Study of the Abnormal CO-Exceedance Phenomenon in the Tailgate Corner of a Low Metamorphic Coal Seam

Lei Li 1,2,*, Ting Ren 1,2,3, Xiaoxing Zhong 1,2,* and Jiantao Wang 1,2

1 Key Laboratory of Gas and Fire Control for Coal Mines, Ministry of Education, China University of Mining & Technology, Xuzhou 221116, China; tren@uow.edu.au (T.R.); tb20120024@cumt.edu.cn (J.W.)
2 School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116, China
3 School of Civil, Mining & Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

* Correspondence: tb18120011b0@cumt.edu.cn (L.L.); zbxxcumt@cumt.edu.cn (X.Z.)

Abstract: Given the difficulty of early warning of coal spontaneous combustion caused by continuous abnormal exceedance of CO in the tailgate corner of a low metamorphic coal seam and taking the 1305-working face of the Dananhu No.1 coal mine in Hami, Xinjiang as an example, this paper studies the abnormal CO-exceedance phenomenon based on field measurements, experimental research, and numerical simulation. The research shows that the abnormal CO-exceedance phenomenon is not caused by spontaneous combustion oxidation but by ambient-temperature oxidation of coal in the goaf. Factors, such as higher amounts of residual coal and higher degrees of fragmentation of the goaf, provide opportunities for the ambient-temperature oxidation of residual coal in the 1305 goaf. The 1305 coal oxidation characteristics at ambient temperature are examined, and the abnormal CO-exceedance mechanism is analyzed in depth. A CO-early-warning-limit model in the tailgate corner for coal spontaneous combustion in the 1305 goaf is established, and the scientific problems needing to be solved by further research are also discussed. The relevant research results have an important guiding significance for improving scholars’ understandings of CO exceedance in similar low metamorphic coal seams and the early warning of coal spontaneous combustion.

Keywords: low metamorphic coal seam; ambient-temperature oxidation; abnormal CO exceedance; spontaneous combustion

1. Introduction

Low metamorphic coals (lignite, long flame coal, and non-caking coal) are the main form of coal found in China, accounting for about 42% of the total coal resources [1]. In recent years, with the large-scale application of fully mechanized top coal-caving technology, in the normal mining process of low metamorphic coal seams, the tailgate corner of the working face often presents the phenomenon of abnormal CO exceedance without any sign of spontaneous combustion. For example, the average tailgate corner CO of the 12,206-working face in the Shangwan coal mine and the 31,301-working face in the Wanli No.1 coal mine in Inner Mongolia are 70–90 and 80–95 ppm, respectively, and the 1305-working face of the Dananhu No.1 coal mine in Xinjiang exceeds 100 ppm. Even after pursuing a lot of fire prevention and extinguishing technical measures, the CO concentration in the tailgate corner often presents the phenomenon of abnormal CO exceedance without any sign of spontaneous combustion. For example, the average tailgate corner CO of the 12,206-working face in the Shangwan coal mine and the 31,301-working face in the Wanli No.1 coal mine in Inner Mongolia are 70–90 and 80–95 ppm, respectively, and the 1305-working face of the Dananhu No.1 coal mine in Xinjiang exceeds 100 ppm. Even after pursuing a lot of fire prevention and extinguishing technical measures, the CO concentration in the tailgate corner is still high. As the most important index gas, the abnormal exceedance of CO leads to confusion in the early warning of coal spontaneous combustion (CSC).

As an organic macromolecular material, coal contains many active components. During the process of coal reacting with O2 and its subsequent heating, functional groups, such as the ketone group, quinone group, and aldehyde group, are activated and are part of the reaction to produce CO [2]. CO is usually generated in an exponential manner with any
increase of temperature [3,4]. Therefore, a higher CO concentration usually means a higher potential for CSC. Safety regulations in Chinese coal mines have strict provisions on the underground CO concentration, which should not exceed 24 ppm, and this 24 ppm is used as the initial discrimination index of CSC in many coal mines. However, in addition to CSC oxidation, there are other sources of CO underground due to the influence of mining technologies, coal seam conditions, and mechanical action. Wu [5] measured the amount of CO gas absorbed in coal core directly through the FHJ-2 CO desorption speed tester and determined the content of primary CO gas in the coal seam of the Tashan Coal Mine to be \((1.8-3.7) \times 10^{-6}\) mL/g. Wang [6] studied the formation mechanism of primary CO in coal seams, and research shows that under non-oxidizing conditions, the self-reaction of the carbonyl and carboxyl groups will produce CO. Taraba [7] broke 12 different kinds of coal samples in an \(O_2\)-free environment and proved that C = O in the grinding process is mechanically activated and decomposed to produce CO. Yu [8] carried out the mechanical breaking of coal with a self-made crushing experimental device and the results show that the rising rate, occurrence time, and absolute production of the CO volume fraction increased with an increase of the coal sample amount and motor speed. Additionally, underground blasting operations and tail gas from trackless rubber tired vehicles will also produce CO, which will interfere with the early warning of CSC [9].

Low metamorphic coal, due to its low metamorphic degree and high activity, can react with \(O_2\) at ambient temperatures to release CO. Through a set of simple ambient-temperature oxidation devices, Luo [10] proved that lignite can produce high concentrations of CO at ambient temperature, and it is not related to coal temperature. Zhang [11] conducted an experimental study on the oxidation of coal at ambient temperature, and the results showed that the production rate of CO is directly proportional to the \(O_2\) consumption rate. A preliminary study by Liu [12] on the formation mechanism of CO produced by long flame coal reacting with \(O_2\) at ambient temperatures based on quantum chemistry calculation gave the possible elementary reaction path.

However, apart from a few coal mines, most Chinese coal mines attribute the abnormal CO exceedance in the tailgate corner of low metamorphic coal seams to the CSC in the goaf. Although preliminary research on the ambient-temperature oxidation of coal has been carried out, the relevant research is not systematic and in-depth, which leads to a lack of understanding around the treatment of abnormal CO exceedance and the early warning of CSC for low metamorphic coal seams. In view of this and taking a low metamorphic coal mining face as an example, this paper systematically introduces and analyzes the phenomenon and causes of CO exceedance in the tailgate corner, studies its production mechanism and the early warning limit of the CO gas index of CSC with the help of experimental research and CFD technology, and discusses the key scientific problems for further research. The relevant research results can guide and improve scholars’ understandings of CO exceedance in similar low metamorphic coal seams and the early warning of CSC.

2. Background

2.1. Working Face Overview

The 1305-working face of the Dananhu No.1 coal mine was selected as the research site. It is located in Hami City, Xinjiang. The coal seam mined is lignite, which is prone to spontaneous combustion, and the shortest natural ignition period is only 37 days. Industrial and elemental analysis of the coal sample is shown in Table 1.

The mining method of strike longwall retreating mining utilizing fully mechanized top coal caving has been adopted at the 1305-working face, and the roof is managed via the full-caving method. The design strike and inclined length are 2498 m and 238 m, respectively. The coal seam dip angle is 8°, and the average height is 9.8 m with the coal-cutting height of the shearer being 2.9 m, and the coal-caving height is 6.9 m. The recovery rate of the working face is 85%, and the thickness of the residual coal in the goaf is about \[9.8 \times (1 - 85\%) = 1.47\text{ m}\]. The working face is provided with air through the maingate1 (MG1) and cut throughs which run through every 200 m. The total air intake volume is
1966 m$^3$/min. A total of 139 supports (1#~139#) are arranged on the working face. To prevent a CSC accident in the goaf, coal mine safety management workers arrange a 180 m long nitrogen injection pipeline from the return air side to the inlet air side, 30 m behind the working face, allowing a nitrogen injection volume of 972 m$^3$/h. The schematic diagram of the working face 1305 and goaf is shown in Figure 1.

| Mad (%) | Vad (%) | Aad (%) | Fcad (%) | Q (MJ/kg) |
|---------|---------|---------|----------|-----------|
| 13.63   | 35.34   | 6.17    | 44.86    | 26.55     |
| C (%)   | H (%)   | O (%)   | S (%)    | N (%)     |
| 74.36   | 4.67    | 18.61   | 1.04     | 0.15      |

Note: Mad—moisture on air drying basis; Vad—volatile matter on air drying basis; Aad—ash on air drying basis; Fcad—fixed carbon on air drying basis; Q—quantity of heat.

Figure 1. Schematic diagram of 1305 working face and goaf.

2.2. CO Monitoring

To determine the CO exceedance range of the 1305 working face, gas monitoring points are arranged along the working face and tailgate (TG). The monitoring scheme is as follows: at supports 49#, 79#, 109#, the tailgate corner (C1), the diagonal corner of the tailgate corner (C2), and the tailgate 25 m away from the working face (G1). A handheld explosion-proof inflation pump is used to collect gas with a bladder during the non-production shift period every day, and this gas is then transported to the surface for gas chromatography analysis. The specific location of the monitoring points is shown in Figure 1.

The CO-concentration change at each monitoring point over a long time period is shown in Figure 2. Before the 79# support, there is little CO in the support area of the working face, but after that, the CO exceedance phenomenon begins to appear and becomes more and more serious along the working face. The average CO concentrations at the 109# support and the tailgate corner reached 29.2 ppm and 117.2 ppm, respectively, the former exceeded the specified limit of 5.2 ppm, and the latter reached 4.8 times the maximum allowable concentration. At C2, although the CO concentration did not exceed the limit, the mean value was 16 ppm, reaching 66% of the limit. We should note that the CO here may only come from the ambient-temperature oxidation of coal in the working face.
In the tailgate, the CO exceedance phenomenon occurs frequently, and the average CO concentration reaches 25.6 ppm. During the whole monitoring process, there was no index gas generation in the accelerated oxidation stage of CSC, such as C$_2$H$_4$, and there were no signs of other CSC, such as sweat on the coal wall, smell of coal coke oil, high temperature rise, etc.

Figure 2. CO-monitoring change.

From here, we see that during the normal mining of the 1305-working face and on the premise there is no sign of spontaneous combustion in the goaf, the CO exceedance area is quite large, accounting for about 43% of the working face support (from the working face 79# support to the tailgate corner), and it is very common that the tailgate corner is in the CO-exceedance state.

2.3. CO Multi-Source Analysis

Due to the complex underground environment of a coal mine, there may be many sources of CO, these mainly include the original coal seam, vehicle emissions, the coal-cutting effect of the shearer, underground blasting, air intake of the working face, low-temperature oxidation of residual coal in the goaf, and so on. According to the report on CO sources for the 1305 fully mechanized top coal-caving face in the Dananhu No.1 coal mine issued by Shenyang Coal Research Institute, there is no CO in the original coal seam of the 1305-working face, no blasting action underground, and no CO in the air intake of the working face; the amount of CO produced by vehicles and the coal cutting shearer is relatively small, and the emission time is short, which can be ignored. Therefore, the abnormal CO-exceedance phenomenon in the tailgate corner of the 1305-working face can only be caused by the low-temperature oxidation of residual coal in the goaf. However, whether it is caused by spontaneous combustion oxidation or ambient-temperature oxidation needs further analysis.

2.4. Low-Temperature Oxidation Analysis of Goaf

2.4.1. Residual Coal

The state of the residual coal plays an important role in the low-temperature oxidation of the goaf. Since the 1305-working face is mined using the fully mechanized top coal-caving technology, the amount of coal left in the goaf is relatively large. The residual coal rate is 15%, and the residual coal thickness is about 1.47 m. Furthermore, the coal seam where the 1305-working face is located belongs to three soft coal seams (the coal seam, roof,
and floor are soft coal and rock), which means that the residual coal in the goaf is highly fragmented with small to average block sizes, resulting in a large surface area per unit volume of residual coal in contact with $O_2$. The large amount and small size of residual coal provides ideal conditions for the coal to react with $O_2$ in the 1305 goaf.

2.4.2. Caving Condition

The caving properties of goaf play a key role in the distribution of the three zones (dissipation zone, oxidation zone, and suffocative zone) of CSC. The longer the periodic pressing step, the larger the “dissipation zone + oxidation zone” will be, which is more conducive to the oxidation reaction of residual coal [13]. According to the research report on control technology of three soft coal seams at Dananhu No.1 coal mine issued by Xi’an University of Science and Technology, the periodic pressure step distance of the 1305-working face is 16~23 m, which is relatively short. Theoretically, the area of “dissipation zone + oxidation zone” will be closer to the working face, which is conducive to inhibiting the oxidation reaction of residual coal. Although there is an isolated coal pillar at the tailgate side, for the two trough areas of the 1305 goaf, the collapse is relatively more complete due to the proximity to the adjacent goaf. In addition to isolating the coal pillar, the air inlet chute is adjacent to the untapped coal seam; thus, the corresponding goaf has good support, and it is not easy to collapse completely, resulting in high porosity, and it becomes the main in-depth area of the “dissipation zone + oxidation zone”. The mining dip angle of the working face of 1305 is $8^\circ$, belonging to a gently inclined coal seam, which has little effect on the caving and filling of the goaf.

2.4.3. Air Leakage

The air leakage channel will transport $O_2$ for the low-temperature oxidation of residual coal in the goaf. Due to the effect of the fully mechanized caving technology, there will be a three-dimensional, large space air leakage channel near the working face. At the same time, the 1305-working face adopts a dual inlet air supply mode, and the sealed cut through may leak air to the goaf due to the influence of the sealing technology, ground pressure, and so on. Furthermore, since the closest distance between the coal seam where the 1305-working face is located and the surface is only 150 m, there is a ground air leakage flow in the 1305 goaf.

According to the monitoring results of the Shenyang Coal Research Institute on the three zones of CSC in the 1305 goaf, at the inlet side, the dissipation zone of the goaf is 40 m, and the oxidation zone is 47 m, and at the outlet side, the dissipation zone is 3 m, and the oxidation zone is 21 m. Once the depth of the goaf is more than 87 m, it all enters the suffocative zone. From the perspective of prevention and control of CSC in the goaf, the minimum advancing speed of a working face can be designated by Formula (1).

$$V_{\text{min}} = \frac{L_{O}}{T_{SC}}$$

(1)

where, $V_{\text{min}}$ is the minimum advancing speed, m/d; $L_{O}$ is the length of the CSC danger area, m; $T_{SC}$ is the shortest natural ignition period of CSC, d.

Considering the high risk of CSC in the 1305 goaf and the threat of CSC in the dissipation zone to a certain extent, for the sake of safety, the $L_{O}$ is set as the length of “dissipation zone + oxidation zone”, then $V_{\text{min}} \approx 2.4$ m/d. The practical advancing speed of the 1305-working face for a period of monitoring is shown in Figure 3. The daily average advancing speed of the 1305-working face is 3.32 m/d, which is much higher than 2.4 m/d. In addition, there was no index gas generation in the accelerated oxidation stage of CSC, such as $C_2H_4$, and there were no other signs of CSC, such as sweat on the coal wall, smell of coal coke oil, high temperature rise, etc. Therefore, there is no possibility of CSC in the 1305 goaf, and the current CO exceedance in the tailgate corner is caused by ambient-temperature oxidation of residual coal in the goaf.
3. CO-Exceedance Mechanism Study

To reveal the mechanism of CO exceedance in the tailgate corner of the 1305 goaf caused by ambient-temperature oxidation, experimental research and CFD technology were conducted in this section.

3.1. Experiment

Because the oxidation of coal at ambient temperature is very slow, it is hard to directly monitor the gas products during the experiment where coal is reacting with O$_2$ at ambient temperature in the flow reactor; thus, the sealed reactor is selected in this research. At the same time, to enhance the reaction phenomenon, the particle size of the experimental coal sample needs to be relatively small, and the reaction amount needs to be relatively high. Combined with the temperature investigation at the 1305-working face, the annual temperature is between 10~25 °C; thus, the temperature required in this research needs to be within this range. Based on the above analysis, the following ambient-temperature-oxidation experiment of coal samples from the 1305-working face was carried out.

The ambient-temperature-oxidation apparatus developed by the Taiyuan University of technology is adopted, as shown in Figure 4, and the detailed introduction of this device can be found in literature [14]. Several kilograms of fresh coal samples were taken from the coal seam where the 1305 working face is located, wrapped with film, transported to the laboratory for crushing, and screened 2548 g coal samples with particle sizes ranging from 60 to 80 mesh. In the experiment, after the coal samples are loaded, the gas composition in the reactor was set to be the same as the atmosphere. The reactor was sealed, and the ambient-temperature oxidation of the coal samples were set until the CO concentration in the reactor did not change. During the experiment, real-time data was continuously collected by temperature sensors and a gas-concentration-monitoring computer.

The changes of coal temperature and ambient temperature during the experimental process are shown in Figure 5. The difference between coal temperature and ambient temperature is quite small; the maximum is 3.5 °C, and the average temperature difference is 1.05 °C, which means that the coal samples have been reacting at ambient temperature. The temperature for the whole experimental process is controlled within 10~16 °C, which meets the experimental requirements.
During the experiment, the changes of O$_2$ and CO over time are shown in Figure 6. According to the results, in the first 10 h, the coal in the reactor rapidly consumes O$_2$ and produces a large amount of CO, and O$_2$ concentration decreases, and CO concentration increases linearly with the progression of time, respectively. The CO-production concentration is about 656 ppm, and the amount is 6.58 cm$^3$. The O$_2$-consumption concentration is about 7.1%, and the amount is 0.733 L. Between 10 h and 60 h, the consumption rate of O$_2$ gradually decreases, and the production rate of CO decreases. At 60 h, the O$_2$ concentration decreases to the lowest level of 7.7%, and the final consumption amount is 1.33 L; the CO concentration reaches the maximum level of 1127 ppm, and the final production amount is 11.3 cm$^3$. Thereafter, the O$_2$ and CO concentrations in the reactor no longer change with time.

When coal reacts with O$_2$ under ambient temperature, the temperature in the reactor does not change greatly; thus, the CO-production rate may have an important relationship with respect to the ambient O$_2$ concentration. To investigate this possibility, the data in Figure 6 is reprocessed, and the results are shown in Figure 7. The CO-production rate and the ambient O$_2$ concentration are fitted with a quadratic function, and the formula obtained is shown as Formula (2).

$$G_M = 0.00192 - 0.00229C_O + 2.65729C_O^2$$  \(2\)

where, $G_M$ is the CO-production rate, cm$^3$/m$^3$·s; $C_O$ is the ambient O$_2$ concentration, %.
The CO-production rate of the coal sample has a good quadratic function fitting relationship with the ambient O\textsubscript{2} concentration, and the adjusted $R^2$ is 0.98081, which means that the CO-production rate of the residual coal in the goaf under ambient temperature is closely related to the O\textsubscript{2} concentration. The higher the ambient O\textsubscript{2} concentration in the goaf, the higher the CO-production rate of the residual coal.

Based on the above study, we know that when the ambient O\textsubscript{2} concentration is greater than or equal to 7.7%, the coal from the seam where the 1305-working face is located can react with O\textsubscript{2} and release CO under ambient temperature, and the CO-production rate is closely related to the ambient O\textsubscript{2} concentration, which is a quadratic function fitting relationship. Traditionally, the idea of preventing the CO exceedance in the tailgate corner is guided mainly by the theory of CSC, and the prevention and control method is carried out around the oxidation zone in the goaf. However, the study shows that the CO-production rate of the dissipation zone is bound to be higher than the oxidation zone due to the higher
O$_2$ concentration. The dissipation zone may have a more important impact on the CO exceedance in the tailgate corner.

3.2. Simulation of CO-Production Mechanism in Goaf Based on CFD

To investigate the mechanism of the CO exceedance in the tailgate corner of the 1305-working face, Fluent and MATLAB software were used. The investigation process is as follows: firstly, the distribution of gas in the 1305 goaf is numerically simulated using Fluent software; then, based on the obtained O$_2$-concentration data in the 1305 goaf and the research results of the ambient temperature oxidation experiment, the distribution of the CO-production rate in different areas of the 1305 goaf can be obtained using MATLAB software. The detailed work follows.

3.2.1. Research on O$_2$ Distribution in Goaf

According to the practical parameters of the 1305 goaf, the CFD model is established, and the mesh division of the CFD model is shown in Figure 8. The height of the floor is 10 m, the thickness of the coal seam is 9.8 m, and the height of the roof is 50.2 m. The total height of the model is 70 m. The boundary conditions of the numerical model are shown in Table 2. Regular quadrilateral mesh is adopted, and the number of mesh and nodes are 461,196 and 570,362, respectively. The “three zones” of spontaneous combustion in the goaf are divided according to the dissipation zone (15% ≤ O$_2$), the oxidation zone (5% ≤ O$_2$ < 15%), and the suffocative zone (O$_2$ < 5%). At ambient temperature, the oxygen-consumption rate of the residual coal in the goaf is expressed by Equation (3). Based on the mass conservation equation, momentum conservation equation, and component migration conservation equation, combined with the permeability distribution setting of the goaf based on “O-Ring” consumption, the model can be solved.

\[
R_O = kC_O
\]  

where, $R_O$ is the O$_2$-consumption rate, %; $k$ is a constant, and the value is $-0.00000002$; $C_O$ is the ambient O$_2$ concentration, %.

Figure 8. 1305 goaf mesh division model.

Table 2. Boundary conditions for the simulation.

| Name   | Boundary Type        | Name   | Boundary Type       |
|--------|----------------------|--------|---------------------|
| Solver | Pressure-based       | Viscous model | Standard k-ε       |
| MG     | Velocity inlet       | Species model | Species transport  |
| TG     | Outflow              | Other faces | Standard wall       |
| Initial | Standard             |                     |                     |
The O\textsubscript{2}-concentration data at the two lanes of the model are compared with the field-monitoring data, as shown in Figure 9. The numerical simulation results have a good correlation with the field-monitoring results, indicating that the numerical-simulation results are reliable. The distribution of gases and the “three zones” in the goaf is presented in Figure 10a–c. Due to the current nitrogen injection measures, the goaf is filled with a high concentration of N\textsubscript{2}, and the high concentration of O\textsubscript{2} is compressed into the area near the working face. The fact that the distribution area of the oxidation zone is narrow shows that the existing nitrogen-injection measures have played a significant role in preventing spontaneous combustion, and there is no threat of CSC in the 1305 goaf.

![Figure 9. Simulation vs. field experiment.](image)

3.2.2. Study of the CO-Production-Rate Distribution in the Goaf

With the help of Fluent software, the distribution of the O\textsubscript{2} concentration in the goaf can be obtained. Based on the experimental research of oxidation at ambient temperatures, the CO-production-rate distribution in the goaf can be simulated by MATLAB software, and the specific operations undertaken are as follows. (1) Export all the calculated O\textsubscript{2}-concentration data from the Fluent software model. Data are from the spatial nodes of the model, and the O\textsubscript{2}-concentration data of the residual coal area in the 1305 goaf through Excel screening are obtained. (2) Based on Formula (1), the CO-production rate of each node in the residual coal area can be obtained. (3) Use MATLAB software to realize the four-dimensional visualization of the CO-production-rate distribution. The results that MATLAB generated are shown in Figure 11.

It can clearly be seen that the CO-production rate gradually decreases with the increase in distance from the working face, and the CO-production rate near the working face is the highest. The distribution range of the high CO-production rate near the MG is far larger than that near the TG. To compare the CO-production rate between the dissipation zone and the oxidation zone, the CO data were further processed, as shown in Table 3.

![Figure 11. Simulation vs. field experiment.](image)

### Table 3. Comparison of CO-production rate between dissipation zone and oxidation zone.

| Zone          | Nodes | O\textsubscript{2} Production Rate/(cm\textsuperscript{3}/m\textsuperscript{3}·s) | Average Production Rate/(cm\textsuperscript{3}/m\textsuperscript{3}·s) | Comparison of Average Release Rate |
|---------------|-------|---------------------------------|--------------------------|-----------------------------------|
| Dissipation   | 6674  | 648.939                         | 0.097234                 | Dissipation:Oxidation = 10:1     |
| Oxidation     | 2491/9853 | 95.125                          | 0.009654                 |                                    |
Figure 10. Gases and “Three Zones” distribution in 1305 goaf. (a) O_2 distribution, (b) N_2 distribution, (c) “Three Zones” distribution.

Figure 11. Distribution of CO-production rate in the residual coal area of goaf.
There are 570,362 nodes in the grid model of the 1305 goaf, 100,416 nodes in the residual coal area, 6674 nodes in the dissipation zone, and 9853 nodes in the oxidation zone. A total of 2491 nodes are in the residual coal-oxidation zone with an $O_2$ concentration of 7.7~15%. The sum of the CO-production rates of all nodes in the dissipation zone is $648.939 \text{ cm}^3/\text{m}^3\cdot\text{s}$, and the average CO-production rate is $0.097234 \text{ cm}^3/\text{m}^3\cdot\text{s}$. The sum of the CO-production rates of all nodes in the oxidation zone is $95.125 \text{ cm}^3/\text{m}^3\cdot\text{s}$, and the average is $0.009654 \text{ cm}^3/\text{m}^3\cdot\text{s}$. The average CO-production rate in the dissipation zone is 10 times that of the oxidation zone, and its CO-production rate is much higher than that in the oxidation zone.

According to the test results from the “three zones” and the length in the 1305 goaf combined with the thickness and width of the residual coal, the volume of the dissipation zone containing residual coal can be estimated to be about $4879.665 \text{ m}^3$, and the oxidation zone’s is about $10,415.685 \text{ m}^3$.

The CO output of the dissipation zone is as follows:
$$4879.665 \times 0.097234 \approx 474.469 \text{ cm}^3/\text{s},$$
and the CO output of the oxidation zone is
$$10,415.685 \times 0.009654 = 100.553 \text{ cm}^3/\text{s}.$$
As a result, the ratio between the dissipation zone and oxidation zone that contributes CO to the tailgate corner is about 4.7:1.

To sum up, under the ambient-temperature-oxidation effect of the residual coal in the 1305 goaf, the average CO-production rate of the dissipation zone is 10 times that of the oxidation zone, and the CO-output proportion is 4.7. The dissipation zone plays a decisive role in the continuous CO exceedance in the tailgate corner. Currently, people mainly adopt various fire-fighting measures to prevent and control CO exceedance in the tailgate corner, such as reducing the width of the oxidation zone and inhibiting its oxidation capacity. However, the management of the dissipation zone is ignored, which we think is the root cause of the CO-exceedance problem in the tailgate corner.

4. Discussion

4.1. The CO-Early-Warning Limit for CSC in the Tailgate Corner

It can be seen from the above that the ambient-temperature oxidation of residual coal in the goaf is the main source of CO in the tailgate corner of the 1305-working face. Considering the air flow sources in the 1305 goaf, the CO-early-warning-limit model for CSC in the tailgate corner of the 1305-working face is constructed as follows:

$$C_s = \frac{Q_G}{Q_L + Q_D + Q_Z}$$

where, $C_s$ represents the CO-early-warning limit for CSC in the tailgate corner of the 1305 goaf, ppm; $Q_G$ represents the CO output of goaf, cm$^3$/s; $Q_L$ represents the air leakage from the working face, m$^3$/s; $Q_D$ represents the air leakage from the ground, m$^3$/s; $Q_Z$ represents the nitrogen injected into the goaf, m$^3$/s.

The air volume of the 1305-working face is 1966 m$^3$/min, and the air-leakage rate is about 8%. The air-leakage volume from the ground is 37 m$^3$/min, and the nitrogen-injection-flow rate is 972 m$^3$/h. Combined with the CO output in the dissipation zone and oxidation zone mentioned above, the following can be calculated.

The CO-early-warning limit in the tailgate corner of the 1305-working face is 163 ppm. When the CO concentration in the tailgate corner exceeds 163 ppm, the CSC will occur in the 1305 goaf. When the CO concentration in the tailgate corner is less than 163 ppm, the 1305 goaf is only in the process of oxidation under ambient temperature. In the daily-monitoring process of the tailgate corner of the 1305-working face, the average concentration of CO monitoring is not higher than 120 ppm, indicating the 1305 goaf is in a safe state, and there is no hidden danger of CSC.
4.2. Further Key Scientific Problems

At present, the safety management of large-scale mining of low metamorphic coal seam is facing two technical problems: firstly, there are no effective prevention and control measures to restrain the abnormal CO exceedance in the tailgate corner, which seriously threatens the physical and mental health of underground operators; secondly, the early-prediction-index system of CSC is chaotic, and the early warning of CSC is difficult. To break through these two technical difficulties, two scientific problems must be studied further.

4.2.1. Combined Oxidation Mechanism Research

Until now, in research relating to low-temperature oxidation of coal, scholars have studied the influence of various factors, including internal factors \([3,14]\) (coal chemical composition, petrological characteristics, carbonization degree, and so on) and external factors \([15–17]\) (temperature, \(O_2\) concentration, water content in air, and so on) on low-temperature oxidation characteristics of coal from macro phenomena \([18–22]\) (gas production, \(O_2\) consumption, heat-production characteristics, and so on) and micro changes \([23–26]\) (functional groups, free-radical concentration, crystal structure, and so on), and fruitful results have been achieved. However, it must be pointed out that current research on the low-temperature-oxidation characteristics of coal is mainly research on CSC, that is, research conducted above the temperature level of 30 \(^\circ\)C, while research on the ambient-temperature-oxidation characteristics of coal below 30 \(^\circ\)C is still relatively limited.

Some scholars have conducted preliminary investigations of the ambient-temperature oxidation of coal. For example, Wu \([27]\) divided the ambient-temperature-oxidation mechanism into five stages according to experimental research results, and they are the chemical reaction inhibition stage, transition stage, diffusion control stage, inhibition control stage, and combustion-like reaction stage. Liu \([12]\) studied the formation mechanism of CO produced by long flame coal reacting with \(O_2\) at ambient temperatures based on quantum chemistry calculations and determined the possible elementary reaction path. Nonetheless, current work on the mechanism of ambient-temperature oxidation lacks systematic and extensive research on low metamorphic coal groups, and the mechanism of ambient-temperature oxidation of coal has not reached a unified understanding. At the same time, all CSC phenomena must undergo ambient-temperature-oxidation processes, and the impact of ambient-temperature oxidation on CSC is still unknown. Research on the combined oxidation mechanism of low metamorphic coal will not only be conducive to the prevention and control of abnormal CO exceedance and CSC but is also of great significance in enriching research on the low-temperature-oxidation process of coal.

4.2.2. Index Gases Migration Law of CSC under Combined Oxidation in Goaf

Nowadays, the index-gases-monitoring method is still the most important and reliable early-warning technology for CSC in the goaf. The establishment of the CSC gas index system in the goaf must be based on research around the migration law of CSC index gases in goaf. A typical gas index system based on the CSC-index-gases-migration law in the goaf, named TARP (trigger, action, response, and plans) is shown in Figure 12. According to the migration law and production law of CSC index gases in the goaf, corresponding goaf-monitoring points and gas early warning limits are set so that TARP can better meet the needs of on-site CSC prevention and control.

However, the current research on the migration law of CSC index gases in the goaf only consider the CSC oxidation process, but does not consider ambient-temperature oxidation, which is particularly unfavorable to the early warning of CSC in the goaf during the mining of low-metamorphic coal seams, which is also the root reason for the current chaotic state of CSC early warning. Therefore, to scientifically prevent CSC accidents in the goaf with low-metamorphic coal, there is an urgent need to study the CSC-index-gases-migration law under combined oxidation conditions.
5. Conclusions

In view of the abnormal CO exceedance in the tailgate corner of low-metamorphic coal seams with the large-scale application of fully mechanized top coal-caving technology and taking the 1305-lignite-working face of the Dananhu No. 1 coal mine as an example, this paper systematically introduces and analyzes the causes and discusses the scientific problems needed to be further studied. The main conclusions are as follows.

(1) Based on field measurements, the abnormal CO-exceedance area of the 1305-working face are systematically investigated. The results show that during the normal mining period of the working face and without any signs of CSC in the goaf, the CO exceedance accounts for about 43% of the support range of the working face, the tailgate is frequently in the CO exceedance state, and the CO concentration in the tailgate corner reaches 4.8 times that of the specified limit. Factors, such as the large amount of residual coal in the goaf, the large degree of fragmentation, complex air-leakage channels, and difficult collapses at the air inlet side, provide opportunities for ambient-temperature oxidation of residual coal in the goaf.

(2) The ambient-temperature-oxidation experiment for lignite shows that when the ambient O$_2$ concentration is $\geq 7.7\%$, the coal sample can react strongly with O$_2$ and release a large amount of CO, and the production rate of CO is closely related to the ambient-O$_2$ concentration, showing a quadratic function fitting relationship. The study of the CO-production mechanism in the goaf based on CFD shows that under ambient-temperature-oxidation conditions, the average CO-production rate of the dissipation zone in the 1305 goaf is 10 times that of the oxidation zone, and the CO-output proportion is 4.7. The dissipation zone plays a decisive role in the continuous exceedance of CO concentration in the tailgate corner.

(3) The early-warning-limit model of CO in the tailgate corner for CSC of low-metamorphic coal seams is established, and the early-warning limit is 163 ppm. When the CO concentration in the tailgate corner exceeds 163 ppm, CSC will occur in the 1305 goaf.
(4) The key scientific problems to ensure CSC safety of low-metamorphic coal seam are discussed. Research on the combined oxidation mechanism and the index-gases-migration law of CSC under the combined oxidation condition in low-metamorphic coal goaf is urgently required.

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