in some parts and gas accumulation. Taking the oxygen concentration as the division standard of “three zones”, the final range of “three zones” is determined as: heat dissipation zone: 0–60 m; oxidation temperature rise zone: 60–200 m; and suffocation zone: more than 200 m.

(6) The distribution of oxygen concentration field in goaf under different air volume ratios in machine roadway and air roadway is simulated. With the increase of the air volume ratio of Q_adhesive tape/Q_track (i.e., the air volume of adhesive tape roadway remains unchanged, and the air volume of track roadway gradually increases), the wider the width of oxygen concentration zone near the return air side, the greater is the change gradient. The ratio of air volume between the adhesive tape roadway and track roadway has an obvious impact on the oxidation temperature rise zone and suffocation zone and has little impact on the dispersion zone. By comparing the oxygen concentration field simulation results with the field-measured oxygen concentration, the rationality of the numerical simulation results is verified within a reasonable difference range. According to the combina-
tion of air leakage wind speed and oxygen concentration, the “three areas” of spontaneous combustion in goaf are divided, and the dangerous area of goaf is determined. At the same time, the linear regression of O2 concentration in goaf is carried out, and the regression equation is obtained. According to the equation, the O2 concentration at a certain point away from the goaf can be determined dynamically, and the “three zones” state of the point can be roughly determined to guide the production increase of the working face. Therefore, the gap between theory and practice can be bridged.

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