Numerical Simulation of the Dynamic Change Law of Spontaneous Combustion of Coal Gangue Mountains

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ABSTRACT: To further study the problem of spontaneous combustion of coal gangue mountains, a multifield coupled simulation model was established based on the mathematical models of temperature field, gas concentration field, and seepage velocity field. In addition, the dynamic development law of these three physical fields in the process of spontaneous combustion is numerically simulated, and the relationship between gas concentration and temperature is studied and verified by experiments. The results show that in the initial stage of the thermal storage and heating process of the coal gangue mountain, the overall heating rate is small. With the passage of stacking time, a high-temperature area will gradually form inside, and the high-temperature area is concentrated near the windward side first and then spread to the leeward side. The oxygen on the windward side keeps a high concentration all of the time and gradually attenuates after entering the interior, and the overall concentration decreases with the extension of stacking time. The variation law of carbon monoxide concentration is opposite to that of oxygen concentration. The correlation between temperature and gas concentration. Among them, the concentration of carbon monoxide and carbon dioxide can well reflect the temperature change inside the coal gangue mountain, and the effect of carbon dioxide is better in the high-temperature area. The research results provide a theoretical reference for the prevention and control measures of spontaneous combustion of coal gangue mountains and have certain guiding significance.

1. INTRODUCTION

China’s total coal resources rank third in the world, accounting for about three-quarters of the national production and consumption structure.1 Coal gangue is a solid waste produced together with coal in the process of coal mining. It is produced in the process of coal mine construction, mining, washing, and processing, and its emission is equivalent to 10–15% of coal production.2 At present, the utilization rate of coal gangue in China is still relatively low. Most of the gangue is piled up as industrial solid waste to form gangue mountains. This long-term storage method not only occupies a large amount of land but also easily causes spontaneous combustion, which brings a series of problems such as geological disasters and air and water pollution to the surrounding areas of the mining area, hindering the green development of cities.3 At the same time, it also brings incalculable hidden harm to the lives of nearby residents.

In recent years, scholars have carried out many studies on the spontaneous combustion of coal gangue mountains through experiments and simulations. Nakamura et al.4 summarized the characteristics of spontaneous combustion of coal gangue mountains and believed that spontaneous combustion started from the inside. Wang et al.5 studied the combustion process of coal gangue by a temperature-programmed test and a thermogravimetric analysis and obtained its combustion characteristics. Du et al.6 established a fitting model of each measuring point changing with depth and obtained the temperature distribution law of coal gangue mountains in different dimensions and directions. Ozdeniz et al.7 constructed a 3.5 dimensional temperature distribution model of a gangue mountain through ArcGIS. Hao et al.8 measured the temperature of nine different depths inside a gangue mountain through experiments and thus divided the gangue mountain into five spontaneous combustion zones. Liu et al.9 conducted a thermogravimetric analysis of calcined coal gangue and believed that the high-temperature oxidation process of coal gangue was divided into four stages: volatilization of adsorbed water, slow oxidation, carbonaceous combustion, and mineral decomposition. Xia10 conducted a simulation experiment on the deep...
temperature field of the coal gangue mountain, obtained the temperature distribution law under different heat source temperatures, and predicted the heat source temperature through the relationship between temperature and depth. Sensogut et al. analyzed the relevant conditions that lead to spontaneous combustion of coal gangue mountains, performed multiple regression analyses on the temperature, and obtained the internal temperature distribution. Chen obtained a temperature prediction model based on univariate quadratic function and exponential function by analyzing the data of a coal gangue mountain temperature detection test and revealed the temperature change trend inside the coal gangue mountain. Yu derived the finite element mathematical model of the temperature field and used ANSYS software to simulate the transient temperature field of the spontaneous combustion gangue mountain. Misz-Kennan et al. explored the movement rule of the fire source inside the gangue mountain by measuring the temperature of the surface, interior, and surrounding air of the gangue mountain for many years. Smoliński et al. obtained the change law of the temperature field of the gangue mountain by monitoring the atmospheric emissions above the gangue mountain for 21 months. Krzysztof et al. determined the spontaneous combustion tendency of coal gangue mountains by experimentally measuring the properties of coal gangue. Wang et al. studied the spontaneous combustion and oxidation characteristics of coal gangue from the microscopic level and analyzed the change law of spontaneous combustion of coal gangue through experiments. Qiao conducted industrial analysis and elemental analysis on the coal gangue in Gongwusu coal mine, looking for the reason for the spontaneous combustion of the gangue mountain, and found that the local environment and stacking method have a great influence on it. Duan et al. used the principal component analysis algorithm to obtain the conclusion that oxygen, carbon monoxide, and temperature affect the spontaneous combustion of gangue. Fei used the gas index and the auxiliary index of the gas ratio to comprehensively predict the temperature and combustion degree of coal spontaneous combustion. Deng et al. used a large experimental bench to study the variation of temperature and oxygen consumption in the process of coal spontaneous combustion, and the results were basically consistent with the actual situation. Li used the Fluent numerical calculation software to simulate and study the coupling mechanism between the temperature field and the heat transfer flow field in the gangue mountain and simulated and predicted the heat transfer characteristics of the fire zone. Yang et al. established a fitting model for calculating the deep temperature from the shallow temperature by analyzing the temperature distribution in the horizontal and vertical directions of the gangue mountain, thus realizing the estimation of the internal temperature of the deep coal gangue mountain.

To sum up, at present, most of the research on coal gangue spontaneous combustion only focuses on temperature changes, but lacks research on the dynamic evolution of spontaneous combustion. Moreover, the construction of numerical models is relatively simple, and there are few reports from the perspective of multiphysics. Therefore, in this study, COMSOL is used to establish a spontaneous combustion simulation model of coal gangue mountains which fully considers the coupling of temperature field, gas concentration field, and seepage velocity field and improves the conventional model and modeling method, so that the model is closer to the natural accumulation state of an actual coal gangue mountain. Based on this numerical simulation, the development law of spontaneous combustion inside the coal gangue mountain is studied and the relationship between the concentration of relevant gases and temperature is analyzed. Finally, the experimental verification is carried out, which has important guiding significance for the prevention and control of spontaneous combustion of coal gangue mountains and the detection of heat source location.

2. MULTIFIELD COUPLING MATHEMATICAL MODEL FOR SPONTANEOUS COMBUSTION OF COAL GANGUE MOUNTAINS

2.1. Multifield Coupling Mechanism of Spontaneous Combustion of Coal Gangue Mountains. The spontaneous combustion process of coal gangue is continuously advancing under the action of multiphysics coupling, and its formation, development, and evolution mechanism are shown in Figure 1. Among them, after the air diffuses into the interior through the pores of the coal gangue mountain, it undergoes an oxidation reaction with the combustibles, releasing heat, and the accumulation of heat increases the internal temperature. On the one hand, the temperature increase will affect the flow of gas inside the gangue mountain, causing the distribution of the seepage velocity field to change, and the variation of the flow field will change the convective heat transfer intensity, thereby

![Figure 1. Mechanism of spontaneous combustion of coal gangue mountains.](https://doi.org/10.1021/acsomega.2c03251)
affecting the temperature field. On the other hand, increasing temperature will increase the oxidation reaction rate, thus affecting the gas concentration distribution. However, the acceleration of the reaction rate will also lead to a rapid decline in oxygen concentration, which will exert the exothermic strength of the reaction, thus limiting the temperature rise. The seepage velocity field formed by the gas flow promotes the diffusion of the gas, thereby forming the gas concentration field. And at the same time, it also continuously provides the oxygen required for the chemical reaction, so that the gas concentration changes with the change of the flow field.

2.2. Seepage Velocity Field. The pores in the coal gangue hill provide the necessary oxygen supply channels for the development of spontaneous combustion. Based on the continuum assumption, most experts and scholars use Darcy’s law to explain the dynamic characteristics of fluids in porous media. However, the pores in the coal gangue are large, and the shear force has a significant effect during the high-speed seepage process. In this case, the fluid motion trajectory will deviate significantly from Darcy’s law. For this reason, this study adopts another extended form of this law, the Brinkman equation, which is more suitable for high-permeability conditions. The flow model of gas in coal and rock mass is expressed by the Brinkman equation as follows

\[
\rho \frac{\partial v}{\partial t} = -\nabla p + \mu \nabla^2 v + \rho \frac{g}{\theta_s} \nabla T
\]

where \( Q_g \) is the unit seepage flow, \( \theta_s \) is the porosity of coal gangue, \( \kappa \) is the permeability, \( \mu \) is the fluid dynamic viscosity, \( \rho \) is the fluid density, and \( v \) is the velocity vector.

Velocity field is the power source of spontaneous combustion of coal gangue mountains, so it is particularly important to study the gas flow inside the mountain. When studying the flow velocity inside the mountain, predecessors only chose to set the initial boundary wind speed. This setting method is relatively rough and cannot accurately know the initial flow rate into the mountain. Therefore, this paper proposes to establish an external airflow field. The flow completing the transition between the external flow field and the gangue mountain is called turbulence, and its continuity equation and momentum equation are expressed by large-eddy simulation (LES) as follows

\[
\frac{\partial \nu_i}{\partial t} + \rho (\nu_i \nabla) v_i = \nabla \cdot (\mu \nabla v_i + \kappa) + \rho g
\]

where \(-\rho \nu_i \nu_i' \) is the sublattice stress (SGS) tensor.

2.3. Gas Concentration Field. Generally, it will be simplified as an overall control body when studying porous media, and the porosity index is used to describe the composition ratio of fluid and solid parts. The coal gangue mountain can be regarded as composed of air and coal gangue. According to the theory of mass transfer in porous media and the law of conservation of mass, the gas concentration change equation is expressed as

\[
\frac{\partial c}{\partial t} + \nabla \cdot (\nu c) = \nabla \cdot (D \nabla c) - (1 - \theta_g) r
\]

where \( c \) is the gas concentration, \( D \) is the gas diffusion coefficient in the pores, and \( r \) is the reaction rate.

Since the temperature on the windward side of coal gangue mountain is always higher than that on the windward side, a constant heat source near the windward side is usually defined in the existing spontaneous combustion simulation. In this study, to simulate the internal heat generation and development of gangue mountain, reaction heat source is defined, and the evolution of heat source is closely related to the reaction rate. The expression of the reaction rate quotes the Arrhenius expression, and the reaction rate \( r \) can be expressed as

\[
r = \epsilon \times A^f \times e^{-E_f^f}
\]

Where \( \epsilon \) is the oxygen concentration, \( A^f \) is the response frequency factor, and \( E_f \) is the activation energy of the reaction.

2.4. Temperature Field. In the spontaneous combustion process of coal gangue mountains, the main substance that reacts is carbon, which reacts with oxygen in the pores to form CO and CO2. The exothermic heat of chemical reaction provides the reaction heat source for the temperature field, and the generated heat is expressed as

\[ Q = r \times H \]

where \( H \) is the reaction enthalpy.

There are three ways of heat transfer, namely, heat conduction, heat convection, and heat radiation. Since the surface of the gangue mountain is not burning, the radiant heat can be ignored. The heat source formed inside the gangue mountain acts on the coal gangue and the gas in its pores. Heat is transferred by heat conduction and heat convection through coal gangue and gas. According to the theory of heat transfer in porous media and the law of conservation of energy and ignoring the work done by thermal stress that causes thermal expansion of coal gangue, the heat \( Q_g \) released from the combustion of coal gangue per unit volume into the matrix coal gangue can be expressed as

\[
Q_g = \frac{\rho \epsilon p \delta H}{\theta_s \delta T_s} - \nabla \times k_s \nabla T
\]

where \( \rho \) is the density of the solid, \( \epsilon p \delta H \) is the heat capacity of the solid at constant pressure, \( k_s \) is the thermal conductivity of the solid, and \( T_s \) is the temperature of the solid.

The heat \( Q_g \) released by the combustion of coal gangue per unit volume into the gas in the pores is

\[
Q_g = \frac{\theta_g \rho \epsilon p \delta H}{\theta_s \delta T_s} + \rho \epsilon p \delta H |v| \times T_g - \nabla \times k_p \nabla T
\]

where \( \rho \) is the gas density in the pores, \( \epsilon p \) is the constant pressure heat capacity of the pore gas, \( T_g \) is the gas temperature, and \( k_p \) is the gas thermal conductivity.

The total heat \( Q \) generated can be expressed by the superposition of \( Q_g \) and \( Q_g \), so the following formula can be obtained

\[
Q = \frac{\rho \epsilon p \delta H}{\theta_s \delta T_s} + \rho \epsilon p \delta H |v| \times T_g - \nabla \times k_{eff} \nabla T
\]

Where \( (\rho \epsilon p)_{eff} \) is the equivalent heat capacity and \( k_{eff} \) is the equivalent thermal conductivity.

To sum up, the spontaneous combustion of coal gangue mountains results from the combined action of the seepage velocity field, gas concentration field, temperature field, and chemical reaction. The seepage velocity field is the power source, which determines the temperature field’s heat convection and heat transfer effects. The heat source in the temperature field is the reaction heat source, which is expressed as a function of the oxygen consumption rate in the
concentration field. Under the coupling effect of the above multiple physical fields, the spontaneous combustion process of coal gangue mountains is promoted.

3. ESTABLISHMENT OF A SIMULATION MODEL

3.1. Parameter Value. To explore the change law of spontaneous combustion after coal gangue is accumulated into mountains and to observe the distribution characteristics of various physical quantities more intuitively, numerical simulations were carried out on the gas concentration field, temperature field, and seepage velocity field, respectively. Considering that the spontaneous combustion of gangue mountains is a very complex unsteady problem, to fully reflect the multiphysics coupling effect in the spontaneous combustion process and facilitate the simulation, the following assumptions are made here: (1) the solar radiation and the radiation heat transfer between coal gangue are not considered, (2) the coal gangue mountain is regarded as a uniform porous medium and is isotropic, (3) the seepage gas in the coal gangue mountain satisfies the ideal gas state equation, (4) the outside air flows evenly, (5) in the process of heating up, various physical parameters of coal gangue, such as thermal conductivity, specific heat capacity, convective heat transfer coefficient, etc., remain unchanged and are not affected by temperature, and (6) the influence of moisture on spontaneous combustion of coal gangue mountains is not considered.

The object of this paper is a gangue mountain in Ordos, Inner Mongolia, which has been piled up for many years, and there is a large number of fire sources inside, extending from the slope to the interior, and smoke can be seen in some places. Due to the large area of the whole gangue hill, only one of the platforms is simulated, as shown in Figure 2.

The model involves processes such as heat transfer and material flow in porous media. In the simulation, it is necessary to set some key parameters that reflect the environmental conditions and the basic characteristics of the gangue, and each physical parameter will participate in the operation of one or several physical fields. The test of coal gangue mountain composition includes carbon content, thermogravimetric–differential thermal–infrared (TG–DT–IR) analysis, thermal conductivity, porosity, and permeability, which can cover all of the data needed in the simulation modeling process. The basic parameters are shown in Table 1 below.

Table 1. Parameter Setting Table

| parameter name          | symbol | value (unit) |
|-------------------------|--------|--------------|
| porosity                | θ      | 0.3          |
| gangue density          | ρ      | 2000 (kg/m³) |
| thermal conductivity of coal gangue | k_p | 0.2 (W/(m·K)) |
| coal gangue constant pressure heat capacity | q_p | 1450 (J/(kg·K)) |
| fluid dynamic viscosity | D      | 1e-9 (m²/s)  |
| gas diffusivity         | D_g    | 1.43 (kg/m³) |
| coal gangue permeability | k   | 1.4e-9 (m²)  |
| pore gas constant pressure heat capacity | q_p | 1000 (J/(kg·K)) |
| response frequency factor | A'  | 5.5e10 (1/s) |
| reaction activation energy | E^f | 135e (J/mol) |

4. ANALYSIS OF SIMULATION RESULTS

Since the spontaneous combustion of coal gangue mountains is the result of an accumulation for a long time, to ensure that the heat and material flows are consistent with the actual situation, the model was set up with a base length of 27 m, a height of 8 m, and a slope angle of 45°, as shown in Figure 3.

The initial temperature was set to 25 °C, the wind speed was 3.5 m/s, the air pressure was 1 standard atmosphere, the initial concentration of O₂ was 9.375 mol/m³, and the initial concentrations of CO₂ and CO were 0 mol/m³ (because the proportion of CO₂ and CO in the actual air composition is very low, the influence of the two is ignored in the simulation). The left boundary was inflow, the top and right boundaries were outflow, and the bottom boundary was no flux. The mesh was divided into free triangular meshes, and the mesh element size was set to superfine. Among them, there were 35,050 units in total, the maximum size was 0.104 m, the minimum size was 0.0012 m, the maximum unit growth rate was 1.08, and the curvature factor was 0.25.

Figure 4. Oxygen concentration field.
simulation results are consistent with the actual situation, the simulation duration of this study is selected as a larger value, which is 150 days.

4.1. Concentration Field Analysis. 4.1.1. Oxygen Concentration Field. The oxygen concentration level will affect the rate of oxidation reaction inside the gangue mountain, thereby affecting its spontaneous combustion process. Figure 4 is the cloud map of the distribution of oxygen concentration field in coal gangue mountains on the 10th, 20th, 30th, 40th, 80th, and 150th days. Since the wind direction is set from left to right, it...
Figure 9. Flow field simulation model.

Figure 10. Vector diagram of the seepage velocity field.

Figure 11. Vector diagram of the velocity field inside the mountain.
can be seen from the figure that a high oxygen concentration is always maintained near the left side slope. And the boundary is consistent with the external environment, which is 9.375 mol/m³, and the concentration gradually reduces after entering the inside of the gangue mountain. However, sufficient oxygen makes the chemical reaction more intense, resulting in faster oxygen consumption, so the oxygen concentration in the area near the windward side gradually drops. Meanwhile, over time, the oxygen supply in the area far from the windward side is insufficient, so the concentration also declines. On the 10th, 20th, 30th, 40th, 80th, and 150th days, its oxygen concentration is about 6.42, 3.59, 1.81, 0.95, 0.1, and 2 × 10⁻³ mol/m³, respectively. It can be seen from the above result that the change in oxygen concentration is mainly concentrated in the first 40 days. After 40 days, the internal oxygen concentration decreases to below 1 mol/m³, and after 80 days, there is almost no oxygen inside. Oxygen keeps coming in from the outside world and it keeps reacting. A dynamic balance will be maintained inside the coal gangue mountain.

### 4.1.2. Carbon Dioxide Concentration Field

It can be seen from the chemical reaction that a large amount of CO and CO₂ will be produced inside the gangue mountain. Therefore, it is of great significance to study the changes in the concentration field of CO and CO₂ for the spontaneous combustion of coal gangue mountains. Figure 5 is the cloud map of the carbon dioxide concentration field distribution on the 10th, 20th, 30th, 40th, 80th, and 150th days. In the figure, CO₂ starts to be generated while the oxidation reaction occurs inside. As time goes by, oxygen is continuously consumed, and CO₂ content gradually increases. The more violent the chemical reaction, the higher the CO₂ concentration. It can be observed that the CO₂ concentration near the windward side is the highest, and it shows a distribution trend of first concentration and then divergence. In contrast, the CO₂ content at the boundary is lower due to direct contact with the external natural environment. At 150 days, the highest CO₂ concentration in the gangue mountain can reach 0.01375 mol/m³.

### 4.1.3. Carbon Monoxide Concentration Field

CO is also the main gas produced by chemical reactions. Figure 6 shows the cloud map of the CO concentration field distribution on the 10th, 20th, 30th, 40th, 80th, and 150th days. It can be seen from the figure that the overall CO concentration in the gangue mountain gradually increases, and the highest can reach 18 mol/m³. By comparing with the O₂ concentration field and the CO₂ concentration field, it is found that the CO concentration is opposite to the O₂ concentration distribution, and compared with the CO₂ concentration, the CO concentration is much higher than the CO₂ concentration. This shows that most of the reactions between coal gangue and O₂ are insufficient oxidation reactions and also indicates that the main component of the flue gas generated by the spontaneous combustion of coal gangue is the toxic gas CO.

### 4.2. Analysis of Temperature Field

Under the initial conditions, the dynamic heating process of the coal gangue mountain was simulated from 1 to 150 days, and the temperature field distribution maps of the 10th, 15th, 20th, 40th, 80th, and 150th days were selected to compare and analyze the development and change laws of the temperature inside the coal gangue. Figure 7 shows the distribution cloud map under six time nodes. It can be observed that it is similar to the distribution law of the CO₂ concentration field in Figure 4. In the initial stage, the overall temperature of the gangue mountain rises slowly, and the maximum temperature inside it is about 30 °C on the 10th day. This is because the internal oxygen is sufficient at the initial stage of stacking, so the coal gangue begins to oxidize and heat up, but due to the obvious effect of air convection heat transfer at this stage, the temperature only rises slightly. With time, oxygen continuously penetrates into the inside of the gangue mountain for reaction, which accelerates the heating rate. On the 15th day, a high-temperature area begins to form near the windward side of the mountain, which is caused by the more active oxidation reaction near the windward side and the faster accumulation of heat. On the 20th day, the high-temperature area is clearly visible, and the maximum internal temperature is 42 °C. In the high-temperature state, due to hot wind pressure, the air inside the gangue mountain is urged to flow rapidly, the reaction is accelerated, and the heating rate is further increased. On the 40th day, the maximum temperature reaches 75 °C, and the area’s temperature other than the high-temperature area also rises to about 45 °C. After that, the high-temperature area gradually spread to the right low-temperature area. Until 150 days, the high-temperature area develops roughly half of the entire coal gangue mountain.

By observing the simulation results of the concentration field and the temperature field, it can be found that there is a certain correlation between the change in gas concentration and the change in temperature. To specifically explore the relationship between the two and avoid chance, four different points are selected in the simulation domain for analysis. That is, near the top of the slope (11,7), near the windward side (6,3), near the bottom surface (13,1), and near the leeward side (20,4). The temperature and gas concentration of these four points are taken every 10 days, and the curves are shown in Figure 8.

### 4.3. Analysis of the Seepage Velocity Field

To study the influence mechanism of gas seepage on the spontaneous combustion of coal gangue mountains, an air domain was set outside the coal gangue mountain model mentioned above. The air pressure in the air domain was 1 standard atmosphere, the left boundary of the domain was set to a constant wind speed of 3.5 m/s, and the direction was from left to right. The model is shown in Figure 9.

Figure 10 shows the vector diagram of the gas seepage velocity field inside and outside the gangue mountain. It can be observed from the figure that the wind blowing toward the gangue mountain will gather at the top, so the wind speed is the highest above the top of the mountain. The faster the flow rate, the lower the pressure, and the slower the flow rate, the higher the pressure. Therefore, due to the influence of the pressure difference on the leeward side, a leeward vortex is formed, so that a certain amount of air is also infiltrated on the leeward side. And the gas flow rate inside the gangue mountain is much lower than the external environment, and the difference is nearly a million times, so the spontaneous combustion of the coal gangue mountain is a prolonged process.

Figure 11 shows the vector diagram of the velocity field inside the mountain. Since the gas flow direction always flows from the high-temperature and high-pressure area to the low-temperature and low-pressure area, a unique gas flow field will be formed inside the gangue mountain. It can be seen from the figure that the airflow not only flows in from the windward side but also flows in from the leeward side, and finally flows out at the top. And its movement trajectory is almost vertically upward in the inner high-temperature area. This is because there is a certain temperature difference between the gangue mountain and the external environment after self-heating, and the wind speed at the top is fast, so that the airflow flows upward under the action
of the hot wind pressure, forming a “chimney effect”, which intensifies the gas convection and causes a large amount of airflow to migrate to the top. Due to the “chimney effect”, a gas channel is formed inside the gangue mountain. The air is continuously transported from the atmosphere into the gangue mountain, which ensures the supply of oxygen to keep the reaction going, releasing heat, and the temperature of the gangue mountain continues to rise until spontaneous combustion.

5. EXPERIMENTAL STUDY
The simulation analyzed the physics change from the start of stacking (0 days) to 150 days. Field tests were conducted to verify the simulated laws of physics changes and the feasibility of reacting to the internal temperature of gangue using gas concentrations.

Figure 12 shows the position diagram of the monitoring points for the layout of the test gangue mountain. The monitoring plane size is 25 m × 8 m, there were six monitoring points in total, and the monitoring depths are 3 m and 5 m, which are represented by the red and blue dots in the figure, respectively. In addition, the windward and leeward slopes required the punching to be perpendicular to the slope, and all of the measurement points were selected in a position that was convenient for punching and the surface was relatively flat.

The measurement of temperature and gas concentration adopted the way of arranging sensors on the site. The experimental site is at a high latitude, the local environment is changeable, with wind and sand, rain, and lightning weather more, to prevent a certain impact on the measurement results, the selected sensors are engineering sensors with strong anti-interference ability. WRNK-type armored thermocouple was used for temperature measurement, and 7E/F-type carbon monoxide electrochemical sensor, O2-A2-type galvanic oxygen sensor, and IR11GJ-type infrared carbon dioxide sensor were used for gas concentration measurement. Then, the signal output by the sensor probe was processed by filtering and amplifying and finally sent to the microprocessor to calculate the relevant value. Figure 13 shows a photograph of the installation of one of the measurement points.

Figure 14 shows a schematic diagram of the monitoring system. Among them, the measuring tubes were buried utilizing mechanical hole forming. The WRNK-type armored thermocouple and gas sensors were sent into the gangue mountain through the measuring tube, and then, the tube hole was sealed and filled so as to measure the temperature and gas concentration at different depths.

The monitoring lasted for 60 days, with data recorded every four days for a total of 15 times. According to the values obtained from each measuring point within 60 days, the daily changes of gas concentration and temperature are summarized, and the curve is shown in Figure 15. The relevant data of the six measuring points are arranged and recorded in Table 2.

Because the actual coal gangue has accumulated for many years, and the wind direction occasionally changes, the overall temperature is relatively high. Although the numerical values of temperature and gas concentration are different from the...
simulation, the factor leading to the temperature rise of the gangue mountain is still the change of multiple physical fields caused by wind.

Observing Figure 15 and Table 2, it can be found that the temperature on the windward side of the coal gangue mountain is higher than that on the leeward side, reaching 87 °C near the windward side and about 64 °C near the leeward side. Moreover, the temperature of the six measuring points increases very slowly over 60 days. The temperature difference in the area on the leeward side is more significant, about 2 °C, and the area near the windward side is about 1 °C. The temperature near the windward side is higher than that near the leeward side, and the chemical reaction rate is faster, but the temperature difference decreases gradually. This is because the fast reaction rate leads to the rapid decrease of O2 concentration, which in turn limits the reaction progress and leads to the slow temperature rise. From the leeward side to the windward side, the concentrations of CO and CO2 in the coal gangue mountain are getting higher and higher, and their variation values are getting smaller and smaller. As can be seen intuitively from Figure 15, the concentrations of CO and CO2 have the same trend, both of which increase linearly with the temperature. In the lower-temperature area, the curve has a large slope and a fast growth rate, while in the higher-temperature area, the growth rate is slow, but the change of CO2 concentration will be more obvious than that of CO. Therefore, the concentrations of CO and CO2 can well reflect the change of temperature, and the location of the high-temperature area can be judged by their concentrations, and the effect of CO2 in the high-temperature area will be better. Generally, the concentration of O2 gradually decreases with the increase of temperature, but its change value has no fixed trend, and the concentration value is almost in a state of oscillation at each position. This is because the surface of the coal gangue mountain has been exposed to wind and sunshine all the year round, and with the high surface temperature, there will be a large number of cracks on the surface, which will penetrate into a certain amount of oxygen, resulting in a large fluctuation of its concentration value. On the whole, the actual O2 concentration can reflect the general development trend of temperature, but it is not sensitive to the change of temperature. The high-temperature area measured by the above experiment is consistent with the simulation, and the distribution of temperature and gas concentration is also consistent with the simulation, which verifies the correctness of the numerical simulation. According to the concentrations of CO and CO2, the internal temperature change of the coal gangue mountain can be correctly reflected, so that the development state of spontaneous combustion can be judged.

6. CONCLUSIONS

(1) The spontaneous combustion of coal gangue mountains results from the combined action of temperature field, gas concentration field, seepage velocity field, and chemical reaction; among them, the exothermic heat of chemical reaction is used as the heat source in the temperature field. Through the finite element software solution, an intuitive cloud map of the distribution of physical fields in coal
gangue mountains is obtained, which has certain guiding significance for the practical work of preventing and controlling spontaneous combustion of coal gangue mountains.

(2) In the temperature field, the migration of the high-temperature area inside the gangue mountain is a dynamic process. Initially, the high-temperature area gradually concentrates on the windward side and then spread to the low-temperature area on the leeward side. In the gas concentration field, the O2 concentration has apparent changes in the early stacking stage, is highest on the windward side, and gradually attenuates after entering the interior. The overall concentration is in a state of decline. The CO2 concentration is consistent with the changing law of temperature. The change in CO concentration is opposite to that of O2. In the seepage velocity field, the vortex phenomenon and the chimney effect intensify the gas convection inside the gangue mountain so that the reaction can continue.

(3) The gas concentration can be used to predict the temperature inside the gangue mountain. The concentrations of CO and CO2 can reflect the temperature change at any position, but the effect of CO2 is better in the high-temperature area. The O2 concentration fluctuates too much in the actual coal gangue mountain and is not sensitive to temperature changes, so it can only reflect the general trend of temperature changes.

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Notes
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