Determination of the Spontaneous Combustion Hazardous Zone and Analysis of Influencing Factors in Bedding Boreholes of a Deep Coal Seam

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ABSTRACT: Accurately determining the spontaneous combustion zone of coal around the borehole plays an important role in preventing borehole accidents. To solve the problem of dividing the hazardous zone of spontaneous combustion in boreholes, a fully coupled model of the gas flow, coal oxidation reaction, and energy transportation is developed in this study. Taking the drainage borehole of the 24130 working face in the No. 10 Coal Mine of the Pingdingshan mining area as an example, the proposed model is used to simulate the seepage velocity field, oxygen concentration field, and temperature field of the coal around the borehole. The simulation results are found to be consistent with the field test results. Based on the simulation results, the coal around the borehole is divided into two areas in the axial direction of the borehole. The intersection of the seepage velocity \[ u \leq 0.004 \text{ m/s} \] and oxygen concentration \[ 7\% \leq C(O_2) \leq 21\% \] are considered the “hazardous zone”, and the union of the oxygen concentration \[ C(O_2) < 7\% \] and seepage velocity \[ u > 0.004 \text{ m/s} \] are considered the “safety zone”. The influences of various factors inducing spontaneous combustion of coal around the borehole on the hazardous zone are revealed by analyzing the drainage negative pressure, sealing length, and roadway temperature. The results show that reducing the drainage negative pressure and increasing the sealing length can effectively restrain the spontaneous combustion of the borehole and can also help reduce the scope of the hazardous zone of the borehole. Finally, a reasonable arrangement of the predrainage period in the appropriate season can also effectively inhibit the spontaneous combustion of coal around boreholes.

1. INTRODUCTION

The spontaneous combustion of coal is one of the main disasters in coal mines. In China, 56% of coal mines are in risk of undergoing spontaneous combustion.¹ The spontaneous combustion of coal is a worldwide problem. It not only exhausts a considerable amount of coal resources but also produces a large amount of harmful gases, which damage the ecological environment and even cause mine gas and dust explosions, threatening human health.²⁻⁵ The fires induced during such combustions have become the main factor restricting the safety production and development of high-yield and high-efficiency mines.⁶⁻⁷ In recent years, with the high-intensity exploitation of energy, shallow resources have been increasingly utilized or even exhausted. Mines worldwide have entered the stage of deep resource exploitation, and the deep mining of coal resources is expected to become the new normal.⁸⁻¹⁰ The dynamic phenomenon in deep coal mining is evident, the surrounding rock fragmentation phenomenon of roadways is increasing, and the coal seam temperature is expected to rise. The spontaneous combustion period of coal in a deep coal seam is significantly different from that of the...
accidents in China during the 12th five-year plan period; with a total death toll of 649, this unfortunately ranks China first in coal mine safety accidents. In the mining of deep coal seams, the spontaneous combustion in the gob is known to be serious, whereas the spontaneous combustion induced by negative pressure drainage along the bedding boreholes is becoming prominent, with major safety hazard accidents reported in recent years. In 2018, a total of 1947 predrainage boreholes were constructed in the 24130 working face of the Pingdingshan mining area. Among them, 425 boreholes were detected to have a CO concentration of over 300 ppm, accounting for 21.8% of all gas drainage boreholes, and a large number of drainage pipelines were burned. Therefore, a scientific and reasonable determination of the scope of spontaneous combustion around the borehole can help take targeted measures to prevent such combustions, which is crucial for safe coal mine production.

The occurrence of spontaneous combustion in a coal mine is a complex physical and chemical process, jointly determined by internal and external factors of the coal. Scholars worldwide have determined the calorific value and storage temperature of coal by analyzing its molecular structure and organic and inorganic components and have established its reaction rate to determine the combustion mechanism. Moreover, the spontaneous combustion area has been divided into three zones, with an objective to prevent and control such combustions by determining the dangerous areas accurately.

The spontaneous combustion area is divided on the basis of three main classification indicators: seepage velocity, oxygen concentration, and temperature. Li et al. used the superposition of high oxygen concentration area and heat storage area to determine the spontaneous combustion oxidation zone in the gob as well as the changes in the shape of the oxidation zone under various boundary conditions. The width of the oxidation zone was found to have a negative exponential relationship with the air volume of the working face. Thus, the authors derived a relevant judgment condition for the spontaneous combustion risk in the gob. Deng et al. plotted a 3D distribution map of the gas and temperature in the gob using the grid data difference method, divided the spontaneous combustion area in the gob into three zones, and established the PSO-SVR model to predict the spontaneous combustion temperature of the coal seam. Wei et al. analyzed coal samples by thermogravimetric analysis and differential scanning calorimetry (TG-DSC), divided the gob into three zones with the oxygen concentration as the division indicator, and selected CO and C2H4 as the prediction indicators for the spontaneous combustion. Xia et al. established a fully coupled hydro-thermomechanical model of the spontaneous combustion of coal seams to quantitatively predict the time and location of spontaneous combustions in the gob and roadway. Hao et al. studied the influences of the ventilation rate and air leakage rate on the spatial distribution of the oxygen concentration in the gob based on the constructed physical simulation experimental platform. Taking the oxygen concentration as the standard, the areas prone to spontaneous combustion were determined. Zhou et al. studied and analyzed the relationship between the fracture field, CH4 concentration field, O2 concentration field, and temperature field, determined disaster areas due to the coexistence of gas and spontaneous coal combustion, and thoroughly discussed the prevention mechanism and technical methods for symbiotic disasters.

In summary, most existing studies have been based on dividing the spontaneous combustion area in the gob into three zones; however, few have considered the hazardous zone associated with the spontaneous combustion around the borehole during the process of negative-pressure drainage. Therefore, in this study, aiming at the spontaneous combustion of the coal induced by negative-pressure drainage, a multi-physical field coupling model of the spontaneous combustion of coal induced by negative-pressure drainage of the boreholes was established. Through the solution process of the numerical simulation, the mechanism of spontaneous combustion around the borehole could be better understood. The hazardous zone of the spontaneous combustion was divided, and the influences of negative pressure, sealing length, and roadway temperature on the hazardous zone were discussed, providing a reference for the prevention of spontaneous combustion around boreholes.

2. ENGINEERING BACKGROUND

The No. 10 Coal Mine of China Pingdingshan Coal Group Co., Ltd. is a coal mine with outburst risk. The No. 15 coal seam can easily undergo spontaneous combustion. The buried depth of the 24130 working face is 1200 m, and the average coal seam thickness is 3.2 m. The main roof of the coal seam is mainly sandy mudstone with a thickness range of 8–13 m, and the bottom is gray fine sandstone with a thickness range of 5–6 m. The gas pressure in the coal seam is in the range of 0.1–2.95 MPa, the gas content is in the range of 2.15–20.0347 m3/t, and the coal seam permeability is poor. Because of disturbances due to coal mining, borehole construction, and borehole sealing, gas leakage channels are formed around the borehole, because of which the coal around the borehole has undergone spontaneous combustions multiple times in the process of negative-pressure drainage.

From June to July 2017, the CO concentration in the drainage pipeline of the 24130 ventilation roadway was in the range of 12–43 ppm and that in the roadway was in the range of 3–10 ppm. Through on-site investigations, it was found that the ignition point was located 59 m outside the ventilation roadway, and the corresponding borehole number was 210.
The drainage pipe in the borehole was burnt out, and only the first 13 m of the drainage pipe was pulled out. The temperature displayed by the infrared thermometer at the ignition point in the borehole was 230 °C, the CO concentration measured by the CO gas detector tube was 2500 ppm, and the temperature in the roadway was 33.5 °C. A portable CO detector was used to check all the boreholes in the working face. Different degrees of CO concentration could be detected in the boreholes. Figure 2 shows typical boreholes associated with spontaneous combustion. Here, the CO concentration in many of the boreholes rises to more than 300 ppm in a short period of time. After applying static pressure water injection and halting gas drainage, the CO concentration in most of the boreholes decreased rapidly. However, after a month of redrainage, the CO concentration increased again, and the rising rate was higher than that before water injection.

Clearly, static-pressure water injection can only delay the spontaneous combustion of the coal around the borehole but not resolve it. To solve the problem of spontaneous combustion around the borehole, it is necessary to divide the location of the ignition point and the range of spontaneous combustion around the borehole, it is necessary to divide the location of the ignition point and the range of spontaneous combustion, which is significant to the prevention and control of spontaneous coal combustion induced by negative-pressure drainage.

3. COMPUTATIONAL METHODS

In this study, the following assumptions were made: (a) The adsorption effect of coal on the gases is not considered in the coal adsorption process, and gases only flow in coal fractures. (b) The gas flow in the coal is in accordance with Darcy’s law. (c) The heat transfer between the gas and the coal satisfies the assumption of local thermal equilibrium, and the effect of temperature on the dynamic viscosity of the gas is not considered.

3.1. Gas Flow Equation. The percolation of the gas in the porous media conforms to Darcy’s law, then

\[ \frac{dm}{dt} + \nabla \cdot (\rho u) = Q_m \]

\[ m = \rho \varphi \]

\[ u = -\frac{k}{\mu} \nabla p_i \]

where \( m \) is the gas content, \( \nabla \) is the gradient of the current velocity, \( \rho \) is the density of the gas, \( u \) is the seepage velocity of the gas, \( Q_m \) is the gas source, \( \varphi \) is the porosity of the coal, \( p_i \) is the drainage negative pressure, \( \mu \) is the dynamic viscosity of the gas, and \( k \) is the permeability of coal.

The gas density \( \rho \) can be expressed as

\[ \rho = \frac{pM}{RT} \]  

where \( p_2 \) is the gas pressure, \( M \) is the molar mass of the gas, \( R \) is the molar constant of the gas, and \( T \) is the temperature of the gas.

The permeability of the coal around the drainage borehole is affected by both roadway excavation and drilling construction. The coal permeability around the drainage borehole gradually decreases both along the axial direction of the borehole and in the radial direction. Therefore, the permeability of the coal around the drainage boreholes in different coal seams is different, and according to the permeability formula proposed by Louis,\(^{34} \) the permeability of coal around a borehole can be expressed as

\[ k_v = k_0 \beta (b - r) \]

\[ k_z = k_0 \beta (b - z) \]  

where \( k_0 \) is the initial permeability of the coal seam, \( b \) is the width of the plastic zone, \( r \) is the radius of the plastic zone, and \( \beta \) is the permeability growth coefficient of the equivalent fracture field around the borehole, and its value is 1.2.\(^{35} \)

The calculation formula for the plastic zone distribution of the coal seam roadway is as follows. The radial stress distribution around the borehole conforms to the small-scale roadway stress distribution, and the plastic zone distribution of the coal around the borehole can be calculated by referring to the calculation formula of the distribution of the roadway loose circle.\(^{36,37} \)

\[ R_L = a_0 \left( \frac{p_3 + c \cot \varphi (1 - \sin \varphi)}{p_3 + c \cot \varphi} \right)^{\sin \varphi / 2 \sin \varphi} \]  

where \( a_0 \) is the radius of the borehole or roadway, \( p_3 \) is the original rock stress zone of the coal seam, \( c \) is the cohesion of the coal and rock mass, \( \varphi \) is the internal friction angle of the coal and rock mass, and \( p_i \) is the support resistance.

The equation governing gas seepage can be obtained by the simultaneous eqs 1–6

\[ \frac{\partial p}{\partial t} - \nabla \left( \frac{k}{\mu} \nabla p_i \right) = Q_m \]

\[ \frac{\partial Q}{\partial t} - \nabla \left( \frac{k}{\mu} \nabla p_i \right) = Q_m \]

3.2. Governing Equation of Coal Oxidation Reaction.

Gas convection and diffusion occur in a porous coal medium, and the equations governing the convection and diffusion can be expressed as follows

\[ \frac{\partial c_i}{\partial t} + \nabla N_i = R_i \]

where \( N_i \) is the reaction rate of the gas, \( c_i \) is the concentration of the gas.\(^{38} \)
Under the action of negative pressure, oxygen enters from the loose circle of the borehole and reacts with the coal. Combining eqs 8 and 9 yields its governing equation
\[
\frac{\partial c_i}{\partial t} + \nabla \cdot (-D_i \nabla c_i) + \mathbf{u} \cdot \nabla c_i = R_i
\]
where \( N_i \) is the molar flux of the gas, \( c_i \) is the gas concentration, and \( D_i \) is the diffusion coefficient of the gas. According to an experimental study,\( ^{38} \) the oxygen consumption reaction rate formula is as follows
\[
R_{O_2} = -\frac{c_{O_2}}{c_{O_2}^0} \gamma_0 \rho g \rho (T - T_i)
\]
where \( R_{O_2} \) is the oxygen consumption rate, \( c_{O_2}^0 \) is the initial oxygen concentration, \( c_{O_2} \) is the oxygen concentration, \( \gamma_0 \) is the oxygen consumption coefficient, \( T \) is the absolute temperature of the coal, \( T_i \) is the initial temperature of the coal seam, and \( \rho \) is the temperature oxidation index of the coal under test conditions.

### 3.3. Heat Transfer Equation

During the oxidation reaction of the coal around the borehole emits, heat is emitted, and the heat transfer follows the energy balance equation.\( ^{38} \) The governing equation can be written as follows
\[
(\rho C_p)_{eff} \frac{dT}{dt} + \rho C_p g \cdot V T - \nabla \cdot (\kappa_{eff} \nabla T) = R_{O_2} q_T + Q_V
\]
where \( (\rho C_p)_{eff} \) is the effective heat capacity coefficient, \( C_p \) is the specific heat capacity of the porous media, \( C_p^g \) is the specific heat capacity of the gas, \( \kappa_{eff} \) is the effective thermal conductivity, \( q_T \) is the coal oxidation reaction heat, and \( Q_V \) is the boundary exchange heat, where \( (\rho C_p)_{eff} \) and \( \kappa_{eff} \) are defined as
\[
(\rho C_p)_{eff} = (1 - \varphi) \rho C_p c + \varphi \rho g C_p^g
\]
\[
\kappa_{eff} = (1 - \varphi) \kappa_c + \varphi \kappa_g
\]
where \( \kappa_c \) and \( \kappa_g \) are the thermal conductivity coefficients of the coal and gas, respectively. The governing equation for \( Q_V \) is
\[
Q_V = h(T_{ext} - T)
\]
where \( h \) is the heat transfer coefficient and \( T_{ext} \) is the roadway temperature.

The simultaneous eqs 7, 10, and 12 can be used to obtain the multifield coupled partial differential equations including the seepage field of the gas in the coal around the borehole, gas convection diffusion field, and the temperature transmission energy field of the coal–oxygen reaction. By solving the equations, the gas seepage velocity, oxygen concentration, and temperature distribution can be obtained.

### 4. RESULTS

#### 4.1. Simulation Case and Conditions

In this study, the gas drainage boreholes in the conveyor roadway of the 24130 working face in the No. 15 coal seam were used as calculation examples. The borehole diameter is 0.1 m, the drainage negative pressure is 23 kPa, the sealing depth is 8 m, that is, the distance from the borehole orifice to the innermost end of the borehole plugging section, is 20 m, the sealing length is 8 m, that is, the distance between the sealing sections in the borehole, is 8 m, the temperature of the coal seam is 48 °C, and the roadway temperature is 28 °C. Figure 3 shows the physical model. Spontaneous combustion mainly occurs in the coal around the borehole; hence, the coal around the single borehole is selected as the main calculation area. The main parameters of this model (Table 1) are from the experimental results and previous studies.\( ^{30,35,38} \) Table 2 lists the initial and boundary conditions based on the actual situation.

#### Table 1. Model Parameters

| Parameter | Value and Units |
|-----------|-----------------|
| \( \rho_s \) | 1250 kg/m\(^3\) |
| \( \varphi_0 \) | 0.047 |
| \( k_0 \) | 5.0 \times 10^{-11} m\(^2\)/s |
| \( \mu \) | 1.79 \times 10^{-5} Pa·s |
| \( M_0 \) | 0.029 kg/mol |
| \( \beta_1 \) | 1.2 |
| \( P_1 \) | 23 kPa |
| \( \rho_1 \) | 0.1 MPa |
| \( \varphi_{O_2} \) | 9.375 mol/m\(^3\) |
| \( D(O_2) \) | 1.6 \times 10^{-5} m\(^2\)/s |
| \( c \) | 2.1 MPa |
| \( h \) | 180 W/(m\(^2\)·K) |
| \( \gamma_0 \) | 0.16 mol/(m\(^3\)·h) |
| \( a \) | 2.4 \times 10^{-10} m\(^2\)/K |
| \( C_p \) | 1530 J/(kg·K) |
| \( Q_T \) | 511.52 kJ/mol |
| \( \kappa_c \) | 0.26 J/(m·s·K) |
| \( \kappa_g \) | 0.026 J/(m·s·K) |

#### 4.2. Model Validation

In this study, the test boreholes in the conveyor roadway of the 24130 working face were taken as examples for comparative verification. Each test borehole was equipped with two AD590JH temperature sensors to monitor the temperature at two positions 12 and 14 m away from the borehole orifice. Figure 4 shows the temperature at the numerical simulation point and the test monitoring point. As shown, the coal temperature increases with time, the average temperature at the simulation point in Figure 4a is 62.5 °C, and the temperature differences between the simulation point and the test monitoring point are 4.95 and 8.47%, respectively. The average temperature of the simulation point shown in Figure 4b is 63.6 °C, and the temperature differences between the simulation point and the test monitoring point are 4.6 and 7.6%, respectively. Clearly, the error is small, and the simulation results are largely consistent with the field test.
results, thus proving the accuracy of the model. A portable CO
detector was used to detect the CO concentration in the test
borehole on site. Figure 5 shows the results. Figures 4 and 5
show that, with the increase in the coal temperature, the
oxidation reaction becomes increasingly intense. The concen-
tration of CO produced by the reaction of coal and oxygen
continuously increases, which is identical to the law of the coal
temperature with time; this verifies the spontaneous
combustion of the coal around the boreholes.

### 4.3. Simulation Results

The distributions of the temperature field and oxygen concentration field at 25, 50,
75, and 90 days are obtained, as shown in Figure 6. The coal
temperature increases with time, and this accelerates the
consumption of oxygen. Under the action of drainage negative
pressure, the air leakage channels around the borehole
continuously replenish oxygen to further accelerate the
spontaneous combustion of the coal. In the radial (R)
direction of the borehole, the monitoring points at R = 0.5
m are analyzed. The coal temperature increases gradually in
the first 50 days; after 50 days, the heating rate of coal at Z =
12−13 m is higher than that at the other monitoring points.
This shows that the coal around the borehole at Z = 12−13 m
is the most prone area for spontaneous combustion, and the
oxygen concentration and air leakage flow contribute to the
occurrence of spontaneous combustion, as shown in Figure 7a.

Figures 6 and 7b show the distributions of the oxygen
concentration field; under the action of the drainage negative
pressure, air enters from the leakage channel and exits at the
GH boundary of the coal wall. Combined with the distribution
of the seepage field, it can be concluded that the oxygen
concentration in the air is highest when it enters the coal
around the borehole. With the coal oxidation reaction, the
distribution of the oxygen concentration in the axial direction
of the borehole decreases with time. When the temperature
reaches the critical value of 70 °C, the coal oxidation reaction
becomes more violent, and the oxygen concentration decreases
rapidly. At a critical oxygen concentration of 7%, as obtained in
the laboratory in the boundary condition, in the axial (z)
direction of the borehole, the oxygen inflow area is mainly in
the range of 0−12 m, and the main oxygen accumulation area
is at 12−20 m, and the gas outflow area is mainly beyond 20 m.
Therefore, it can be judged that the initial spontaneous
combustion area around the borehole is 12−20 m in the axial
direction of the borehole.

The solution to the seepage field of the coal around the
borehole is a steady-state solution, and the seepage velocity
does not vary with time and is only related to the pressure

### Table 2. Boundary and Initial Conditions

| definite conditions | gas flow | convection diffusion | heat transfer |
|---------------------|----------|----------------------|--------------|
| initial conditions  | p = 0.1 MPa, p₂ = 0 | c(O₂) = 0 | T = 301.15 K |

| boundary conditions | AB | BC | CD | DE | FG | GH | HI | EF |
|---------------------|----|----|----|----|----|----|----|----|
|                     | p = 0.1 MPa | p = 0.1 MPa | zero flux | zero flux | zero flux | p_1 | p_1 | zero flux |
|                     | no flux | no flux | no flux | no flux | convection flux | convection flux | no flux | no flux |
|                     | insulation | insulation | insulation | symmetry | symmetry | symmetry | symmetry | symmetry |

**Figure 4.** Temperature variation at the simulation and test points with time: (a) simulation point (0.5,12); (b) simulation point (0.5,14).

**Figure 5.** Variation in the CO concentration with time.
difference, as shown in Figure 8. The seepage field is distributed in the form of a “leaf” shape. The main source of air leakage is at the outer end of the borehole sealing section, namely, the AB boundary, and the secondary air leakage source is the BC boundary. In the R direction, the seepage velocity gradually decreases, and the seepage velocity is highest in the plastic deformation zone of −1 to 1 m. In the Z direction, the seepage velocity increases gradually under the drainage negative pressure, reaches maximum at 20 m, and thereafter decreases gradually at distances beyond 20 m. When Z = 12 m, the seepage velocity increases first and then decreases, mainly because it is the main air leakage source on the AB boundary.

4.4. Division of the Hazardous Zone. Typically, when dividing the zones using the three indicators, the essential differences between the three zones must be considered. For the boundary between the heat dissipation zone and the oxidation zone, the focus must be on the heat storage conditions for spontaneous coal combustion, and the critical seepage velocity corresponding to the heat storage required for oxidation-induced spontaneous coal combustion should be taken as the main indicator. In comparison, for the boundary between the oxidation zone and the suffocation zone, the focus should be on the supply conditions for spontaneous combustion, the critical oxygen concentration required for spontaneous combustion should be the main indicator, and factors such as the air leakage and temperature distributions should be comprehensively considered. Therefore, determining the critical oxygen concentration and seepage velocity required for the spontaneous combustion is key to reasonably dividing the dangerous area of the spontaneous combustion. Based on a seepage velocity of 0.004 m/s and a critical oxygen concentration of 7% obtained in the laboratory, the spontaneous combustion area of the coal around the borehole is divided. The oxygen concentration and velocity distributions are transparently superimposed, and the common region between the seepage area and high oxygen concentration area that satisfies the heat storage conditions is taken as the spontaneous combustion oxidation zone with double effects.

Although the spontaneous combustion of the coal around the gas drainage borehole and the spontaneous combustion of the coal in the gob are due to the heat released during the oxidation of coal, the seepage velocity of the coal around the borehole varies from low to high in the axial direction of the borehole, and the oxygen concentration varies from high to low, while the oxygen concentration and seepage velocity of the gob gradually decrease from the air leakage channel to the coal. In addition, the three zones of spontaneous combustion in the gob are dynamically affected by the advancing speed of the working face and other factors, while the borehole is not. It
is static and is related to the leakage channel of the coal around the borehole and the negative pressure of extraction. Therefore, the division of the hazardous zone of coal around the borehole can draw lessons from the index of spontaneous coal combustion in the three zones of the gob; however, the hazardous zone of the spontaneous combustion of coal around the borehole is different from that of the gob.

As shown in Figure 9, the “leaf” shape distribution represents the seepage velocity field, whereas the “two palms closed” shape distribution represents the oxygen concentration field. Under the condition of drainage negative pressure, the air in the roadway and at the outer end of the sealing section of the borehole penetrates the inner end of the sealing section through the coal fissures around the borehole, and its flow velocity varies from low to high, while the oxygen concentration in the air varies from high to low. The coal around the borehole can oxidize and store heat, thereby causing a spontaneous combustion. When the seepage velocity $u \leq 0.004 \text{ m/s}$ and oxygen concentration $C(O_2) \geq 7\%$, that is, in the axial direction of the borehole $z = 12.5 \text{ m}$, the coal first reaches the critical temperature of spontaneous combustion, causing a spontaneous combustion. As the drainage continues, the spontaneous combustion of the coal around the borehole spreads to the direction of sufficient oxygen and low seepage velocity. When the drainage time is 70 days, the superposition area of the oxygen concentration field and seepage velocity field is $Z = 12.5 - 14 \text{ m}$, as shown in Figure 9, which is the oxidation spontaneous combustion zone of the borehole. In the area with $Z < 12.5 \text{ m}$ in the axial direction of the borehole, the coal in this area is exposed at the roadway and the outer end of the sealing section in the borehole, and the coal around the borehole also undergoes an oxidation reaction; however, the heat generated by the oxidation reaction is less than the heat transferred outside. Therefore, the coal in this area cannot easily undergo spontaneous combustion in the early stages of drainage, and this area corresponds to the heat dissipation zone of boreholes. In the area $Z > 14 \text{ m}$ in the axial direction of the borehole, the seepage velocity of the coal body around the borehole is higher, and the oxygen concentration is lower. Although oxidation reaction also occurs in this area, the reaction is very slow. However, because of the higher velocity, the heat is taken away and does not accumulate, and the coal in this area cannot easily undergo spontaneous combustion, and therefore, this area is where the heat dissipation zone and suffocation zone co-exist.

With continuous drainage, under the condition of sufficient oxygen concentration and good heat storage, the oxidation degree of the coal in the oxidation zone is accelerated, the oxidation reaction becomes more intense, and the heat generated in the oxidation zone diffuses to the surrounding area. When the heat transferred from the oxidation spontaneous combustion zone to the heat dissipation zone is greater than the heat released from the heat dissipation belt to the outside, the coal in the heat dissipation zone also undergoes spontaneous combustion, and the spontaneous combustion

Figure 7. Variation in the temperature and oxygen concentration with time at different simulation points at $R = 0.5 \text{ m}$: (a) variation in the temperature with time at simulation points; (b) variation in the $O_2$ concentration with time at simulation points.

Figure 8. Seepage velocity distribution of coal around borehole: (a) seepage velocity distribution of coal around the borehole; (b) distribution of seepage velocity at $0.05 \text{ m}$ of the borehole.
The combustion area continues to spread outward to the roadway wall. On the other hand, the heat dissipation zone near the inner end of the borehole is close to the drainage pipe, because of which the heat in the heat dissipation zone quickly diffuses into the drainage pipe under the action of the negative pressure of the drainage; hence, there is no spontaneous combustion where the heat dissipation zone and the suffocation zone coexist. This suggests the presence of four zones in the process of spontaneous combustion induced by drainage: a heat dissipation zone, an oxidation spontaneous combustion zone, a heat dissipation zone, and a suffocation zone in the axial direction of the borehole. Here, the oxidation spontaneous combustion zone and heat dissipation zone of the borehole are collectively referred to as the “hazardous zone” of the borehole. The heat generated by the oxidation spontaneous combustion zone is carried away by the wind to the suffocation zone, and this increases the temperature of the coal in the suffocation zone. However, the oxygen reaction mainly occurs in the oxidation zone, where a considerable amount of oxygen is consumed, thereby decreasing the oxygen concentration in the suffocation zone and making it difficult for the coal in the suffocation zone to undergo spontaneous combustion; this area is called the “safety zone” of the borehole.

In summary, in this study, the two indicators were used to divide the spontaneous combustion area around the borehole into hazardous and safety zones. The intersection of the seepage velocity $u \leq 0.004$ m/s and oxygen concentration $7\% \leq C(O_2) \leq 21\%$ is considered the hazardous zone of the borehole, and the union of the oxygen concentration $C(O_2) < 7\%$ and seepage velocity $u > 0.004$ m/s is considered the safety zone. Figure 10 shows the corresponding schematic.

5. DISCUSSION
In order to explore the influencing factors of the spontaneous coal combustion hazardous zone around the borehole, the influence of negative pressure, sealing length, and roadway temperature on the spontaneous combustion hazardous zone of the borehole is analyzed. The results are as follows.

5.1. Effect of Drainage Negative Pressure on the Hazardous Zone. Figure 11 shows the variations in the oxygen concentration and temperature with time at points (0.5,12.5) and the variation in the seepage velocity at $R = 0.1$ m when the sealing depth is 20 m, the sealing length is 8 m, the roadway temperature is 28 °C, and the negative pressures are $-18$, $-23$, and $-30$ kPa. Figure 11 shows that the greater the change in the drainage negative-pressure, the greater the seepage velocity, the greater the corresponding oxygen concentration, the more intense the coal oxidation reaction, and the higher the temperature of the spontaneous combustion. The more intense the coal oxidation reaction, the faster the oxygen consumption. The increase in the drainage negative-pressure increases the range of the seepage velocity field and oxygen concentration field, thereby increasing the hazardous zone of the borehole. Therefore, reducing the drainage negative pressure has an inhibitory effect on the spontaneous combustion of coal around the borehole.

5.2. Effect of Sealing Length on the Hazardous Zone. Figure 12 shows the variations in the oxygen concentration and temperature with time at points (0.5,15), (0.5,12), (0.5,8), (0.5,5), and (0.5,1) when the sealing lengths are 5, 8, 12, 15, and 19 m. Figure 12 shows that the smaller the sealing length, the higher the oxygen consumption in the coal oxidation reaction, the more intense the coal oxidation reaction, and the faster the temperature rise of coal around the borehole. For example, when the sealing lengths are 5 and 19 m, the heating rates in 90 days are 1.1 and 0.16 °C/day, respectively. Since the seepage velocity is only related to the difference in the drainage negative pressure, the seepage velocity does not change under the condition of drainage negative pressure. The longer the sealing length, the higher the oxygen consumption in the coal oxidation reaction, the more intense the coal oxidation reaction, and the faster the temperature rise of coal around the borehole. For example, when the sealing lengths are 5 and 19 m, the heating rates in 90 days are 1.1 and 0.16 °C/day, respectively. Since the seepage velocity is only related to the difference in the drainage negative pressure, the seepage velocity does not change under the condition of drainage negative pressure. The longer the sealing length, the higher the oxygen consumption in the coal oxidation reaction, the more intense the coal oxidation reaction, and the faster the temperature rise of coal around the borehole. Therefore, reducing the drainage negative pressure has an inhibitory effect on the spontaneous combustion of coal around the borehole.
borehole, the greater the inhibition of the spontaneous combustion around the borehole, and the hazardous zone of the borehole is reduced. For a safe and efficient drainage, it is recommended to seal the full sealing depth of the borehole.

5.3. Effect of Roadway Temperature on the Hazardous Zone. The roadway temperature varies with the seasons, with the highest temperature recorded in summer and the lowest in winter. Figure 13 shows the variations in the temperature and oxygen concentration with time at points (0.5, 12.5) when the roadway temperatures are 28, 32, 36, and 40 °C. As shown, the roadway temperature also influences the spontaneous combustion of coal around the borehole. The higher the roadway temperature, the higher the oxygen consumption in the coal oxidation reaction around the borehole, and the more intense the oxidation reaction. Since the negative pressure and sealing length are constant, the seepage velocity field remains unchanged, and the intersection between the oxygen concentration field and seepage velocity field does not change. However, the increase in the roadway temperature accelerates the oxidation reaction of the coal. Therefore, to inhibit the spontaneous combustion of the coal around the borehole, it is suggested to set the predrainage period reasonably, and it is not recommended to conduct gas drainage in summer.

6. CONCLUSIONS

In order to more accurately determine the location of spontaneous coal combustion around the borehole, a multiphysical field coupling model of the gas flow, coal oxidation reaction, and heat transfer was established in this study. Taking the critical oxygen concentration obtained in the laboratory and the seepage velocity as indicators, the hazardous zone around the borehole was divided, and the influencing factors were analyzed. Based on the obtained results, the following conclusions can be drawn:

(1) A multiphysical field coupling model suitable for spontaneous coal combustion induced by drainage negative pressure was established. The model was simulated and verified by field-measured data. The field-measured results proved the correctness of the model. The reasons for the spontaneous combustion were analyzed in terms of the temperature, oxygen concentration, and seepage velocity, and the location where the coal around the borehole is most prone to spontaneous combustion was determined, i.e., at the outer end of the borehole plugging section to the inner 1–2 m region, representing the first occurrence of heat storage and spontaneous combustion, which then spreads to both ends of the borehole.

(2) The spontaneous combustion process around the borehole was summarized in terms of the oxygen concentration and seepage velocity. The oxygen concentration in the coal around the borehole gradually decreased in the axial direction of the borehole, whereas the seepage velocity gradually increased from low to high. The coal undergoes spontaneous combustion first in the oxidation zone, and the combustion is then extended to the heat dissipation zone at the outer end of the borehole and to the area where the heat dissipation zone and suffocation zone co-exist at the inner end of the borehole.

Figure 11. Variations in the oxygen concentration, temperature, and seepage velocity under different drainage negative-pressure conditions: (a) variation law in the O₂ concentration and temperature with time; (b) variation law in the seepage velocity.

Figure 12. Variations in the oxygen concentration and temperature with time under different sealing lengths.

Figure 13. Variation law of oxygen concentration and temperature with time under different roadway temperature conditions.
the borehole. Finally, a hazardous zone for spontaneous combustion in the borehole is formed. These insights can play a theoretical role in preventing spontaneous combustion of boreholes.

(3) Based on the experimental and simulation results, the method of the hazardous zone division suitable for spontaneous combustion of the coal around boreholes was put forward. The intersection of the seepage velocity \( u \leq 0.004 \text{ m/s} \) and oxygen concentration \( 7\% \leq C(O_2) \leq 21\% \) is taken as the "hazardous zone" of the borehole, and the union of the oxygen concentration \( C(O_2) < 7\% \) and the seepage velocity \( u > 0.004 \text{ m/s} \) is taken as the "safety zone".

(4) From the perspective of spontaneous combustion, the influencing factors of the hazardous zone of the borehole were systematically analyzed. The results showed that reducing the negative pressure of the drainage, reducing the roadway temperature, and increasing the sealing length can help inhibit the spontaneous combustion of the coal around the borehole, whereas varying the roadway temperature has no effect on the scope of the hazardous zone. Therefore, optimizing the negative pressure and sealing length and reasonably setting the gas predrainage period can help effectively ensure the safety of coal mine production. This study provides technical support for preventing spontaneous combustions around boreholes induced by negative pressure.

7. EXPERIMENTAL SECTION

A gas controller GC 20 measurement thermogravimetry analyzer was used to carry out experimental analysis on fresh coal samples taken from the 24130 working face. The heating rate was set to \( 5 \degree\text{C/min} \), and the oxygen concentration in the laboratory was set to 20.9%. Figure 14 shows the TG-DSC-DTC curve obtained from the experiment.

![Figure 14. TG-DSC-DTC curve of the coal sample.](https://doi.org/10.1021/acsomega.1c00139)

In the process of spontaneous coal combustion and oxidation, the change in the coal temperature itself is an important thermodynamic characteristic of coal oxidation. The change curve of the coal temperature can directly reflect the degree of oxidation reaction in the process of spontaneous coal combustion. Fresh coal samples from the 24130 working face were taken for low-temperature oxidation experiments. Figure 14 shows the change curve.

In the process of the experiment, the furnace temperature rises at a certain rate, the temperature of the coal sample rises with the increase in the furnace temperature, and the coal sample produces different gas products at different temperatures. However, when the coal sample enters a violent oxidation phase, the oxidation reaction releases a considerable amount of heat, making the temperature of the coal sample higher than that in the furnace. Figure 15 shows that under an oxygen concentration of 20.9%, coal oxidation shows an evident intense oxidation stage, and the temperature of the coal sample is evidently higher than that in the furnace. Even at an oxygen concentration of 10.0%, there is an evident intense oxidation stage; however, the intense oxidation during the spontaneous coal combustion is inhibited to a certain extent compared with that at an oxygen concentration of 20.9%. The coal temperature with an oxygen concentration of 7.0% is significantly lower than that at an oxygen concentration of 20.9%, coal oxidation shows an evident intense oxidation stage, and the temperature of the coal sample is evidently higher than that in the furnace. Even at an oxygen concentration of 10.0%, there is an evident intense oxidation stage; however, the intense oxidation during the spontaneous coal combustion is inhibited to a certain extent compared with that at an oxygen concentration of 20.9%. The coal temperature with an oxygen concentration of 7.0% is significantly lower than that at an oxygen concentration of 20.9%. The coal temperature with an oxygen concentration of 7.0% is significantly lower than that at an oxygen concentration of 20.9%.
10.0%, and the oxidation process is not evident. Moreover, at an oxygen concentration of 7%, the temperature of the coal sample hardly changes with the change in the furnace temperature, and there is no evident sign of severe oxidation. This shows that the oxidation-induced spontaneous combustion of coal can be inhibited when the oxygen concentration is 7.0%, which is therefore taken as the critical oxygen concentration of the spontaneous combustion.

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