INTRODUCTION

Coal spontaneous combustion has always been a major issue in mine production, which mainly occurs in longwall gobs. The active functional groups in the coal surface molecules react with oxygen molecules and release heat.\textsuperscript{1-3} When the oxygen supply is sufficient and the heat storage condition is good, the heat released by the oxidation reaction accumulates continuously and causes the coal temperature to rise. This can ultimately result in spontaneous combustion in the gobs.
Until now, the percentage of spontaneous combustion in gobs accounts for 60% of the total number of mine fires, whereas in roadways and other locations, it accounts for 29% and 11%, respectively. To resolve this problem, researchers have adopted many methods to study the spontaneous combustion process in gobs to prevent mine fire accidents, including gas analysis methods, temperature observation methods, and numerical simulation methods. The gas analysis method uses the concentration change in the gas products generated by coal spontaneous combustion to identify the self-ignition state of coal, such as CO, C₂H₂, and C₂H₄. Yu et al deduced the possible location of the combustion in relation to the change in the oxygen concentration inside a gob. Zhongpeng determined the dangerous area in a broken roadway according to the pressure distribution and gas concentration change of the working face. Despite this, concentration change in a gob cannot be accurately estimated based on the gas products so as to determine the degree of spontaneous combustion. In theory, temperature reflects the degree of coal spontaneous combustion most directly, and the temperature inside the gob can be determined from preburied temperature measuring lines. However, the mined-out area is widely distributed, which makes it impossible to determine in advance where the high-temperature point may appear, as well as to lay the temperature measuring lines in such a large area. Therefore, temperature monitoring inside gobs remains a formidable challenge.

From the above analysis, the temperature monitoring process inside gobs is difficult, and there are many issues to be resolved in the equivalent simulation experiment of spontaneous combustion, such as the difficulty to realize the process of continuous propulsion of the simulated working face. Thus, in the absence of effective research means, the use of a numerical simulation method to prevent coal spontaneous combustion has become inevitable. This method often makes certain assumptions when establishing the mathematical models, which are verified by on-site observation data. Researchers have devised a variety of mathematical models, including a computational fluid dynamics (CFD) model, a gas flow model, and a porous fluid dynamics model. Xie et al used the back propagation (BP) neural network model to predict the temperature inside a gob. Yueping et al determined the change of temperature fields and predicted the location of high-temperature points in gobs. Additionally, Xia et al and Chu et al established mathematical models to discuss the symbiotic relationship between coal spontaneous combustion and gas drainage. They also conducted a hazard analysis of the longwall advance rate, air supply, and coal oxidation rate. However, the numerical simulation results mentioned in the above literature still lack reliability. The main reason is that the change of mining progress of working face has been ignored, and it is difficult to simulate the long-term evolution of coal self-heating in the gob.

We previously developed 3D numerical simulation software (COMBUSS-3D) based on moving coordinates. When the working face advances at a constant speed, the calculated multi-physical fields are in steady state. However, because geological faults often cause the longwall advance rate to change, it is impossible to calculate the dynamic distribution of pressure, gas concentration, and temperature in the gob by using the original software. Therefore, we have improved the original software and simulated the spontaneous combustion process in longwall gobs from mining discontinuation to resumption. The sensitivity analysis is introduced to understand how to adopt more targeted measures to prevent coal spontaneous combustion.

2 | NUMERICAL METHODS

2.1 | Multi-field coupling relations

From a macro perspective, the formation and migration of a CO concentration field is the result of the coupling action of:
an air flow field (AFF), oxygen concentration field (OCF), air temperature field (ATF), and solid temperature field (STF). The spontaneous combustion in gobs is also caused by the coupling of air seepage, oxygen transport, heat transfer, and coal oxidation exothermic reaction. Therefore, the generation of CO inside a gob is closely related to the occurrence and development of coal spontaneous combustion, which indicates that the CO concentration field should be incorporated into the multi-field coupling mathematical model to judge the degree of spontaneous coal ignition.\textsuperscript{26} The coupled interaction of multi-physical fields is presented in Figure 1.

\section{Model establishment}

Before establishing the multi-field coupling mathematical model, several conditions need to be assumed: (a) the mined-out area is regarded as an isotropic, continuous porous medium; (b) the presence of methane and moisture inside the gob is not considered; (c) the solid temperature of the caving coal rock is different from the air temperature, which needs to be modeled separately.

In a gob, the closed surface containing any point can be regarded as a finite volume with a volume \( V \) and a surface area \( S \). Based on this, the multi-field coupling mathematical model is established under unsteady-state conditions,\textsuperscript{26,27} the final modeling results are shown in Equations (1)-(5).

\subsection{Equation of the air flow field:}

\[
\begin{align*}
\mathbf{K} & \cdot \frac{\partial (P + \rho g h)}{\partial n} dS - \mathbf{V} \cdot \frac{\partial \rho g}{\partial t} dV = 0 \\
\mathbf{V} & = \frac{\mathbf{K}}{\rho g} \left( \frac{\partial P_i}{\partial x_i} + \frac{\partial P_j}{\partial y_j} + \frac{\partial P_k}{\partial z_k} \right)
\end{align*}
\]

\subsection{Equation of the oxygen concentration field:}

\[
\begin{align*}
\phi \rho g \frac{\partial C_{O_2}}{\partial n} dS - \mathbf{C} \cdot \frac{\partial v}{\partial n} dS - \mathbf{U} \cdot \frac{\partial \rho}{\partial t} dV - \mathbf{V} \cdot \frac{\partial C_{O_2}}{\partial t} dV = 0
\end{align*}
\]

\subsection{Equation of the air temperature field:}

\[
\begin{align*}
\phi \lambda \frac{\partial T_s}{\partial n} dS + \mathbf{K} \cdot S_e (T_s - T_g) dV \\
- \phi \rho C_s T_s \frac{\partial v}{\partial n} dS = \mathbf{V} \cdot \frac{\partial T_s}{\partial t} dV
\end{align*}
\]

\subsection{Equation of the solid temperature field:}

\[
\begin{align*}
\int_S (1 - \phi) \lambda \frac{\partial T_s}{\partial n} dS - \int_V \mathbf{K} \cdot S_e (T_s - T_g) dV \\
+ \int_V Q^T dV = \int_V (1 - \phi) \rho C_s \frac{\partial T_s}{\partial t} dV
\end{align*}
\]

\subsection{Boundary conditions}

The advancing of the working face will cause the gob boundary to move forward while the caving coal rock, after moving the hydraulic support, continuously flows in from the boundary near the working face and flows out from the deep boundary of the gob. Given that the air leakage wind speed is very small and the oxygen concentration is very low in the deep part of the gob, the residual coal is no longer oxidized and exothermic. Therefore, the mined-out area within a certain depth and height from the working face is taken as the calculation area, which is shown in Figure 2.

With regards to the AFF, OCF, ATF, and CO concentration field, the boundary of the calculation area is the boundary of the actual gob. For the STF, the calculation area is composed of two parts, the actual gob and the coal pillar. The extended boundary outside the coal pillar is regarded as the adiabatic boundary. The boundary conditions that correspond to the mathematical model are shown in Table 1.

\section{SOFTWARE OPTIMIZATION}

\subsection{Mesh generation}

The internal pores are large because the caving coal rock near the working face and coal pillar are in free accumulation state. However, the caving coal rock in the middle of the working face is gradually compacted by the overlying strata, and the internal pores become small.\textsuperscript{28} Therefore, considering the irregular cuboidal shape of the longwall gob area, we use a tetrahedral unit to divide the calculation area based on hexahedral mesh generation and encrypt the gob mesh near the working face and coal pillar, as shown in Figure 3.

At the end of mesh generation, the mesh nodes and tetrahedral units in the calculation area are numbered with the coordinate origin as the reference point, which provides the basis for handling the mining progress of the working face and the discretization of the model.
expressed as temperature is the original rock temperature, which can be mesh in the gob near the side of the working face, the node support is always a caving coal rock. Therefore, for the number \(m\) is the new range corresponding to the previous mesh node the gob mesh after the working face advancing, \(m'\) is the range of mesh node divided along the gob depth direction, and the working face advancing, \(m\) is the working face daily advance distance, and \(m'\) is the working face can change every day, with the advance speed changing often because of geological faults. It is unreasonable to take the average speed of advance as a parameter and introduce it into the software calculation process. To solve this problem, we take a hexahedral mesh generation result as an example to introduce the treatment method of the actual working face daily advance distance in detail, as shown in Figure 4.

In Figure 4, the dashed line is the gob mesh before the working face advancing, \([0 \sim m]\) is the range of mesh node numbers divided along the gob depth direction, and the temperature of each mesh node is known. The solid line is the gob mesh after the working face advancing, \([0' \sim m']\) is the new range corresponding to the previous mesh node number \([0 \sim m]\). The back of the working face hydraulic support is always a caving coal rock. Therefore, for the mesh in the gob near the side of the working face, the node temperature is the original rock temperature, which can be expressed as

\[
T_{0'} = T_0 = T
\]

where \(T_0\) is the temperature of the mesh node 0' after the working face advancing, \(T_0\) is the temperatures of mesh node 0, and \(T\) is the original rock temperature.

For the internal and other boundary mesh nodes in the gob, the linear interpolation method can be used to calculate the mesh node temperature after the working face advancing. If we use the mesh node \(m'\) as an example, it can be expressed as

\[
T_{m'} = \frac{S-L}{S} \times T_m + \frac{L}{S} \times T_n
\]

where \(T_{m'}\) is the temperature of mesh node \(m'\) after the working face advancing, \(T_m\) and \(T_n\) are the temperatures of mesh node \(m\) and the adjacent \(n\), respectively, \(S\) is the mesh size, \(L\) is the working face daily advance distance, and \(L = 0\) during stoppage.

According to Equations (6) and (7), the temperature in the gob after each advance of working face can be deduced as

\[
\begin{align*}
T_f &= \frac{S-L}{S} \times T_i + \frac{L}{S} \times T_{i-1} \\
T_0 &= T
\end{align*}
\]
where $T_i$ and $T_j$ are the temperatures of mesh nodes $i$ ($0 < i \leq m$) after and before the working face advancing, respectively.

Through this method, the temperature of each mesh node in gobs can be calculated based on the actual mining progress of the coal wall, the two cases of advancing and mining discontinuation for the working face can be unified, and the continuity calculation of multi-physical fields in the gob under the condition of longwall advance rate changes can be realized.

### 3.3 Discretization and solution

The multi-field coupling mathematical model established in this study takes the time factor into consideration and is a transient-state model. This, we use the finite volume method to discretize the mathematical model and obtain the linear equations of each node. On this basis, in order to greatly reduce the calculation time of software, we use the successive over-relaxation method to solve the linear equation.\(^{26}\)

The software algorithm is shown in Figure 5. When time-based unsteady-state iteration calculations begin, the program reads the value for the working face daily advance distance at each time step. Next, according to the temperature of each mesh node of the previous moment, the temperature distribution after the working face advancing is calculated as the initial temperature field in gob. Then, according to the multi-field coupling theory, the linear equations of each physical field in gobs are calculated at each time in turn. Finally, the iterative calculation is performed until the maximum relative variation of the two calculations meets the precision condition and achieves the calculation number, and the 3D cloud maps of physical fields are exported.

### 4 NUMERICAL SIMULATIONS

#### 4.1 Simulation case

Zhangji Coal Mine is located in Huainan City, Anhui Province and belongs to Huainan Mining Co., Ltd. Table 2 lists the basic parameters of coal samples in this area. The results show that the sample is medium-high volatile bituminous coal, which is prone to spontaneous combustion. As a result of roof collapses caused by faults over the past few years (2017-2019), the working face has often had to temporarily stop mining, which has in turn led to a number of spontaneous combustion accidents after remining. In this study,
the longwall working face 1415A with U-type ventilation is taken as the physical model for a 3D numerical simulative investigation.

4.2 Parameter setting and software solving

The crushed coal in the gob was oxidized and heated along with the normal operation of coal mining. The temperature in the gob increased to a certain level by the time the coal mining ended. Therefore, we take the temperature distribution when coal mining ends as the initial condition to simulate the spontaneous coal combustion in gobs from the end of mining to its resumption. The simulation results are strongly dependent on the parameter values and thus should be consistent with the actual on-site scenarios presented in Table 3. The daily advance distance of the working face within 160 days is shown in Figure 6, where the working face resumes mining from the 100th day.

In a previous study, we independently developed a software called COMBUSS-3D, which was used to simulate the coal self-heating scenario in a gob when the fully mechanized top coal caving face was advancing. In this study, the original software is improved. The improved software can characterize the coal spontaneous combustion process during the mining period and is renamed as COMBUSS-During Mining.

4.3 Results and discussion

Figure 7 shows the dynamic evolution of the oxygen concentration field, the solid temperature field, and CO concentration field on the 0th, 50th, 100th, 120th, 140th, and 160th days. The results show that (a) before the end of coal mining, the working face moved forward for a certain distance, and a high-temperature region formed in the deep part of the gob under the conditions of sufficient oxygen and heat storage; (b) after the working face stopped mining, the range of oxygen concentration shrank, and the residual coal continued to accumulate heat and oxidize; (c) with the increase of discontinued mining time, the high-temperature region begins to move to the inlet side of the working face, and its temperature increases rapidly; (d) after the working face resumes mining, the high-temperature region gradually moved to the deep part of the gob, and its temperature decreased slowly. For example, the maximum temperature was 66.5°C on 120th day, and it was observed at a point 50 m away from the working face, whereas it decreased to 59°C on 160th day while this distance increased to 110 m. In addition, the final stop position of the high-temperature region effectively

| TABLE 2 | Basic parameters of coal samples |
|----------|----------------------------------|
| Items    | Symbol | Value | Unit | Items    | Symbol | Value | Unit |
| Moisture (dry basis) | $M_{ad}$ | 0.12 | wt% | Sulfur | $S_{lad}$ | 0.03 | wt% |
| Ash (dry basis) | $A_{lad}$ | 17.03 | wt% | Oxygen absorption at 30°C | $V_d$ | 0.56 | cm$^3$/g |
| Volatile (dry basis) | $V_{lad}$ | 27.41 | wt% | Critical temperature point | $T_c$ | 60 | °C |
| Fix carbon (dry basis) | $F_{lad}$ | 55.44 | wt% |
explains why this area appears in the deep part of the gob before the end of mining.

In our simulation, the spontaneous combustion hazardous area is distributed on the air inlet side of the gob. Stopping mining for a long period of time leads to the accelerated oxidation of coal and formation of large amount of CO. However, CO concentration always appears in the overlapping position of the oxidation zone and the high-temperature region, as shown in Figure 7D. Further, to verify the correctness of the established mathematical model, we compare the simulation results with the on-site observation data, as shown in Figure 8. The data were monitored for 160 days using a gas collection system based on bundle tubes, which was deployed close to the wall of the air intake roadway of the working face. The results show that the simulated CO concentration is consistent with the overall change trend of the on-site observation data. This implies that our multi-field coupling mathematical model has high accuracy.25,31

4.4 Model validation

There is often a misconception that the spontaneous coal combustion during the mining-stopped period is calculated starting from the original rock temperature. However, with the advancement of the working face, high-temperature points appear in the gob, and the residual coal temperature rises to a certain level by the end of coal mining. Therefore, in the subsequent content, we compare the spontaneous coal combustion under the two initial conditions.32,33 In addition, it is worth noting that, during the mining period, the working face stops advancing for most of the time. Therefore, in order to emphasize the importance of the remining process, we also compare the spontaneous ignition process in the mined-out area during continuous stoppage with that under actual mining conditions.

It can be seen from Figure 9A that, if the calculation starts from the original rock temperature, the oxidation process of residual coal is very slow, and the temperature change is very weak. There is no hidden danger of spontaneous combustion.

| Coal properties (unit) | Value | Gob parameters (unit) | Value |
|-----------------------|-------|-----------------------|-------|
| Density of coal \(\rho_s\) (kg m\(^{-3}\)) | 1410  | Longwall length (m) | 239   |
| Density of air \(\rho_g\) (kg m\(^{-3}\)) | 1.29  | Gob depth (m) | 300   |
| Thermal conductivity of coal \(\lambda_s\) (W m\(^{-1}\)C\(^{-1}\)) | 0.29  | Ventilation flux during stoppage (m\(^3\) min\(^{-1}\)) | 1400   |
| Thermal conductivity of air \(\lambda_g\) (W m\(^{-1}\)C\(^{-1}\)) | 0.026 | Ventilation flux during resumption (m\(^3\) min\(^{-1}\)) | 3600   |
| Specific heat capacity of coal \(C_s\) (J kg\(^{-1}\)C\(^{-1}\)) | 1200  | Thickness of crushed coal \(h_0\) (m) | 0.6 |
| Specific heat capacity of air \(C_g\) (J kg\(^{-1}\)C\(^{-1}\)) | 1010  | Longwall advance rate \(v_0\) (m d\(^{-1}\)) | 1.8 |
| Convective heat transfer coefficient \(K_e\) (W m\(^{-2}\)C\(^{-1}\)) | 10    | Inflow temperature (°C) | 20.5 |
| Surface-to-volume ratio \(S_e\) (m\(^{-1}\)) | 36    | Outflow temperature (°C) | 25.5 |
| Molar concentration of oxygen \(c_{O_2}\) (mol m\(^{-3}\)) | 9.375 | Original rock temperature (°C) | 25.0 |
| Oxygen dispersion coefficient \(k_{O_2}\) (m\(^2\) s\(^{-1}\)) | 1.5 \times 10\(^{-5}\) | Stoppage period (days) | 100 |
| Oxidation heat of coal \([H_o]\) (kJ mol\(^{-1}\)O\(^2\)) | 300   | Resumption period (days) | 60 |

※Longwall advance rate is defined as an average advancing speed of the longwall face after resuming mining.
FIGURE 7   Simulation results obtained with COMBUSS-During Mining under varying mining progress
This is evidently not in accordance with the detection of a large amount of CO during the mining period, especially after resuming mining. In addition, if the working face does not resume mining in time and mining is stopped, the risk of coal spontaneous ignition will be significantly increased and the coal mine fire will be inevitable, as shown in Figure 9B. Thus, it is necessary to resume mining as early as possible to prevent coal spontaneous combustion during the production of coal mine.

5 | SENSITIVITY ANALYSIS

There are many parameters involved in our model, but the main factor affecting the coal spontaneous combustion in a gob is external mining parameters. In this study, the influence of the longwall advance rate and thickness of crushed coal on coal spontaneous combustion in a gob is quantitatively studied using the software program COMBUST-During Mining. The mining parameters for simulation are shown in Table 4.

| Mining parameter                  | Units |
|----------------------------------|-------|
| Longwall advance rate            | m/d   |
| Thickness of crushed coal        | m     |

Table 4: The mining parameters for simulation

5.1 | Longwall advance rate

Longwall advance rate \( (v_0) \) is defined as the average advancing speed of the working face after resuming mining. Figure 10 shows the effect of longwall advance rate on the solid temperature field during the mining period. The results show that, for a slower longwall advance rate, the final stopping position of the high-temperature point is closer to the working face, and the risk of spontaneous ignition is higher. For example, when \( v_0 = 1.2 \) m/d, the maximum temperature in the gob after resuming mining first rises slowly and then decreases slightly, the temperature decreases from 69.8°C to 66.5°C and the high-temperature region finally stops 70 m away from the working face. However, when \( v_0 = 3.6 \) m/d, the maximum temperature in the gob decreases from 68.5°C to 51.7°C, and the distance between the final stop position of the high-temperature region and working face is 190 m. Thus, for the former, the risk of coal spontaneous combustion is higher after resuming mining.

Figure 11 shows the variation in maximum temperature in the gob over time under different longwall advance rates. The results show that the maximum temperature in the gob generally shows a trend of first rising and then decreasing during the mining period. Temperature gradually decreases within 60 days of resuming mining. This is because of the continuous mining of the coal wall, the high-temperature region is gradually thrown into the scope of the suffocation zone in the deep part of the gob, which inhibits the accelerated oxidation of coal. Therefore, increasing the longwall advance rate can significantly reduce the risk of coal self-heating and considerably extend the spontaneous combustion period after...
resuming mining. During the production of coal mines, the stoppage time should be shortened as much as possible, and the mining progress should be improved.

### 5.2 Thickness of crushed coal

Figure 12 shows the effect of the thickness of the crushed coal on the solid temperature field during the mining period. The results show that, for a larger thickness of crushed coal, the initial temperature before the end of coal mining is higher, causing a higher risk of coal spontaneous combustion. For example, when $h_0 = 0.5$ m, the maximum temperature in the gob increases from 46.7°C to 59.1°C during the stop mining period, only increasing by 12.4°C. However, when $h_0 = 0.9$ m, the maximum temperature in the gob increases from 56.7°C to 113.8°C in the same time. It takes 20 days to reach the critical temperature point.\textsuperscript{35,36} After the resumption
**FIGURE 12** Effect of thickness of crushed coal on the evolution of solid temperature field, where the longwall advance rate $v_0 = 1.8 \text{ m/d}$

**FIGURE 13** Change in the maximum temperature in the gob over time for different thicknesses of crushed coal

**FIGURE 14** Effectiveness of reducing the thicknesses of crushed coal and increasing the longwall advance rate during the mining period
of mining, with the oxygen concentration gradually returning to normal, the temperature begins to decrease. Even then, spontaneous combustion may occur when the amount of residual coal exceeds a certain amount. Thus, in the process of coal mining, the amount of residual coal should be reduced to the greatest possible extent to prevent further thermal storage and oxidation of residual coal.

Figure 13 shows the variation in maximum temperature in the gob over time under different thickness of crushed coal. The results show that the maximum temperature in the gob increases sharply at first and then decreases rapidly, and considerable amount of residual coal will significantly increase the risk of spontaneous coal ignition. Figure 14 shows that in the case of $h_0 = 0.5$ m and $v_0 = 1.2$ m/d, the temperature only drops by $1.4^\circ$C within 60 days after resuming mining, while it decreases by $34^\circ$C when $h_0 = 0.8$ m and $v_0 = 3.6$ m/d in the same time, where the final temperature is the same as the former. To conclude, if the amount of residual coal in the gob cannot be reduced, increasing the remaining advance rate can prevent the occurrence of spontaneous coal ignition. Thus, the two strategies of improving the longwall advance rate and reducing the thickness of the crushed coal should be combined to ensure the safest and most efficient progress of coal mining.21,37

6 | CONCLUSIONS

In this study, we extend the multi-field coupling mathematical model and improve the numerical simulation software. The spatial and temporal distributions of the multi-physical fields in a gob are obtained and the effects of key parameters on spontaneous ignition are investigated using the improved version of the software.

- First, the CO concentration field is incorporated into the multi-field coupling mathematical model to determine the initial and boundary conditions of each physical field. By using the linear interpolation method to deal with the change of the mining progress, the process of advancing and stop mining of working face are unified. Thus, the problem of spontaneous combustion under the condition of the longwall advance rate changes can be solved. These modifications improve the accuracy of the model and make the simulation results more reliable.
- Subsequently, the 3D cloud map of oxygen, temperature, and CO concentrations in longwall gobs is obtained. The results show that (a) the high-oxygen-concentration region and high-temperature region are located at the air inlet side of the gob, and for a longer stoppage time, the oxygen concentration range is narrower and the high-temperature region is closer to the working face; (b) after resuming mining, the high-temperature region gradually moves to the deep part of the gob, and the oxygen concentration range gradually returns to normal; (c) the high CO concentration region always appears in the overlapping position of the oxidation zone and high-temperature region, which is consistent with the scenario on-site.
- Finally, the effects of two mining parameters on spontaneous combustion are quantitatively evaluated. The results show that (a) increasing the longwall advance rate and reducing the thickness of the crushed coal can break the original thermal storage conditions of residual coal and throw the hazardous area into a suffocation zone in time; (b) these comprehensive measures will more effectively prevent the spontaneous combustion of the mined-out area and ensure the production safety of the coal mine, but whether there is a quantitative functional relationship between the location of the hazardous area and mining parameters needs further research.

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NOMENCLATURE

Model parameter

- $P$: Total pressure difference of longwall face (Pa)
- $g$: Acceleration of gravity (m s$^{-2}$)
- $K$: Permeability coefficient (m s$^{-1}$)
- $S_e$: Surface-to-volume ratio (m$^{-1}$)
- $K_c$: Convective heat transfer coefficient (W m$^{-2}$°C$^{-1}$)
- $\rho_s$: Density of coal (kg m$^{-3}$)
- $\rho_g$: Density of air (kg m$^{-3}$)
- $\lambda_1$: Thermal conductivity of coal (W m$^{-1}$°C$^{-1}$)
- $\lambda_T$: Thermal conductivity of air (W m$^{-1}$°C$^{-1}$)
- $C_s$: Specific heat capacity of coal (J kg$^{-1}$°C$^{-1}$)
- $C_g$: Specific heat capacity of air (J kg$^{-1}$°C$^{-1}$)
- $T_s$: Temperature of coal (°C)
- $T_g$: Temperature of air (°C)
- $C_{O_2}$: Molar concentration of oxygen (mol m$^{-3}$)
- $C_{CO}$: Molar concentration of CO (mol m$^{-3}$)
- $\bar{v}$: Velocity vector of air (m s$^{-1}$)
- $v$: Gas seepage velocity (m s$^{-1}$)
- $\phi$: Void fraction of residual coal (%)
- $n$: Normal line
- $U^{T}_{O_2}$: Oxygen consumption rate of coal (mol m$^{-3}$ s$^{-1}$)
- $U^{T}_{CO}$: CO generation rate of coal (mol m$^{-3}$ s$^{-1}$)
- $k_{O_2}$: Oxygen dispersion coefficient (m$^2$ s$^{-1}$)
- $k_{CO}$: CO dispersion coefficient (m$^2$ s$^{-1}$)
- $Q^{T}$: Exothermic rate of coal (W m$^{-3}$)

Boundary parameter

- $l_{1-in}$: Air intake segment
- $l_{1-out}$: Air return segment
- $l_2$: Wall boundary
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