Study of the influence of the characteristics of loose residual coal on the spontaneous combustion of coal gob

Nan Liⁱ | Xuelong Li²,³ | Cai Shu⁴ | Wenlong Shen⁴ | Miao He⁵ | Jingjing Meng⁶

Abstract
Mine fires are becoming a serious issue as the intensity of mining increases, especially in deep mines. Loose coal gob has a hidden ignition location and a high possibility of spontaneous combustion, which makes fire prevention difficult. Therefore, based on the theory of gas seepage and the characteristics of loose coal, a model of air leakage and spontaneous combustion in gob is established in this paper. Using working face #10414 in the Yangliu coal mine as an example, the relationship between the three spontaneous coal combustion (CSC) zones and the three stress zones is analyzed and verified by combining a FLAC3D simulation with field monitoring. In addition, the influence of advancing speed on the CSC is discussed, and suggestions for fire prevention are presented. The results show that the variation in the calorific value of the CSC with increasing degree of looseness of the residual coal in the gob forms an arch-shape. There is a one-to-one relationship between the distribution of the three stress zones and the three CSC zones. In addition, as the advancing speed increases, the contact time between the loose coal body and the air decreases and the possibility of CSC decreases. This study provides a scientific basis for fire prevention and control in mines.

KEYWORDS
air leakage and spontaneous combustion model, degree of looseness of residual coal, fire prevention measures, in situ monitoring, numerical simulation
1 | INTRODUCTION

Mine fires are one of the main disasters in coal mines. They burn up a large amount of coal resources, reduce the calorific value of the coal, and are the major source of toxic gas and greenhouse gas emissions. Mine fires caused by spontaneous coal combustion (CSC) in gob accounts for more than 90% of the total number of fires. Because the shear resistance of the top of the coal in the gob is poor, it is easy to produce deformation, fractures, and loose coal in deep mines. The location of the loose coal is concealed and is difficult to deal with, which increases the possibility of spontaneous combustion, thus posing a serious threat to safe production in the mine. Therefore, it is important to study the relationship between the degree of looseness of the residual coal (LDRC) and CSC in gob to prevent and control mine fires.

Until now, scholars have studied the problem of CSC in gob by means of experimental research, numerical simulations, and in situ testing. Cai et al considered the movement from the working face to the surface to be a dynamic development process characterized by three stress zones and three destruction zones. Su et al established a similar model and studied air leakage and CSC in gob for different ventilation modes and different inclination angles. Wang et al studied the pore structure of coal using a nitrogen adsorption isotherm and concluded that coal contains a complete and continuous pore system, and the fractal dimension of coal is negatively correlated with its permeability. Wang et al and Shen et al established a CSC prediction model for roadside gob in a fully mechanized top-coal caving method. The 2D numerical model of the entire CSC process was carried out using a computer and was compared with the actual ignition period. Their prediction accuracy was higher. Lázaro and Torrent put forward the steady-state simulation process of coal mine fires using the principle of hot air pressure, which is attached to the ventilation network as an auxiliary ventilator to obtain the airflow state and leakage situation during the fire. Ma et al measured the oxygen uptake of the coal in the low-temperature stage using gas chromatography, determined how the oxygen uptake changes with the coal temperature and the degree of metamorphism, and analyzed the relationship between the oxygen concentration and CSC in gob. However, the present CSC situation is complex, and the research on the influence of LDRC on CSC is lacking.

To this end, we establish a model of air leakage and spontaneous combustion (ASM) to determine the relationship between the LDRC and heat dissipation in loose coal. Using working face #10414 in the Yangliu coal mine as an example, the relationship between the three CSC zones and the three stress zones in the gob is studied using a FLAC3D simulation and in situ testing. Finally, the influence of the advancing speed on CSC is discussed, and corresponding fire prevention suggestions are given. The results of our research are valuable information for the prevention and control of mine fires.

2 | ANALYSIS OF THE RELEVANT THEORIES

2.1 | Establishment of the ASM

Spontaneous coal combustion depends on the oxidation of the raw coal itself, the LDRC of the gob, the thermal conductivity of the coal, and the air leakage intensity. In addition, it is affected by the advancing speed of the working face and the protective measures implemented. The loose characteristics of the coal body in the gob are directly related to CSC, which reflect the spatial-temporal characteristics of the air leakage and oxygen supply during the CSC process. Furthermore, gas migration within the gob is restricted by the spatial-temporal distribution of the fractures in the overlying coal-rock and the looseness of the caved coal-rock mass, while based on the rock pressure, the coal-rock mass in the gob exhibits obvious zoning.

The LDRC decreases with increasing rock pressure, which is caused by the pressure from caving of the old roof above. Once the stress has increased to a certain extent, the LDRC is close to zero. The specific relationship is approximately represented by a negative exponential function:

\[ w = Ae^{-\sigma} + B, \quad A = e^{\sigma_0}(K_0 - K_1)/(e^{\sigma_0} - 1), \]
\[ B = (K_1 e^{\sigma_0} - K_0)/(e^{\sigma_0} - 1), \]

where \( w \) is the LDRC in the gob (nondimensional); \( \sigma \) is the stress on the broken coal-rock mass (MPa); \( K_0 \) and \( K_1 \) are the natural coefficient of crushing expansion and the residual coefficient of crushing expansion, respectively; and \( \sigma_0 \) is the initial stress (MPa).

Generally, we regard the residual coal in the gob as a porous medium, and its porosity and permeability affect the flow field within the gob. The relationship between the porosity and the LDRC is as follows:
The air leakage intensity of the loose coal caused by the local resistance is

\[ Q_f = kH_f / \mu L \quad H_f = \xi \rho g v^2 / 2, \]

where \( \xi \) is the drag coefficient and \( v \) is the average wind speed (m/s).

Therefore, the total air leakage intensity of the loose coal in the gob is

\[ Q = Q_v + Q_c + Q_m + Q_f + Q_l. \]

The air leakage from the mine will continuously supply oxygen to the coal in the gob, which provides favorable conditions for CSC in the gob. However, if the amount of air leakage is too large, it will not be conducive to the accumulation of the heat generated by the oxidation of the residual coal in the gob. This is also related to the location of the gob where the residual coal is located. If the gob is idealized as an infinite one-dimensional plate, theoretical formulas for heat transfer under different air leakage intensities can be obtained as follows\(^\text{27,28}\):

\[ C_{O_2} > \frac{C_{O_2}^0}{q_0(T_m)} \left[ \frac{8 \times \lambda_c (T_m - T_x) + \rho_g c_g Q}{h^2} \frac{2 \times (T_m - T_g)}{x} \right] \]

where \( C_{O_2} \) is the actual oxygen concentration value within the gob (mol/L); \( C_{O_2}^0 \) is the concentration of oxygen in the fresh airflow (mol/L); \( q_0(T_m) \) is the experimentally determined heat release intensity of the coal at an average temperature of \( T_m \) (J/(cm\(^3\)·s)); \( \lambda_c \) is the thermal conductivity of the floating coal (J/(cm·s·K)); \( c_g \) is the specific heat capacity of the working face air (J/(kg·K)); and \( \rho_g \) is the wind flow density of the working face (g/cm\(^3\)). \( T_m \) is the maximum temperature of the coal body (K); \( T_m \) is the average temperature of the coal body (K); \( T_y \) is the temperature of the rock formation (K); \( T_g \) is the temperature of the wind flow (K); \( h \) is the thickness of the floating coal (m); and \( x \) is the working area of the gob length (m).

As can be seen from Equation 10, when the length of the working face, the coal temperature, and the thickness of the floating coal are constant, the value of \( C_{\text{min}} \) increases with increasing air leakage intensity. Therefore, when the airflow is in the one-dimensional plane, the heat generated by the enthalpy change is

\[ \Delta H = \rho_g c_g \frac{\partial}{\partial x} (Q(x) T) = \rho_g c_g \left[ \frac{-Q(x)}{Q(x) \frac{\partial T}{\partial x} + T \frac{\partial Q(x)}{\partial x}} \right]. \]

Based on Equation 11, when the temperature of the residual coal in the gob is constant, the heat dissipation of the residual coal oxidation is positively correlated with...
the intensity of the air leakage, and the relationship between the intensity of the air leakage and the LDRC is arch-shaped. Therefore, the relationship between CSC in the gob and the LDRC is arch-shaped. That is, when the LDRC is large, the gob has a good ventilation environment, heat does not accumulate easily, and the residual coal cannot spontaneously ignite. As the LDRC decreases, there is enough oxygen supply, and the heat is not easily released, so the risk of CSC is the greatest. When the loose coal is gradually compacted, the oxygen supply is insufficient, and the residual coal does not easily spontaneously combust.

2.2 Relationship between the spatial distribution of the LDRC in gob and CSC

The intensity and the state of the air leakage are mainly determined by the roof caving rule and the stress state of the gob. Redistribution of the underground pressure within the gob during mining results in different degrees of compaction of the coal-rock in the falling zone, which causes the porosity and permeability to change, affecting the air leakage state and the air leakage intensity of the gob. Then, the three CSC zones in goaf can be divided based on the stress distribution of the overlying strata in the goaf, that is, the three stress zones.

According to the movement of the overlying strata structure and the related underground pressure distribution theory, after mining is complete, the movement and deformation of the overburden strata in the gob occur as collapse, separation, and bending. This creates three stress zones (I, the supporting influence zone of the coal wall; II, the separation zone; and III, the recompaction zone) and three destruction zones (A, the caving zone; B, the fissure zone; and C, the entire bending subsidence zone) in the horizontal and vertical directions, respectively. The peak stress of coal body in front of the support and the peak stress of the gangue at the basic roof contact behind the gob constitute a dynamic stress double peak, which controls the LDRC within the gob. The distribution is shown in Figure 1.

Combining the stress distribution in Figure 1 with the quantitative relationship given by Equation 1, in zone I, close to the working face, the overburden is present as a cantilever beam structure, which avoids the area being affected by the stress of the basic top. Together with the coal wall and floor of gob, this area forms a loose triangle, which results in the area containing both broken coal and gangue material. This creates a seal that is worse than that in the middle of the gob, making it the main air leakage passage within the gob. Thus, this region is defined as the dissipation zone. Zone II is in the low-stress area where the coal and gangue are further broken by compressive stress. In this zone, the density increases, and heat accumulates easily but does not spread easily. This region is defined as the oxidation zone. Zone III is in the peak stress area, which is significantly affected by the stress. In this zone, the broken coal is compacted, the degree of compactness is high, and the influence of the ventilation is very weak. This region is defined as the suffocation zone.

Based on the ASM and the above analysis, there is a significant relationship between CSC and air leakage within the gob. The LDRC within the gob provides channels for airflow from the working face to the gob, which is an important

FIGURE 1 Distribution of the horizontal and vertical failure of the overburden strata in the gob
factor controlling the occurrence of CSC. Thus, we conclude that there is a one-to-one correspondence between the three CSC zones and the three stress zones.

3 | SIMULATION STUDY OF THE THREE STRESS ZONES

In this paper, the above-described results are applied to many rockburst coal mines such as the Qingdong coal mine, the Tongting coal mine, and the Qinan coal mine. The results show that the three stress zones can accurately and effectively be used to predict the three CSC zones. Due to space limitations, in this paper we use the Yangliu coal mine, which has recently had a CSC test, as an example to verify our results.

3.1 | General situation of the mine

The Yangliu coal mine is located in Huaibei City, Anhui Province, China. It contains three layers of minable coal. In this study, working face #10414, which is located in coal seam #10, was selected as the research object. This coal seam is a class II spontaneous combustion coal seam with an average burial depth of 590 m, an average coal seam thickness of 3.5 m, and a dip angle of 1°-3°. Working face #10414 has a length of 180 m and a tendency length of 1500 m. According to synchronous observations of working face #10412 of this coal seam, the possibility of CSC occurring during the mining process is significant. The in situ sampling results and laboratory measurements of the mechanical parameters of each coal-rock seam are shown in Figure 2.

![Figure 2](image2.png)

**Figure 2** Simplified panel formation and geotechnical parameters of the coal seam, roof, and floor formations

![Figure 3](image3.png)

**Figure 3** Geometric model diagram of the numerical simulation
3.2 | Numerical model

The FLAC3D software was selected to simulate the stress of the strata above the goaf, because it uses the explicit Lagrange algorithm and hybrid-discrete partition technology, which can simulate the plastic failure and flow of materials very accurately. In addition, this software can be used to solve large-scale 3D geotechnical engineering problems using a small amount of memory space and without forming a stiffness matrix.

Based on the profile of the Yangliu coal mine, a 500 m × 300 m × 100 m numerical model was established and divided into 1,875,000 unit cells. The boundary width of 60 m was reserved on both sides of the model roadway to eliminate the influence of the boundary effect. A total of 15 MPa was applied to the top to offset the influence of the self-weight of the overburden. The lateral stress coefficient was set to 1, and fixed constraints were applied all around. In order to ensure the accuracy requirements of the simulation, each 5 m was excavated once, and a total of 205 m was excavated to achieve the actual excavation length. The Mohr-Coulomb constitutive model was used for the calculation (Figure 3).

3.3 | Analysis of the results

Movement of the overburden is the fundamental cause of changes in the stope stress and roof caving disasters. A change in the stope stress is often a precursor to roof caving disasters, which initiates coal-rock falls in the gob. The plastic zone directly and effectively reflects the changing state of the overlying strata in the gob. Thus, in this paper, we select the monitoring line at the center of the gob at \( x = 250 \) m, and then, we obtain the stress curve and the cloud maps of the change in the stress, displacement, and plastic zone (Figure 4).

As can be seen from the change in the stress curve shown in Figure 4, stress concentration occurs in the front and back regions of the gob after mining. The maximum stress concentration factor can reach 3.5, and then, it gradually decreases to about 17 MPa. The stress in the gob increases slowly from the working face to the open-off cut, and then, it decreases gradually back to the initial stress. Based on the distribution cloud maps of the stress, displacement, and plastic zone, when the distance is between 25 and 76 m of the working face, the stress of the overlying strata in the gob increases slowly to the initial stress, and the plastic change is significant, but the displacement subsidence is small. Due to the influence of the support of the front coal wall, the overlying strata are deformed, cracked, and collapse, and a loose coal body is formed in the gob. Within this region, the possibility of CSC is higher, which is consistent with the results of the ASM. After 76 m, the underground pressure gradually increases and reaches its maximum, the height of the plastic zone above the gob is high, and the displacement and subsidence of the overlying strata are obvious. We assume that the coal-rock mass has completely collapsed, and the area of the rock strata, which has been above the pressure for a long time, gradually transitions from the initial loose accumulation, into the compaction state and to the peak stress value. Based on the above analysis, the ASM, and the roof caving rule, we can confirm that in working face #10414, the 0-25 m range is the dissipation zone, the 25-76 m range is the oxidation zone, and the suffocation zone occurs after 76 m.

FIGURE 4 The cloud map of the stress, displacement, and plastic zone and the stress curve
FIELD VERIFICATION OF THE THREE CSC ZONES

4.1 In situ testing plan and layout of the measured points

In order to control the occurrence of mine fires and to understand the influence of LDRC on CSC in gob during mining, pumping gas pipes and temperature sensors were buried in the ventilation roadway and the transportation roadway to monitor the changes in temperature and oxygen concentration according to the actual layout of working face #10414. Measurements were taken at four locations: Monitoring point #1 was located at the junction of the wind lane and the working face; monitoring point #2 was located along the wind lane, 12 m from monitoring point #1; monitoring point #3 was located at the junction of the machine lane and the working face; and monitoring point #4 was located along the machine lane, 12 m from monitoring point #3. The specific arrangement of the monitoring points is shown in Figure 5. In addition, since the nature of the coal has a significant influence on CSC, the parameters of the coal are reported in Table 1.

4.2 Temperature and oxygen concentration

The variation in the oxygen concentration within the gob is an important indicator of CSC, which can be used to reflect the air leakage within the gob and the risk of CSC. The temperature change within the gob is the most intuitive indication of CSC. Thus, temperature and oxygen concentration data were collected at four monitoring points during mining (Figures 6 and 7).

As can be seen from Figure 6, there is no significant difference between the four monitoring points because there is no CSC in the gob, and the four monitoring points gradually enter the goaf as the working face is advanced. The temperature increase at monitoring points #1 and #2 is relatively slow in the range of 0-20 m from the working face. Within the range of 20-70 m from the working face, the temperature of the ventilation roadway initially increases, then decreases, and finally, it remains unchanged after 70 m. Monitoring points #3 and #4 have a relatively slow temperature increase in the range of 0-30 m from the working face. In the range of 30-80 m from the working face, the temperature initially increases and then decreases, and after 80 m, the temperature does not change significantly. Based on the temperature trends at the four monitoring points, we preliminarily determined the ranges of the three CSC zones in the gob of working face #10414: The heat dissipation zone is 0-20 m in the ventilation roadway and 0-30 m in the transportation roadway; the spontaneous combustion zone is located 20-70 m in the ventilation roadway and 30-80 m in the transportation roadway; and the suffocation zone is located >70 m in the ventilation roadway and >80 m in the transportation roadway.

TABLE 1 Coal seam parameters for determining the spontaneous combustion tendency

| Coal seam | Oxygen of dry coal ($V_d$, cm$^3$/g) | Total sulfur ($S_{dat,\%}$) | Volatile matter ($V_{daf,\%}$) | Classification | Conclusion | Coal dust explosion |
|-----------|-------------------------------------|-----------------------------|-------------------------------|---------------|------------|-------------------|
| #10 coal  | 0.54                                | 0.9                         | 25.79                         | Class II      | Spontaneous combustion | Hazard of coal dust explosion |
As can be seen in Figure 7, the consumption rate of the oxygen concentration is slow in the initial stage, but it is still above 18%. As the mining continues, the consumption rate gradually increases, and the oxygen concentration at each monitoring point decreases to 18%. We conclude that the monitoring point is located is the dissipation zone: Monitoring point #1 is 18 m, monitoring point #2 is 20 m, monitoring point #3 is 30 m, and monitoring point #4 is 36 m. Although the temperature increased, it did not cause CSC. After further mining, each monitoring point decreased to 6%, and the monitoring points entered the suffocation zone: Monitoring point #1 is located at 68 m, monitoring point #2 is located at 70 m, monitoring point #3 is located at 82 m, and monitoring point #4 is located at 80 m. The reason for the unsynchronized change in the oxygen concentration in the ventilation roadway and the transportation roadway is mainly due to the fact that the mine airflow is transported from the transportation roadway to the ventilation roadway, so the airflow pressure within the gob on the side of the transportation roadway is larger than that on the side of the ventilation roadway, which makes the air leakage intensity within the gob large, makes the oxygen concentration difficult to lower, and makes the heat dissipation zone large. In addition, the breathing of the personnel decreases the oxygen concentration in the ventilation roadway.

4.3  |  Division of the three CSC zones

In this paper, oxygen is considered to be the main indicator, while temperature is considered to be an auxiliary indicator. In summary, according to the weighting analysis of the factors affecting CSC in gob, for the ventilation roadway, the range of the three CSC zones gob of working face #10414 is as follows: The dissipation zone is located <18 m (the distance from the working face to the gob), the oxidation zone is 18-70 m, and the suffocation zone is >70 m. For the transportation roadway, the range of the three CSC zones gob of working face #10414 is as follows: The dissipation zone is <30 m, the oxidation zone is 30-82 m, and the suffocation zone is >82 m. Each region is represented by a different color in Figure 8.

5  |  DISCUSSION

5.1  |  Comparison of the three CSC zones and the three stress zones

According to the simulation of the roof caving rule within the gob and the in situ testing data analysis of CSC, it is
found that the three zones are basically consistent with the three CSC zones determined from the temperature and oxygen concentration data: ranges of 0-20 m, 20-80 m, and >80 m from the working face. The three CSC zones measured on site are as follows: For the ventilation roadway, the dissipation zone, oxidation zone, and suffocation zone are 0-20 m, 20-70 m, and >70 m, respectively, while for the transportation roadway dissipation zone, oxidation zone, and suffocation zone are 0-30 m, 30-80 m, and >80 m, respectively. The scope of the two methods is basically the same, but the ionospheric zones cover the oxidation zone completely and are larger than the oxidation zone. The space of the gob increases continuously after the mining is completed, and new cracks develop and expand within the overlying coal-rock strata due to external forces. In the end, after the maximum breaking distance is reached, the overlying strata gradually break, collapse, and fill the gob, which results in the loose coal body accumulating in the gob. Influenced by mining stress, the loose coal in the gob changes from the natural dilatation state to the compaction state, and the LDRC decreases gradually.

In the supporting influence zone of the coal wall, due to the influence of the coal wall, the subsidence of the overlying coal-rock strata is small, incomplete collapse occurs, and the stress of the loose coal in the gob is small. According to the ASM, the closer to the working face the gob, the smaller the stress on the coal body, the larger the porosity and permeability, the higher the LDRC, and the bigger the air leakage intensity. Most of the heat generated by oxidation is removed from the gob by the air leakage, which prevents heat accumulation. There is no good thermal storage environment in this area, and the coal oxidation reaction lacks a sufficient energy supply. Therefore, the number of CSC events in this area generally decreases, and the area enters the dissipation zone.

In the separation zone, the residual coal bears a certain pressure, and the pressure increases as the working face is advanced, which decreases the LDRC, and the porosity and permeability become smaller than those of the supporting influence zone of the coal wall. However, because of the short time it is under the bearing pressure, the LDRC decreases slightly and the loose coal is not fully compacted. The airflow at the front of the working face passes through this area and into the gob area at a deeper depth. However, the intensity of the air leakage in this area has been significantly attenuated. This combined with the fact that the recompaction area occurs after this area and prevents the escape of the heat generated by the coal oxidation, and the long-term accumulation of heat leads to CSC. This area is defined as the oxidation zone.

In the recompaction area, the coal-rock mass bears the pressure of the overlying coal-rock strata for a long time, so it gradually changes from an initial loose state to a compacted state. The longer it bears the pressure, the smaller the LDRC, until it finally enters a stable state. At this time, the permeability has been decreased by two times compared to the initial permeability, the air leakage is weak, the fresh airflow in the working face has difficulty penetrating into the region, and the protection coal pillars on both sides of the roadway and the oxidation reaction of the residual coal in the gob also consume a certain amount of oxygen, which decreases the oxygen concentration. Thus, this area is in the suffocation zone.

The three CSC zones tested in situ have the geological conditions required for mining. In particular, when the underground terrain is rugged or there is a large amount of accumulated water, the layout of the test pipeline is extremely complex. Therefore, for coal mines that do not have the conditions necessary for on-site testing for CSC and/or when the field test distance is insufficient, predvision of the three CSC zones can be carried out by numerically simulating the law of deep coal seam roof caving. As a result, corresponding fire prevention measures can be established to ensure safe production in the mine.

### 5.2 Influence of the advancing speed on the spontaneous combustion of coal

The advancing speed of the working face determines the contact time between the air and the coal ruins and the residual coal in the gob. Then, the LDRC of the gob is controlled, and the possibility of CSC in the gob is affected. When the advancing speed is faster, the contact time between the air and the ruins and residual coal is shorter, the time the gob is under pressure is shorter, the porosity is relatively large, and the air leakage is larger; the heat dissipation increases, the scope of the dissipation zone covers more deep gob areas, and the residual coal does not easily spontaneously ignite. Therefore, a reasonable advancing speed has an important influence on CSC in gob. Based on the results of the in situ testing and the numerical simulation, the widths of the three CSC zones can be determined. In addition, based on these results and the minimum CSC period, a reasonable advancing speed can be determined.

The minimum CSC period was introduced by Kalenkin. He defined it as the time required for the coal to absorb oxygen in adiabatic conditions, to heat the coal, to release the water and gas from the coal, and to increase the temperature of the coal to the ignition temperature. He used this to establish a calculation model for the minimum CSC period:

$$T = \frac{C(T_c - T_0) + W \cdot \lambda / 100 + \mu \dot{Q}}{3600 \times 24 K_c V_0 Q},$$  \hspace{1cm} (12)$$

where $T$ is the time required for the temperature of the coal to increase to the critical temperature (days), $T_0$ is room temperature (293 K), $T_c$ is the critical temperature at which the
heating of the coal begins to accelerate (K), \( W \) is the total moisture content of the coal (%), \( C \) is the average specific heat of the coal from the normal temperature to the critical temperature (J/(kg·K)), \( \lambda \) is the evaporative heat absorption of the water (J/kg), \( \mu \) is the content of the residual coal gas in the gob (m\(^3\)/kg), \( Q \) is the heat of the oxygen adsorption in the coal (J/m\(^3\)), \( Q' \) is the heat of the gas desorption (J/m\(^3\)), \( K_c \) is the oxygen uptake rate of the coal between \( T_0 \) and \( T_c \) (m\(^3\)/(kg·s)), and \( T_c \) is 328-353 K according to the coal quality. The value of \( V_0 \) is 0.10-0.21 according to the ventilation condition of the coal seam.

According to the minimum CSC period model, the following parameters were obtained through laboratory experiments and calculations.

As can be seen in Table 2, the minimum CSC period of the No. 10 coal seam in the Yangliu coal mine is 66 days. Combined with the results for working face #10414, the width of the dissipation zone is 18 m, and the width of the oxidation zone is 64 m. The minimum advancing speed is

\[
V_i > \left( L_z + L_b \right) / T = 37.3 \text{ (m/mo)},
\]

where \( V_i \) is the minimum advancing speed (m/mo), \( L_z \) is the width of the oxidation zone (64 m), \( L_b \) is the width of the dissipation zone (18 m), and \( T \) is the minimum CSC period (days).

Taking into consideration an adequate safety factor (1.2 from field experience), we suggest that the advancing speed for working face #10414 should be 44.76 m/mo in order to prevent CSC in the gob.

### 5.3 Suggestions for fire prevention and extinguishing in the mine

The oxygen content of the coal-rock mass, the contact area with the oxygen and the ventilation and heat dissipation conditions are determined from the LDRC in the gob. In order to prevent mine fires, during the mining process, we should comprehensively use the fire prevention and extinguishing methods of colloidal plugging, foam covering, and inert gas dilute oxygen; the pouring technology; and the pipe injection, buried pipe injection of inert gases, and borehole injection. In addition, the three-dimensional coverage and rapid inertia method is carried out in the gob.

The buried pipe grouting method was used in the ventilation roadway of working face #10414. The grouting covers the surface of the coal and seals the voids in the loose coal, reducing or even preventing air leakage, and isolating the contact between the coal and oxygen. In addition, the grouting absorbs the heat stored in the spaces around the coal, reduces the temperature of the coal, destroys the various active groups on the surface of the coal (Figure 9), and prevents oxidation of the coal.\(^{42-44}\)

We suggest the adoption of the step-by-step nitrogen injection method for fire prevention and extinguishing in working face #10414. The recommended nitrogen injection step is 30 m. When a large amount of high concentration nitrogen is injected into the gob (Figure 9), the oxygen concentration and the air leakage into the gob can be reduced.\(^{45-48}\)

In addition, we suggest that block walls be constructed at the top and bottom ends every 30 m or so. In addition,

![Comprehensive layout of mine fire prevention and control](image)
dame sheets should be arranged outside the block wall and at the corner of the transportation roadway and the ventilation roadway of working face #10414. The anchor cable parts should be removed to fully cave the top coal at the corner of the roadway, reduce air leakage, and prevent heat accumulation (Figure 9).49-54

6 | CONCLUSIONS

In this paper, for the situation where the roof caving strength in a deep coal seam mine is relatively high, we analyze the relationship between the LDRC and CSC in the gob. In addition, we present a calculation model for CSC based on porosity and use working face #10414 in the Yangliu coal mine as an example to verify the correctness of the ASM. Based on a FLAC3D simulation and in situ monitoring, we discuss the influence of the advancing speed on CSC and suggest measures for mine fire prevention and extinguishing. The following conclusions are drawn.

Based on the analysis of the loose characteristics and air leakage intensity of the residual coal in the gob, we established the ASM for the loose coal in the gob, determined that the vertical stress on the roof of the gob varies in an arch-shape as the mining advances, and determined that the three stress zones in the gob correspond to three CSC zones.

Using working face #10414 in the Yangliu coal mine as an example, the underground pressure distribution and the characteristics of crack development in the gob were analyzed using the FLAC3D numerical simulation software. Based on the in situ monitoring data for the three CSC zones, we determined that within 25 m of the gob (close to the working face), the caved floating coal and gangue accumulation in the gob is relatively loose, the surrounding cracks have good connectivity, the compactness is poor, and there are many air leakage passages, which places it in the heat dissipation zone. In the range of >70 m, the subsidence of the overlying strata behind of gob reaches the limit and is in a compacted state, which places it in the asphyxiation zone. Within the range of 25-70 m, the LDRC in the gob is in the range of the arch peak value, which places it in the oxidation heating zone. Our results verify the correspondence between the three stress zones and the three CSC zones. In addition, our results provide a theoretical basis for fire prevention and extinguishing and monitoring of the first mining face with a CSC tendency and/or mining without in situ testing of the three CSC zones.

Based on the above analysis results and the geological data from the Yangliu coal mine, a reasonable advancing speed of 44.76 m/mo was determined for the mining to ensure that the length of the oxidation heating zone within the gob is at the minimum distance. In addition, we suggest that the following measures be implemented to reduce the possibility of mine fires: nitrogen injection in the machine lane, grouting in the wind lane, the construction of a windshield wall, and hanging of a windshield curtain.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (51874296, 51804049), the Natural Science Foundation of Jiangsu Province (BK20190080), the China Postdoctoral Science Foundation Grant (2018M640533), the State Key Laboratory of Coal Resources and Mine Safety of China (SKLCRSM19X002, SKLCRSM19KF008), the research fund of Henan Key Laboratory for Green and Efficient Mining & Comprehensive Utilization of Mineral Resources (KCF201806), and Science and Technology Projects of Chongqing Education Committee in 2019 (KJQN201904703).

ORCID

Xuelong Li https://orcid.org/0000-0003-2037-2525
Wenlong Shen https://orcid.org/0000-0002-5021-0183

REFERENCES

1. Lu Y, Shi S, Wang H, et al. Thermal characteristics of cement micro-particle-stabilized aqueous foam for sealing high-temperature mining fractures. Int J Heat Mass Transf. 2019;131:594-603.
2. Kong XG, Wang EY, He XQ, Zhao EL, Zhao C. Mechanical characteristics and dynamic damage evolution mechanism of coal samples in compressive loading experiments. Eng Fract Mech. 2019;210(4):160-169.
3. Kong B, Li Z, Wang E, et al. An experimental study for characterization the process of coal oxidation and spontaneous combustion by electromagnetic radiation technique. Process Saf Environ Prot. 2018;119:285-294.
4. Fan JY, Jiang DY, Liu W, et al. Discontinuous fatigue of salt rock with low-stress intervals. Int J Rock Mech Min Sci. 2019;115(3):77-86.
5. Li XL, Li ZH, Wang EY, et al. Pattern recognition of mine micro-seismic (MS) and blasting events based on wave fractal features. Fractals. 2018;26(3):1850029.
6. Yang Y, Li Z, Si L, et al. Study on test method of heat release intensity and thermophysical parameters of loose coal. Fuel. 2018;229:34-43.
7. Liu XF, Zhang HJ, Wang XR, et al. Acoustic emission characteristics of graded loading intact and holey rock samples during the damage and failure process. Appl Sci. 2019;9(8):1595.
8. Gürdal G, Hosgörmez H, Özcan D, et al. The properties of Çan Basin coals (Çanakkale—Turkey): Spontaneous combustion and combustion by-products. Int J Coal Geol. 2015;138:1-15.
9. Lu W, Cao YJ, Tien JC. Method for prevention and control of spontaneous combustion of coal seam and its application in mining field. Int J Min Sci Technol. 2017;27(5):839-846.
10. Kong B, Wang EY, Lu W, et al. Application of electromagnetic radiation detection in high-temperature anomalous areas.
experiencing coalfield fires. Energy. 2019. https://doi.org/10.1016/j.energy.116144

11. Liu XF, Song DZ, He XQ, et al. Quantitative analysis of coal nanopore characteristics using atomic force microscopy. Powder Technol. 2019;346:332-340.

12. Cai W, Dou LM, Si G, et al. A new seismic-based strain energy methodology for coal burst forecasting in underground coal mines. Int J Rock Mech Min Sci. 2019;123:104086.

13. Su HT, Zhou FB, Song XL, et al. Risk analysis of coal self-ignition in long wall gob: modeling study on three-dimensional hazard zones. Fire Saf J. 2016;83:54-65.

14. Wang Z, Cheng Y, Qi Y, et al. Experimental study of pore structure and fractal characteristics of pulverized intact coal and tectonic coal by low temperature nitrogen adsorption. Powder Technol. 2019;350(5):15-25.

15. Wang G, Xu H, Wu M, et al. Porosity model and air leakage flow field simulation of gob based on DEM-CFD. Arab J Geosci. 2018;11(7):148.

16. Shen WL, Wang M, Cao ZZ, et al. Mining-induced failure criteria of interactional hard roof structures: a case study. Energies. 2019;12:3016, 1-17.

17. Lázaro CE, Torrent JG. Experimental research on explosibility at high initial pressures of combustible dusts. J Loss Prev Process Ind. 2000;13(3-5):221-228.

18. Ma L, Wang D, Xin H, et al. The competitive reaction mechanism between oxidation and pyrolysis consumption during low-rank coal combustion at lean-oxygen conditions: a quantitative calculation based on thermogravimetric analyses. Can J Chem Eng. 2018;96(12):2575-2585.

19. Zou QL, Liu H, Cheng ZH, et al. Effect of slot inclination angle and borehole-slot ratio on mechanical property of pre-cracked coal: Implications for ECBM recovery using hydraulic slotting. Nat Resour Res. 2019. https://doi.org/10.1007/s11053-019-09544-y

20. Peng K, Liu ZP, Zou QL, et al. Static and dynamic mechanical properties of granite from various burial depths. Rock Mech Rock Eng. 2019;52:3545-3566.

21. Deng J, Lei C, Xiao Y, et al. Determination and prediction on “three zones” of coal spontaneous combustion in a gob of fully mechanized caving face. Fuel. 2018;211:458-470.

22. Zhang DH, Yang SQ, Wang QF, et al. Numerical simulation of spontaneous combustion of loose coal mass in high-caving area of coal roadway. J China Univ Min Technol. 2006;6:757-761.

23. Zhang M, Zhang P, Wang R, et al. Numerical analysis of air leakage characteristics of coal seam gob close to thin band. Geotech Geol Eng. 2018;36(5):3149-3158.

24. Li HE, Zheng C, Lu J, et al. Drying kinetics of coal under microwave irradiation based on a coupled electromagnetic, heat transfer and multiphase porous media model. Fuel. 2019;256:115966.

25. Wang DM. Mine ventilation and safety. Xuzhou: China University of Mining and Technology Press; 2007.

26. Chen X, Li H, Wang Q, Zhang Y. Experimental investigation on the macroscopic characteristic parameters of coal spontaneous combustion under adiabatic oxidation conditions with a mini combustion furnace. Combust Sci Technol. 2018;190(6):1075-1095.

27. Su EL, Liang YP, Zou QL, et al. Analysis of effects of CO2 injection on coalbed permeability: implications for coal seam CO2 sequestration. Energy Fuels. 2019;33(7):6606-6615.

28. Liu S, Li X, Wang D, Wu M, Yin G, Li M. Mechanical and acoustic emission characteristics of coal at temperature impact. Nat Resour Res. 2019;1-18. https://doi.org/10.1007/s11053-019-09562-w

29. Li X, Wang E, Li Z, Liu, Song D, Qiu L. Rock burst monitoring by integrated microseismic and electromagnetic radiation methods. Rock Mech Rock Eng. 2016;49:4393-4406.

30. Yang X, Wen G, Dai L, Sun H, Li X. Ground subsidence and surface cracks evolution from shallow-buried close-distance multi-seam mining: a case study in Bulianta coal mine. Rock Mech Rock Eng. 2019;52(8):2835-2852.

31. Kong L, Qi Q, Ouyang Z, et al. Relationship between rock burst and strata movement in fully mechanized sublevel caving mining in deep mine. Phys Numer Simul Geotech Eng. 2005;19:119.

32. Majdi A, Hassani FP, Nasiri MY. Prediction of the height of de-stressed zone above the mined panel roof in longwall coal mining. Int J Coal Geol. 2012;98:62-72.

33. Li J, Li Z, Yang Y, et al. Study on oxidation and gas release of active sites after low-temperature pyrolysis of coal. Fuel. 2018;233:237-246.

34. Liu J, Zhang R, Song DZ, et al. Experimental investigation on occurrence of gassy coal extrusion in coalmine. Saf Sci. 2019;113(3):362-371.

35. Li J, Li Z, Yang Y, et al. Laboratory study on the inhibitory effect of free radical scavenger on coal spontaneous combustion. Fuel Process Technol. 2018;171:350-360.

36. Cinefra M. Numerical method for frequency response in visco-embedded nanoplate. Int J Hydromechatron. 2019.2(2):119-130.

37. Zhou YB, LiZH, Zhang RL, et al. CO2 injection in coal: advantages and influences of temperature and pressure. Fuel. 2019;236(1):493-500.

38. Tang Y. Experimental investigation of applying MgCl2 and phosphates to synergistically inhibit the spontaneous combustion of coal. J Energy Inst. 2019;89(5):639-645.

39. Wang G, Liu Q, Sun L, et al. Secondary spontaneous combustion characteristics of coal based on programed temperature experiments. J Energy Res Technol. 2018;140(8):082204.

40. LiZH, Niu Y, Wang EY, et al. Experimental study on electric potential response characteristics of gas-bearing coal during deformation and fracturing process. Processes. 2019;7(2):72.

41. Kong XG, Wang EY, Li SG, et al. Fractals and chaos characteristics of acoustic emission energy about gas-bearing coal during loaded failure. Fractals. 2019;27(5):1950072.

42. Zhao X, Wang B, Jiang S, et al. Oxygen distribution and air leakage law in gob of working face of U+L ventilation system. Math Probl Eng. 2019;2:1-10.

43. Osterland S, Weber J. Analytical analysis of single-stage pressure relief valves. Int J Hydromechatron. 2019.2(2):32-53.

44. Wang G, Qin X, Shen J, et al. Quantitative analysis of microscopic structure and gas seepage characteristics of low-rank coal based on CT three-dimensional reconstruction of CT images and fractal theory. Fuel. 2019;256:115900.

45. Xin C, Lu L, Shi B, et al. Numerical investigation of local thermal non-equilibrium effects in coal porous media with cryogenic nitrogen injection. Int J Therm Sci. 2018;133:32-40.

46. Fan CJ, Elsworth D, Li S, et al. Modelling and optimization of enhanced coalbed methane recovery using CO2/N2 mixtures. Fuel. 2019;253:1114-1129.

47. Fan JY, Chen J, Jiang DY, et al. A stress model reflecting the effect of the friction angle on rockbursts in coal mines. Geomech Eng. 2019;18(1):21-27.
48. Li H, Shi SL, Lin BQ. Effects of microwave-assisted pyrolysis on the microstructure of bituminous coals. *Energy*. 2019;187:115986.

49. Wang K, Tang H, Wang F, et al. Research on complex air leakage method to prevent coal spontaneous combustion in longwall gob. *PLoS ONE*. 2019;14(3):e0213101.

50. Zheng C, Jiang B, Xue S, Chen Z, Li HE. Coalbed methane emissions and drainage methods in underground mining for mining safety and environmental benefits: a review. *Process Saf Environ Prot*. 2019;127:103-124.

51. Guanhua N, Hongchoa X, Shang LI, et al. The effect of anionic surfactant (SDS) on pore-fracture evolution of acidified coal and its significance for coalbed methane extraction. *Adv Powder Technol*. 2019;30:940-951.

52. Liu T, Lin BQ. Time-dependent dynamic diffusion processes in coal: model development and analysis. *Int J Heat Mass Transf*. 2019;134:1-9.

53. Fan C, Elsworth D, Li S, Zhou L, Yang Z, Song YU. Thermo-hydro-mechanical-chemical couplings controlling CH₄ production and CO₂ sequestration in enhanced coalbed methane recovery. *Energy*. 2019;173:1054-1077.

54. Wang S, Li X, Yao J, et al. Experimental investigation of rock breakage by a conical pick and its application to non-explosive mechanized mining in deep hard rock. *Int J Rock Mech Min Sci*. 2019;122:104063.

---

**How to cite this article:** Li N, Li X, Shu C, Shen W, He M, Meng J. Study of the influence of the characteristics of loose residual coal on the spontaneous combustion of coal gob. *Energy Sci Eng*. 2020;8:689–701. [https://doi.org/10.1002/ese3.542](https://doi.org/10.1002/ese3.542)