ABSTRACT: Coal bunkers are relatively closed systems. Due to their own oxidation characteristics and the increase of temperature, spontaneous combustion will occur beyond the spontaneous combustion period. Moreover, spontaneous combustion of coal bunkers is a disaster caused by multi-field coupling, so it is imperative to carry out inerting fire prevention and fire extinguishing. Based on this fact, combined with the actual situation in Huanghua Port, this paper establishes a two-dimensional geometric model of a coal bunker, selects CO2 as the inert gas sprayed in the coal bunker, determines the position of the inert gas port of the coal bunker hopper, and studies the influence of fireproof and fire-extinguishing inerting on coal bunker inerting. The results show that the arrangement of the inert gas port of the bunker hopper outside the bunker is more conducive to the diffusion of CO2 gas in the bunker. In about 35–41 days, the inerting temperature decreases slowly between 345 and 350 K. After 41 days, the maximum temperature of the coal bunker decreases rapidly and the spontaneous combustion of the coal bunker is completely controlled. Under the preset conditions, the best fire inerting time is 32.3 days after coal storage.

1. INTRODUCTION

Coal plays a vital part as an energy source. In the mining process, it is transported to a coal bunker by belts. A coal bunker is a relatively closed environment, with only two outlets at the top and bottom, and the heat is not easily diffused outward, causing the temperature of the coal body to gradually increase. Generally, the height of a coal bunker is about 30–50 m, and the “chimney effect” will appear. The increase in coal temperature will in turn accelerate the oxidation—reduction reaction of coal, which will cause the coal temperature to continue to rise. In addition, coal bunker fires generally occur inside the bunker, and the location is relatively hidden. During the fire-extinguishing process of a coal bunker onsite, an inert gas can be injected into the coal bunker to spread the inert gas throughout the coal bunker, reduce the oxygen concentration, and achieve the effect of firefighting and fire prevention. There are also many studies and successful precedents in the application of coal bunker inerting fire prevention technology. By way of examples, Chu believed that under different working conditions, for deep solid fires, a staged inerting plan should be adopted including factors such as inerting amount and inerting time; Xu studied the advantages and disadvantages of N2 and CO2 as inert gases and carried out inerting experiments to inhibit low-temperature oxidation of coal; Wang simulated the inerting effect of a closed coal bunker through experiments and focused on the analysis of the chimney effect on the changes in inert gas flow and pressure in the coal bunker; Wang used FLUENT software to carry out a numerical simulation study on the injection of CO2 in a closed ball bin, obtained the diffusion characteristics of CO2 in the coal body, and analyzed the influence of inerting parameters on the inerting effect; Akgun studied the different stacking methods of coal and predicted a two-dimensional model of coal spontaneous combustion; and Li designed N2 injection to prevent fire in a Dananhu coal...
bunker. N\textsubscript{2} injection ports were set on the square cone slope of the coal bunker coal hopper and above the filling part between the coal hopper and the bunker wall, and the N\textsubscript{2} injection pipeline was designed. In the choice of inert gas, Xu determined through experiments that the critical oxygen concentration of N\textsubscript{2} that effectively inhibits low-temperature coal oxidation is 1.5% and the critical oxygen concentration of CO\textsubscript{2} that effectively inhibits low-temperature coal oxidation is 3%.

From this perspective, under the same conditions, the effect of injecting CO\textsubscript{2} to suppress the spontaneous combustion of coal is better. (1) There is a clearer understanding of the mechanism of coal spontaneous combustion and the spontaneous combustion of coal piles on the ground, but there is still a lack of research on the spontaneous combustion law for closed cylindrical coal bunkers and the multiphysics coupling model and numerical simulation of coal bunker spontaneous combustion. (2) The study of coal bunker spontaneous combustion law is important to prevent coal spontaneous combustion. At present, there are few studies that consider the initial wind speed effect of coal bunkers through simulation research, but these are actual problems encountered on-site and need to be further studied. (3) At this stage, injecting an inert gas to prevent and extinguish fire in coal bunkers is a relatively fast and effective means. There are few reports on the selection of CO\textsubscript{2} as the inert gas to prevent and extinguish fire in closed cylindrical coal bunkers. The specific application effect remains to be further studied.

Therefore, this paper selects CO\textsubscript{2} as the inert gas, uses COMSOL software to simulate the position of the inert gas port of the coal bunker hopper, and studies the influence of fireproof and fire-extinguishing inerting on coal bunker inerting.

2. GEOMETRIC MODEL

2.1. Geometric Model of a Coal Bunker. There are 24 coal storage silos in the third-phase project of Huanghua Port. The silos are divided into four groups; each group of six silos constitutes a stacking and reclaiming operation line. A single silo has a diameter of 40 m and a height of 43 m, with a coal storage capacity of approximately 30,000 tons. According to the Huanghua Port coal bunker field survey and the existing coal bunker coal pile spontaneous combustion model,\textsuperscript{8,9,12} a two-dimensional coal bunker geometric model is established, as shown in Figure 1. The height of the coal bunker is 38 m and the width is 40 m. The coal bunker has two unloading ports at the top with a width of 1.5 m and two funnel-shaped coal outlets at the bottom with a width of 3.5 m;\textsuperscript{13} the coal outlet is regarded as the air inlet, and the unloading port is regarded as the air outlet.

According to the research focus, we have made targeted simplifications to the model as the following assumptions:

(1) The influence of solar radiation on the coal bunker is ignored.

(2) The influence of moisture on the spontaneous combustion of the coal bunker is not considered.

(3) The coal body in the coal bunker is regarded as a homogeneous porous medium with the same properties.

2.2. Grid Subdivision. This research takes the calculation accuracy and efficiency into account; the mesh module of COMSOL software is used for “more refined” mesh generation. The mesh generation area is 1269 m\textsuperscript{2}, with a total of 3061 element meshes, including 2767 triangles, 294 quadrangles, 173 edge elements, and 13 vertex elements. The sectional grid diagram of the coal bunker is shown in Figure 2.

| Shape    | Number | Minimum Unit Mass | Mean Cell Mass | Unit Area Ratio | The Grid Size |
|----------|--------|-------------------|----------------|-----------------|---------------|
| Triangle | 2767   | 0.1941            | 0.7953         | 0.007033        | 1209          |
| Quadrangle | 284   | 0.4936            | 0.8420         | 0.07142         | 60.33         |

It can be seen from Table 1 that the mesh is mainly divided into triangles, accounting for 90.4% of the divided mesh area. The average element masses of triangles and quadrangles are 0.7953 and 0.8420, respectively.

3. MULTIFIELD COUPLING EQUATION

3.1. Oxygen Component Transport Equation. The coal stored in the coal bunker can be regarded as a porous medium...
material, which is composed of a solid (coal body) and a fluid (air). Therefore, when discussing issues later, the porosity of the porous medium is determined according to the fluid-to-solid ratio. The oxygen in the air is transported in the coal bunker mainly through convection and diffusion. The coal is in contact with oxygen, and an oxidation-reduction reaction occurs. In this process, the transportation process can be described by eq 1.

\[
\frac{\partial c}{\partial t} + (U \cdot \nabla)(c) = D \nabla^2 c - (1 - \varepsilon) r
\]

(1)

where \(\varepsilon\) is the porosity, \%; \(C\) is the oxygen concentration in the air, mol/m\(^3\); \(D\) is the diffusion coefficient of species in gas phase, m\(^2\)/s; and \(r\) is the reaction speed, mol/(m\(^3\) s).

### 3.2. Gas Flow Equation.

The internal low-temperature oxidation reaction rate of coal in the coal bunker is limited by the seepage and diffusion of the porous medium of the coal; the porous medium has a large porosity, and the mass-transfer efficiency is high, and the reaction is not limited by the oxygen concentration. The coal is regarded as a porous medium, and the void ratio and permeability parameters need to be set during the numerical simulation. Assuming that the coal is evenly distributed, eq 2 is used to estimate the void ratio of the coal seam.

\[
\varepsilon = 1 - \frac{\rho_p}{\rho_c}
\]

(2)

where \(\varepsilon\) is the void ratio of coal; \(\rho_p\) is the unit weight of coal, N/m\(^3\); and \(\rho_c\) is the density of coal particle, kg/m\(^3\). The permeability in the coal seam is homogeneous and isotropic, and the permeability can be obtained by eq 3.

\[
k = \frac{\varepsilon d^2}{150(1 - \varepsilon)^2}
\]

(3)

where \(k\) is the permeability of coal, m\(^2\), and \(d\) is the diameter of the coal particle, m.

Compared with coal rock mass or pulverized coal, the particle diameter inside the coal bunker is larger, the internal gas seepage is mainly driven by wind, and the gas flow speed between the particles is also faster, so Darcy’s law is no longer applicable. Instead, the Brinkman equation of high permeability flow, shown in eq 4, is more suitable for the coal bunker.

\[
V^2 U = \frac{1}{\mu} \left( \frac{\mu}{k_0} U + \nabla P - \rho g \left( 1 - \frac{T}{T_f} \right) \right)
\]

(4)

where \(U\) is the airflow velocity vector, m/s; \(k_0\) is the permeability tensor, m\(^2\); \(\mu\) is the dynamic viscosity coefficient, kg/(m s); \(P\) is the pressure, Pa; and \(g\) is the gravitational acceleration, m/s\(^2\).

Considering wind drive in the vertical direction, the chimney effect is an important factor, especially for coal bunkers with large vertical height. The coal temperature in the coal bunker increases, and the gas density changes, resulting in an increase in thermal buoyancy. The last term in the above formula represents the cause of the chimney effect of gas inside the coal bunker.

### 3.3. Spontaneous Ignition Temperature Equation.

The heat transfer in a coal bunker is nothing more than the following three methods: convection, conduction, and radiation. As coal is in the coal bunker, thermal radiation effects are not considered for the time being. Assuming that the temperature of the fluid (air) and solid (coal) is equal, the energy conservation equation satisfied by the spontaneous combustion process of coal in the coal bunker is given by eq 5.

\[
C_{p,\text{eff}} \frac{\partial T}{\partial t} + (U \cdot \nabla)(\rho_c C T) = \lambda_c \nabla^2 T + (1 - \varepsilon) r \Delta H
\]

(5)

where \(C_{p,\text{eff}}\) is the specific heat capacity, J/(kg K); \(r\) is the reaction speed, mol/(m\(^3\) s); \(\Delta H\) is the heat of coal oxidation, J/(mol O\(_2\)); and \(\lambda_c\) is the effective thermal conductivity, W/(m K). When solving \(C_{p,\text{eff}}\) (specific heat capacity), two contents of solid (coal body) and fluid (air) are considered, as shown in eq 6.

\[
C_{p,\text{eff}} = (1 - \varepsilon) C_{p,\text{fl}} + \varepsilon C_{p,\text{g}}
\]

(6)

where \(C_{p,\text{eff}}\) is the porous media equivalent volume heat capacity, J/(m\(^3\) K); \(C_{p,\text{fl}}\) is the volumetric heat capacity of coal (solid), J/(m\(^3\) K); and \(C_{p,\text{g}}\) is the volumetric heat capacity of air, J/(m\(^3\) K).

### 4. SIMULATION CONDITION SETTING

#### 4.1. Boundary Conditions and Parameter Settings.

##### 4.1.1. Boundary Condition Settings.

The set ambient temperature and the temperature of the coal bunker are both 300 K, and the coal heat transfer coefficient between the bunker wall and external environment is 1.5 (W/(m\(^2\) K)). Combining the authors’ previous simulation conclusions, it is assumed that when the mixed wind speed is \(V_x = 0.5\) m/s and \(V_y = 0.05\) m/s, the spontaneous combustion period of the coal bunker is 34.3 days. The two coal outlets on the lower side of the coal bunker are airflow inlets, and the two coal unloading ports above the coal bunker are airflow outlets. It is considered that the oxygen concentration in the coal bunker and the air is 9.375 mol/m\(^3\). The boundary condition description is shown in Figure 3.

Regarding the airflow in the coal bunker and the flow of oxygen in the reaction of spontaneous combustion of coal piles and oxygen, the bottom two positions are defined as inlets, the top two ports are outlets, and the rest are nonflux walls.

For the flow of CO\(_2\) injected after spontaneous combustion of coal piles and CO\(_2\) during the reaction, the eight ports...
around the coal bunker are defined as inverting inlets, the top outlet is the same as the outlet for airflow, and the rest are nonflux walls.

For the heat transfer process of a coal pile, it is defined that all of the previous inlets and outlets are excluded and the rest are nonflux walls.

4.1.2. Approximate and Iteration. In the traditional multiphysics coupling solution method, the value of one physics field is generally obtained first and then the value is transferred to the second physics field to obtain the value of the second physics field, and so on. Finally, the multiphysics settlement result is obtained. This is actually a simplified multiphysics solution method. Dr. Keyes proposed three processes for multiphysics coupling solution, namely, Gauss–Seidel multifield coupling, operator-splitting multifield coupling separation operation method, and Newton’s method. Among them, the Gauss–Seidel multifield coupling iterative calculation and the operator-splitting multifield coupling separation operation belong to the ”loose” coupling algorithm, and Newton’s method belongs to the ”tight” coupling algorithm. Newton’s method organizes the changing balance equation into a general equation and performs nondiagonal processing of the Jacobian matrix, so that the calculated result is more accurate and, at the same time, the resulting curve is also smoother. Therefore, this study chooses to use Newton’s method for approximate iteration.\(^1\)

4.1.3. Parameter Settings. Many parameters are involved in the simulation process of coal bunker spontaneous combustion, and the parameter list is shown in Table 2. The physical parameters of coal given in the table refer to previous research papers about the Huanghua Port coal bunker.\(^2\) Specific heat capacity, material density, Reynolds number, and other parameters are determined according to the software material library and common sense. Some variables in the reaction process, such as temperature, pressure, etc., change in real time during the calculation process and are not set here.

### Table 2. Parameter Input\(^1\)

| input parameter (unit) | symbol | value |
|------------------------|--------|-------|
| activation energy \(J/(mol)\) | \(E\) | \(5 \times 10^4\) |
| pre-exponential factor \((1/s)\) | \(A\) | 180 |
| ideal gas constant \((J/(mol K))\) | \(R\) | 8.314 |
| initial temperature \((K)\) | \(T_0\) | 300 |
| dynamic viscosity coefficient \((kg/(m s))\) | \(\mu_d\) | \(1.8 \times 10^{-5}\) |
| permeability \((m^2)\) | \(K_t\) | \(8 \times 10^{-9}\) |
| specific heat capacity \((J/(kg K))\) | \(C_p\) | 1000 |
| heat of coal oxidation \((J/(mol O_2))\) | \(\Delta H\) | \(5 \times 10^8\) |
| molar concentration of oxygen in the air \((mol/m^3)\) | \(c_a\) | \(9.375\) |
| Reynolds number \((dimensionless)\) | \(Re\) | 0.72 |
| Schmidt constant \((dimensionless)\) | \(Sc\) | 0.78 |
| thermal conductivity \((W/(m K))\) | \(\lambda_i\) | 0.2 |
| density \((kg/m^3)\) | \(\rho_d\) | 1.85 |
| coal \((kg/m^3)\) | \(\rho_c\) | 1.300 |
| void ratio \((dimensionless)\) | \(\varepsilon\) | 0.25 |
| default thickness | \(m_0\) | 1 |

where \(v\) is the inlet velocity, \(m/s\); \(w\) is the volume fraction of \(CO_2\); \(t\) is the inert gas injection time, \(s\); and \(L\) is the width of the inert gas injection port, \(m\). Here, \(w\) is 30%, \(t\) is 120 s, and the calculated inlet velocity \(v\) is 3.965 m/s. Of course, this is the state of \(CO_2\) injection under ideal conditions. Considering that the coal bunker is a porous medium, the diffusion of \(CO_2\) gas in the coal bunker will be affected. Therefore, the inlet velocity is set to twice the calculated velocity, which is 7.93 m/s.

4.2. Boundary Condition Setting for Inert Gas Injection. 4.2.1. Amount of \(CO_2\) Gas Injected. According to the National Fire Protection Association (NFPA)’s 850 standards, when the volume fraction of \(CO_2\) reaches 65%, \(CO_2\) inverting can be considered successful.\(^3\) In addition, as mentioned above, in the \(CO_2\) inverting environment, when the \(O_2\) concentration is reduced to 3% or below, the \(CO_2\) volume fraction in the coal bunker should be 85.7%, and the coal redox reaction can be completely suppressed. Combining the two current mainstream inert gas firefighting concepts, we formulated different coal bunker firefighting and fire-extinguishing inert gas standards based on these two standards.

4.2.1.1. Boundary Conditions of Fire-extinguishing Inert Gas Injection. In coal bunker firefighting \(CO_2\) injection, it is known that the coal bunker reaches the spontaneous combustion period and the temperature of the coal bunker begins to rise sharply. The rapid \(CO_2\) injection fire-extinguishing method reduces the oxygen concentration in the bunker to below 3% in a short time. At this time, the volume fraction of \(CO_2\) in the coal bunker should be 85.7%, which is converted to a concentration of 38.259 mol/m³, that is, the \(CO_2\) in the coal bunker reaches this concentration, and the oxidation-reduction reaction in the coal bunker can be considered to be completely suppressed. According to the “Code for Design of \(CO_2\) Fire Extinguishing System” (GB50193-93), when extinguishing a deep fire, the \(CO_2\) concentration should reach 30% (13.393 mol/m³) within the first 2 min.\(^23,24\) According to this regulation, we carry out the speed entrance design. In this two-dimensional coal bunker model, the default thickness of the coal bunker is 1 m, the area \(Q\) in the two-dimensional domain is 1269 m², and the coal bunker is designed with eight inert ports, each with a width of 0.1 m. Each inlet velocity \((v)\) can be calculated by eq 7.

\[
v = \frac{Q_w}{8L}
\]

4.2.1.2. Boundary Conditions of Fireproof Inert Gas Injection. In coal bunker fire prevention \(CO_2\) injection, it is necessary to inject \(CO_2\) into the coal bunker before the coal spontaneous combustion period. At this time, a large amount of \(CO_2\) injection is not required. When the volume fraction of \(CO_2\) in the coal bunker reaches 65%, it is converted into a \(CO_2\) concentration of 29.017 mol/m³, that is, when the \(CO_2\) concentration in the coal bunker reaches this concentration, it can be considered to achieve the inverting effect of effective fire prevention in the coal bunker. Fireproof inert gas injection is a preventive inverting that starts before the critical temperature, so the inlet velocity of the inverting port is also related to the timing of inverting, which will be discussed below.

4.2.2. Position of the Inert Gas Injection Port. Aiming at the design of the inert port for a silo-type coal bunker, the inert gas injection port is mainly set on the bunker wall and the slope of the funnel. When designing the silo wall injection port, Li, Guo, et al.\(^{13}\) designed it in layers and set the same layer of open and closed inert gas injection ports on the same horizontal plane in a symmetrical distribution. This paper combines the actual coal bunker on-site and the existing case design and arranges eight inert gas injection ports in the coal bunker; each inert gas injection port width is 0.1 m, as shown in Figure 4. Three inert
gas injection ports are set on the left and right sides of the coal bunker, and the distance between each two inert gas injection ports is 6 m. There is no uniform application case for the inert gas injection port setting on the slope of the coal bunker funnel. This paper will consider arranging inert gas injection ports at two different positions on the outside of the coal bunker funnel and the inside of the funnel. As shown in Figure 4, the inert gas injection ports are marked in blue and red, and the following settings are made: inlet velocity is set to 0.1 m/s and the inlet CO2 concentration is set to 44.643 mol/m3. In this study, the influence of coal temperature rise is not considered. Under these conditions, the CO2 injection time for the coal bunker is 16 h. Furthermore, the influence of the positions of two inert gas injection ports on the inclined plane of the coal bunker on the CO2 diffusion in the coal bunker is studied.

The change of coal bunker CO2 concentration with time is shown in Figure 5. On the whole, the inert gas injection port is more conducive to the increase of coal bunker CO2 concentration on the outside than on the inside. According to the CO2 concentration standard (38.259 mol/m3) for the complete suppression of the coal bunker, the inert gas injection port reaches the expected concentration about 0.4 h earlier than on the inside. According to the final CO2 concentration (44.643 mol/m3) of the coal bunker, the inert gas injection port reaches the expected concentration about 1 h earlier than on the inside. Therefore, the inert gas injection port at the funnel of the coal bunker is chosen to be arranged outside, which is more conducive to the diffusion of CO2 gas in the coal bunker.

5. Results and Discussions. 5.1. Firefighting Indolence Injection. As can be seen from the above result, it takes about 34.3 days for the coal bunker to reach spontaneous combustion, and the firefighting inert gas study takes into account the firefighting CO2 situation when the fire in the bunker is about to get out of control. It should be noted that under this condition, to avoid the continuing spread of fire in the bunker, it is necessary to close the coal outlet and restrain the chimney effect so as to reduce the flow of fresh air into the coal bunker. At the same time, all eight inert gas injection ports are opened, and the inlet CO2 concentration is set to 44.643 mol/m3, and the inlet velocity is 7.93 m/s. To ensure the calculation efficiency and accuracy, the calculation time step is set as follows: In the first stage, 0–34.3 days and the step size is 86 400 s (1 day). In the second stage, 34.3–35.3 days and the step size is 10 s, mainly considering that CO2 enters the coal bunker with an extremely high flow rate and various parameters in the bunker change rapidly. To ensure the simulation accuracy, after debugging, the step size of this stage is set to 10 s. In the third stage, 35.3–50 days and the step size is 86 400 s.

5.1.1. Concentration Field Changes. As CO2 enters the coal bunker at an extremely high flow rate, the concentration of CO2 and O2 in the bunker changes rapidly within 10 min after the start of inert gas injection. Figure 6 depicts the change of the gas concentration field and reaction rate within 13 min after the start of inert gas injection; it can be seen from the chart that the concentration of CO2 increases rapidly after the start of inert gas injection, reaching more than 40 mol/m3 in 2 min, which meets the requirement of 30% CO2 concentration in the initial 2 min. Figure 7 depicts the CO2 concentration in
the coal bunker at different times. CO$_2$ diffuses from the inert port to the coal bunker at the beginning and then gradually to the upper exit. After 2 min of CO$_2$ gas injection, a high CO$_2$ concentration is maintained in all areas except the most central position of the coal bunker. Figure 6 shows that the concentration of O$_2$ continues to decrease, gradually from 9.375 mol/m$^3$ to below 0.5 mol/m$^3$. The decrease of O$_2$ concentration directly leads to the decrease of coal oxidation reaction rate, and the decreasing trend is similar, which can be explained by the coal oxidation reaction rate formula (eq 8). It can be seen from formula (eq 8) that the O$_2$ concentration will directly affect the reaction rate and then affect the heat release of the oxidation reaction, restraining the coal bunker from continuing to rise.

\[ n = 10^{(\frac{-E_a}{(R \times T)} \times (1 - \text{epi})/\text{epi})} \]  

(8)

5.1.2. Temperature Field Changes. After the injection of CO$_2$, the temperature increment trend in the coal bunker changed obviously. The temperature change in the coal bunker within 50 days is shown in Figure 8, and the temperature field in the coal bunker at different times is shown in Figure 9. Combined with Figures 8 and 9, it can be seen that the highest temperature of the coal bunker reached the critical temperature of spontaneous combustion (350 K) at the beginning of the injection (34.3 days), and finally the injection of CO$_2$ began to put out the fire urgently; otherwise, according to this trend, the spontaneous combustion in the coal bunker would be out of control. At the beginning of CO$_2$ injection, the maximum temperature (T-max) did not decrease immediately but continued to increase by about 5 K, which may be due to the fact that in the initial stage of inert gas injection, because the CO$_2$ gas has not yet reached the high-temperature area in the center of the coal bunker, the oxygen concentration field and flow field in this area have not changed obviously. In the period of about 35—41 days, the temperature did not continue to rise but decreased slowly between 345 and 350 K. The reason may be that the flow field in the high-temperature area...
of the coal bunker gradually increased and took away more heat after CO₂ injection for a period of time, while the O₂ concentration decreased continuously, resulting in the decrease of coal oxidation reaction rate and heat release. After 41 days, the maximum temperature of the coal bunker decreased rapidly, indicating that the maximum temperature of the coal bunker was completely controlled and the interior of the coal bunker began to cool.

From the average curve of the average temperature in Figure 8, the average temperature of the coal bunker decreases rapidly after the beginning of inert gas injection, which is mainly due to the low temperature of the injected CO₂ gas itself, which reduces the average temperature of the whole coal bunker.

5.2. Fireproof Indolence Injection. On the basis of the study of firefighting indolence injection, from the point of view of early control of oxygen concentration in the coal bunker to restrain spontaneous combustion, and considering the application of minimum cost, from the point of view of minimum damage to coal quality with the least material, this research carries out a study of preventive coal bunker inert gas injection. Fireproof inert injection means that the coal bunker is inert by slowly injecting CO₂ before the coal bunker reaches the critical temperature. In the actual production, the storage state of the coal bunker is divided into two kinds: one is that the coal bunker only uses the coming storage of coal, and at this time, to avoid air entering the coal bunker, the coal outlet is generally closed to reduce the air intake of the coal bunker; the other situation is that the coal bunker has two processes of coal intake and coal outlet, and the lower coal outlet is open, so the airflow will enter the coal bunker by the coal outlet, forming the so-called chimney effect. In addition, in the application of fireproof inert injection, the initial time of inert injection will also affect the inerting effect of the coal bunker, so the reasonable timing of indolence injection is also a problem worth discussing.

5.2.1. Effect of the Initial Wind Speed on the Concentration Field and Temperature Field. Here, it is considered to start the inert material injection simulation study on the day before the coal bunker reaches the spontaneous combustion period, that is, 33.3 days. When injecting the inert material, all eight inert ports are opened at the same time, the inlet CO₂ concentration is set to 44.643 mol/m³, and the inlet speed is 0.1 m/s. To better demonstrate the inert material injection effect of simulation, this section will simulate the inert material injection effect of 60 days. In the transient calculation, to ensure the calculation efficiency and accuracy, the calculation time step is set as follows: in the first stage, 0, 33.3 days and the step size is 86 400 s (1 day); in the second stage, 33.3 days and the step size is 10 s; and in the third stage, 34.3 days and the step size is 86 400 s.

To study the influence of the initial wind speed on fireproof inert material injection, the initial wind speed of the coal outlet was set when inert material injection began on the 33.3 day. The first case is that the coal outlet is closed, and the wind speed of the coal bunker is 0. The second case is that the coal outlet is open in the whole process, and the initial wind speed of the coal outlet is consistent with that mentioned above, that
is, \( V_x = 0.5 \) m/s and \( V_y = 0.05 \) m/s. So there has always been the chimney effect in bunkers.

5.2.1.1 Effect of the initial Wind Speed on the Concentration Field

After the initial inert injection, the gas concentration field and reaction rate change curve in the coal bunker is shown in Figure 10. The zero point of the abscissa is the time to start indolence, that is, 33.3 days; the abscissa is in units of hours, from which it can be seen that the change of gas concentration and reaction rate described in the figure is consistent with that described in Figure 6, but there is a change in the rate of change of gas concentration, for example, the concentration of \( \text{CO}_2 \) reaches 40 mol/m\(^3\) in about 15 h. There is no obvious change in the gas concentration field in the coal bunker under the two states of closing and opening the coal outlet, which may be related to the fact that the abscissa of the diagram is in units of hours and some minor changes are not shown in the diagram. Considering the actual situation, the main purpose of fireproof inert injection is to make the coal bunker maintain a state of high \( \text{CO}_2 \) and low \( \text{O}_2 \) before spontaneous combustion. This research only needs to pay attention to the final coal bunker concentration field and temperature field. Below, the paper discusses the changes of the coal bunker temperature field under two conditions.

5.2.1.2 Effect of the Initial Wind Speed on the Temperature Field

The temperature of the coal bunker changed after the injection of \( \text{CO}_2 \) gas, and the temperature change in the coal bunker in 0–60 days is shown in Figure 11. From the highest temperature curve of the coal bunker, it can be seen that the maximum temperature of the coal bunker under the condition of opening the coal outlet is about 2 K higher than that of closing the coal outlet. This may be due to the fact that after the injection of \( \text{CO}_2 \) gas, when the coal outlet is open, there is still flow of fresh air into the coal bunker, resulting in the reaction to continue for a period of time, and the \( T_{\text{max}} \) will continue to rise. In the following period of time, the \( T_{\text{max}} \) of the coal bunker decreased in both states, which indicated that it was mainly due to the gradual diffusion of the injected \( \text{CO}_2 \) gas to the high-temperature area, which reduced the oxygen concentration in this area. The last period is a steady decline period, and the maximum temperature in this section decreases slowly, mainly because the coal no longer produces heat, and the existing heat is transferred through convective heat transfer and heat conduction. From the point of view of the coal bunker \( T_{\text{average}} \), in both cases, the coal bunker \( T_{\text{average}} \) began to decrease on the 33.3 day, and the \( T_{\text{average}} \) in the coal outlet open state decreased more rapidly. The reason for this phenomenon may be that when the coal outlet is open, the injected \( \text{CO}_2 \) gas can flow out of the coal bunker through a total of four outlets, especially since the \( \text{CO}_2 \) gas density is higher than the air density, and \( \text{CO}_2 \) will spread to the lower coal outlet. The coal outlet is open to facilitate the diffusion of \( \text{CO}_2 \) gas in the coal bunker, and the low-temperature \( \text{CO}_2 \) gas will cool the coal wherever it is.

5.2.2. Timing of Inert Gas Injection. The timing of inert gas injection is an important issue in the application of fireproof inert injection. If the time to start inert injection is too early, the temperature of the coal bunker can be kept at a low level, but the cost of labor and materials will be wasted. It may not be conducive to controlling the temperature of the coal bunker, resulting in the oxidation of coal in the bunker and affecting the quality of coal. For this reason, the temperature field of inert gas injection from three time points is studied, which are 31.3, 32.3, and 33.3 days, respectively (corresponding to 3, 2, and 1 day before the spontaneous ignition period). The change of the temperature field of the coal bunker in 60 days under three conditions is shown in Figure 12. It can be

![Figure 10](https://example.com/fig10.png)

**Figure 10.** Effect of the closed/open state of the coal outlet on the coal bunker concentration field and reaction rate.

![Figure 11](https://example.com/fig11.png)

**Figure 11.** Changes in coal bunker temperature under closed/open conditions.
seen from the diagram that the earlier the time of inert injection, the lower the T-max and T-average of the coal bunker, which can be explained from the process of spontaneous combustion of the coal bunker. In the early stage of the coal low-temperature oxidation stage, the coal temperature is lower, and reducing the oxygen concentration in the coal bunker can restrain the coal oxidation temperature and keep the coal bunker at a lower temperature.

Summing up the three kinds of inert injection time simulated above, when the inert injection begins on the 33.3 day, the T-max is close to 345 K, which will have a certain impact on the coal quality of the coal bunker; when the inert injection begins on the 32.3 day, the T-max is at 335 K; and when the inert injection begins on the 31.3 day, the T-max is at 332 K. The comparative study found that when the inert injection began on the 32.3 day, the T-max decreased by 10 K and decreased by about 8 K one day earlier than that on the 33.3 day. When the inert injection began on the 31.3 day, the cooling effect decreased slightly and the material loss was increased. Therefore, under the premise of ensuring the inerting effect and reducing the cost, we choose to carry out fireproof inert injection from 32.3 days after coal storage.

6. Conclusions. This paper focuses on the fire-extinguishing method of injecting inert gas into a coal bunker, determines the fire prevention and extinguishing mechanism of CO₂ injection after comprehensive consideration, and analyzes the economic and environmental impact.

(1) Based on the study of the position of the injection inert port at the coal bunker funnel, it is found that the injection inert port at the coal bunker funnel is arranged on the outside, which is more conducive to the diffusion of CO₂ gas in the coal bunker.

(2) Aiming at the inert injection in the fire-extinguishing coal bunker, the inlet CO₂ concentration is set at 44.643 mol/m³ and the inlet velocity is 7.93 m/s. The changes of the gas concentration field and temperature field during 50 days are studied. It is found that after the beginning of inert gas injection, the CO₂ concentration increases rapidly and reaches more than 40 mol/m³ in 2 min, which meets the previous requirement of 30% CO₂ concentration in the initial 2 min. From the point of view of the temperature field, the maximum temperature T-max does not decrease immediately after the start of CO₂ injection. In about 35–41 days, the temperature decreases slowly between 345 and 350 K, and after 41 days, the maximum temperature of the coal bunker decreases rapidly, indicating that the maximum temperature of the coal bunker is completely controlled and the interior of the coal bunker begins to cool.

(3) In view of the inert injection in the fireproof coal bunker, the effect of the initial wind speed on the inerting of the coal bunker is studied, which will increase the maximum temperature of the coal bunker and decrease the average temperature. The timing of inert gas injection is discussed on the premise of ensuring the inerting effect and reducing the cost, and the fireproof inert injection of the coal bunker is chosen from 32.3 days.

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Notes
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