

Distribution Characteristic and Migration Mechanism of Toxic Gases in Goafs during Close-Distance Coal Seam Mining: a Case Study of Shaping Coal Mine

Dapeng Wang, Pengming Zhang, Yulong Zhang,* Shihao Tu, Junfeng Wang, and Zijing Hao



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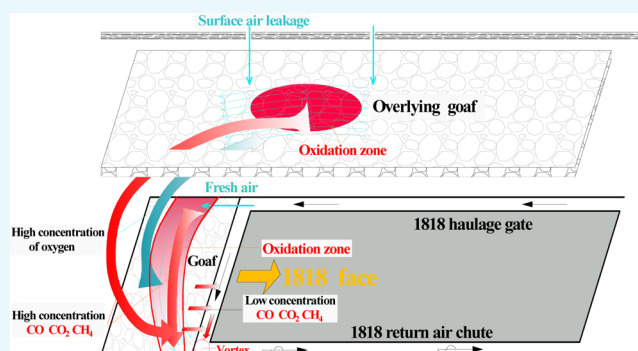
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ABSTRACT: It is imperative to have an in-depth understanding of the gas migration mechanism during close-distance coal seam mining, not only to prevent fires in the coal industry but also to propose safety strategies for controlling toxic gases. The 1818 working face of the Shaping Coal Mine was used as an exemplary close-distance coal seam mine. Through the construction of boreholes and the arrangement of bundle pipes in the two parallel grooves of the working face and the upper goaf at the corresponding positions in the working face, the gases in the upper and lower goafs were monitored online timely. The firsthand information about the gas distribution was obtained through on-site tests, which provided the robust data for studying the migration mechanism of toxic gases during close-distance coal seam mining. By studying the spatial distribution of harmful gases in the upper goaf without mining the overlying coal, the static distribution law of gas was obtained. By discussing the spatial distribution and migration of harmful gases in the goaf of the overlying coal seam during mining, the dynamic distribution law of the gas was obtained. By studying the spatial distribution and migration of toxic gases in the mined-out area of the lower coal seam during mining, the dynamic distribution of gases in the mined-out area of the lower coal seam was obtained. Moreover, the migration mechanism of gas emission from the goafs in the close-distance coal seam was explored. By analyzing the factors responsible for the accumulation of toxic gases in the return air corner, feasible safety measures were also proposed to prevent this hazard during close-distance coal seam mining.



1. INTRODUCTION

The toxic and harmful gases released during coal mining and those emitted from goafs seriously impact the production of coal mines and the health and safety of workers, and they can also cause fires, explosions, and other accidents.^{1–5} Especially for the exploitation of close-distance coal seams, due to the influence of secondary mining, many interlayer fissures are produced, and a large number of air leakage channels are formed,^{6–10} which cause gas migration in the upper and lower goafs. The residual coal in the overlying goaf is subjected to secondary oxidation by air leakage from fractures, which makes the overlying goaf more prone to spontaneous combustion.¹¹ The toxic and harmful gases produced in the goaf of the upper coal seam will also enter the lower coal seam, which will seriously affect the safety of the workers in the lower coal seam;¹² therefore, it is important to develop management measures to control the emissions of toxic and harmful gas from goafs during close-distance coal seam mining.^{13,14}

At present, most scholars mainly use the theories of gas seepage, diffusion, and coupling in goafs to conduct numerical simulations to study the seepage and migration laws of gases in

goafs during mining.^{15,16} Other scholars have built physical experimental models to study the gas distribution characteristics and migration laws in goafs.¹⁷ CFD numerical models are commonly used by scholars to study the self-heating evolution trend of residual coal in the goafs of longwall working faces under complex conditions.^{18,19} Through CFD numerical models, researchers have calculated the distribution of the oxygen concentration and wind speed in goafs and then studied the air leakage law, gas distribution, and migration law in the goafs under complex conditions;^{20–23} however, few scholars have studied the gas distribution and migration laws in goafs through field tests by measuring a large number of data obtained in the field.²⁴ Most research mainly relies on numerical modeling, and there is a lack of field tests, causing a large

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discrepancy between the two methods. Especially for close-distance coal seam mining, there is a lack of systematic research on the distribution and migration characteristics of gas from the upper and lower coal seams, which restricts the development of safety strategies for controlling toxic and harmful gas emissions during close-distance coal seam mining.

In the actual mining process, the distribution and migration of gas in the mined-out area of a close-distance coal seam are closely related to the mutual relationship between the upper and lower coal seams.^{25,26} According to the characteristics of the upper and lower coal seams, the gas distribution in a goaf can be divided into two types: a static distribution and dynamic distribution. When the lower solid coal is not mined, the temporal and spatial distribution characteristics of airflow in the goaf of the overlying coal seam can be defined by its static distribution characteristics. In the case of lower coal seam mining, the spatial and temporal distribution characteristics of airflow in the upper and lower coal seam goafs can be defined by their dynamic distribution characteristics. The two types of distributions jointly determine the migration laws of gases in the upper and lower goafs. Most research has mainly studied the gas migration law in the goaf of a single mining coal seam, and there is a lack of systematic research on the gas distribution and migration law of the upper and lower goafs before and after close-distance coal seam mining. The static and dynamic distribution characteristics and migration of close-distance coal seams are still unclear. Moreover, the current research methods are numerical simulations, and there is a lack of comprehensive field tests and research methods; thus, the results may greatly deviate from the actual situation, which may affect the prevention and control of toxic and harmful gases during close-distance coal seam mining.

With these considerations in mind, the present study aims to explore the migration mechanism of gas emissions during close-distance coal seam mining and propose a safety strategy for the prevention of toxic and harmful gases based on the results of field tests. By constructing boreholes and arranging bundle pipes in two parallel grooves of the working face and the upper goaf, the gas concentration changes in the upper and lower goafs were monitored timely. The artificial sampling method was used to monitor the gas concentrations in the return air corner and the working face. The gas migration law of the upper and lower goafs was revealed, and the gas migration mechanism of the goaf during close-distance coal seam group mining was explored. By analyzing the factors responsible for the accumulation of toxic and harmful gases in the return air corner, safety measures were also proposed.

2. DESCRIPTION OF THE WORK FACE AND FIELD TESTS

The buried depth of the no. 8 coal seam in the Shaping Mine was about 147–257 m. The coal seam was prone to spontaneous combustion. The western and northern parts of the coalfield are a combined area, while the central-eastern part of the coalfield is a bifurcated area. The upper coal was mined out, and now the lower coal is being mined. The distance between the upper and lower coal seams varied between 0.81 and 10.86 m, with an average height of 4.22 m. The 1818 fully mechanized working face was arranged at the lower leaf along the coal seam direction, and the working face trough was arranged along the coal seam strike. The average thickness of the coal seam in the working face was 4.5 m. The advancing length of the 1818 working face was 947 m, and the width of the working face was 216.5 m. The

comprehensive mechanized coal mining method with full-seam mining was adopted for the 1818 working face. During the mining of the no. 8 coal seam, the surface collapsed twice; thus, the upper residual coal and coal pillar were further broken, and the upper and lower coal mined-out areas were connected and compounded. Due to the existing spontaneous combustion in the mined-out areas of the original volcanic coal mine, there may be a high-temperature area or a new fire area, and toxic and harmful gases might be released into the lower coal seam working face, which poses a serious threat to the safety of the working face.

The scheme of longwall ventilation (Figure 1) is presented in the U type together with the ventilation rate of $1598 \text{ m}^3 \text{ min}^{-1}$.

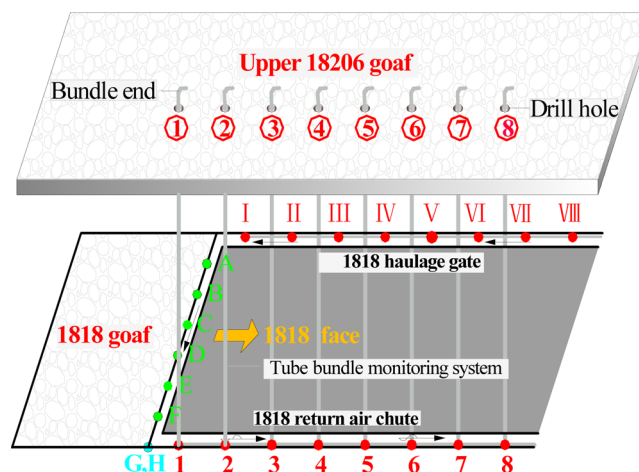


Figure 1. Layout of the measurement points of the 1818 working face.

The coal mining speed of the 1818 working face is 5 m every day. Because the roof of the 1818 haulage gate is solid coal, the test boreholes cannot be arranged in the upper coal seam goaf along the haulage gate. In the roof of the 1818 return air trough, eight boreholes are arranged every 25 m in the eight upper coal seam goafs for extracting gas in the eight upper coal seam goafs, as shown in Figure 1. Eight bundle tubes with a diameter of 8 mm were then laid at these eight borehole locations. Three bundle tubes were arranged relative to the roadway roof of the return air entry and the haulage gate of the 1818 working face and the drilling position of the upper coal seam. This was used to determine the gas concentration in the goaf behind the inlet and return air sides of the 1818 working face. The measurement points were recorded as 1, 2, 3, 4, 5, 6, 7, 8 and I, II, III, IV, V, VI, VII, VIII, and the gases in the upper and lower goafs were detected every day until the upper goaf could not be monitored and when the lower coal seam goaf entered the asphyxiation zone. In addition, six measuring points were arranged on the 1818 working face (between supports), as shown in Figure 1, which were A, B, C, D, E, and F. Two measurement points were arranged in the upper and middle parts of the return air corner, denoted as G and H. The gases including CH_4 , O_2 , CO_2 , and CO were sampled daily, and their composition and concentration were determined by gas chromatography.

3. SPATIAL AND TEMPORAL DISTRIBUTION CHARACTERISTICS OF THE AIRFLOW IN GOAFS

3.1. Gas Static Distribution Law in the Upper Goaf.

Figure 2 shows the static distribution trends of CH_4 , O_2 , CO_2 , and CO gases in the overlying goaf of the 1818 working face

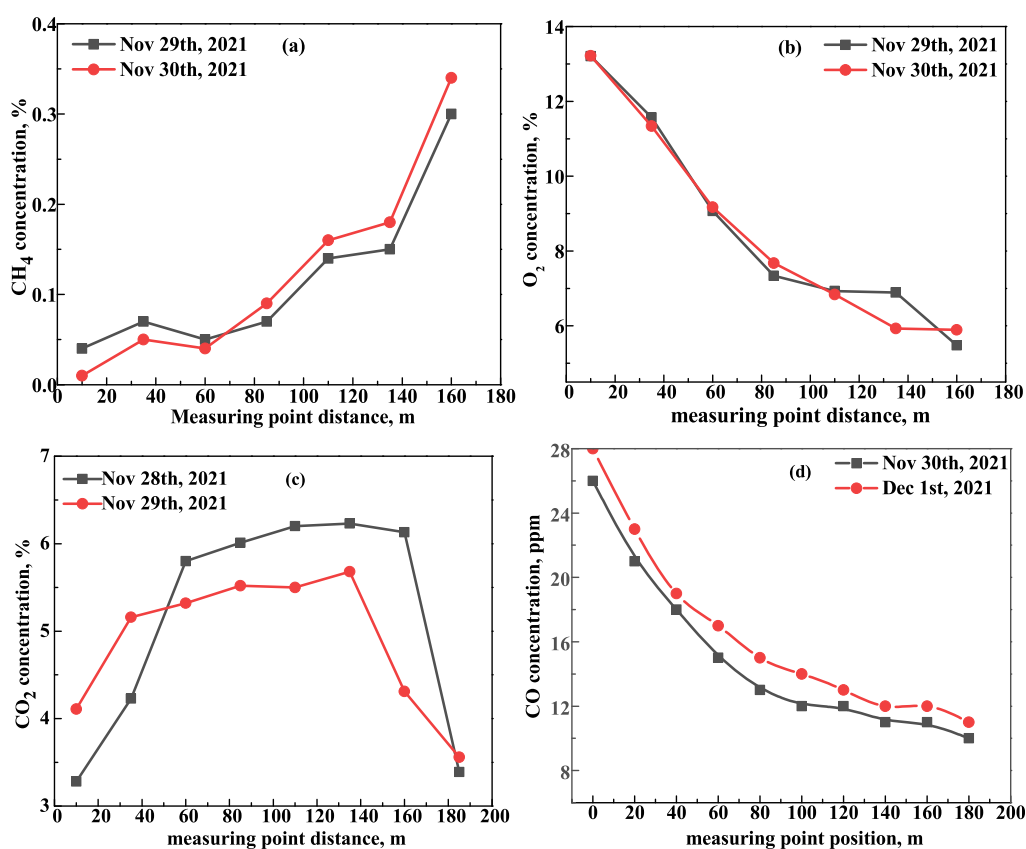


Figure 2. Change trends of (a) CH₄, (b) O₂, (c) CO₂, and (d) CO in the goaf of the 1818 working face.

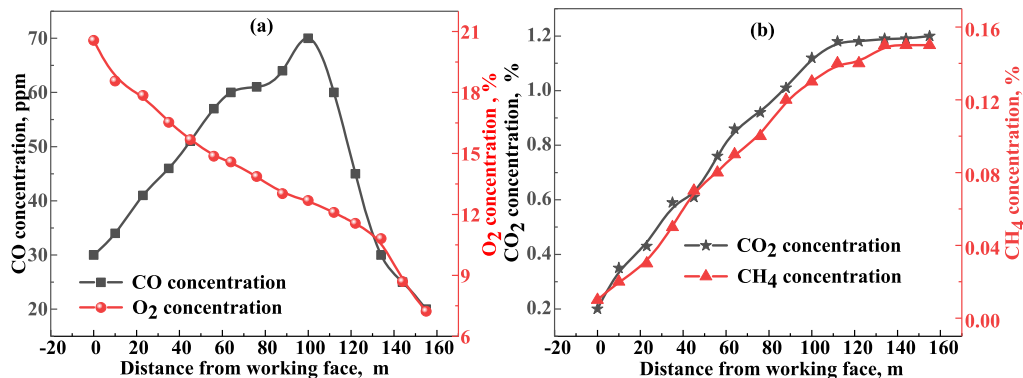


Figure 3. (a) CO and O₂ and (b) O₂ and CH₄ distribution in the goaf at the air inlet side of the 1818 working face.

before mining. The axis of the abscissas represents the distance between the measurement points and the stop line of the mined-out area, and the ordinate represents the concentration of each gas. When the upper mined-out area was not mined from the lower coal seam, the O₂ concentration was the highest closest to the stop line of the upper mined-out area, which was about 13%. This was because the coal pillar at the stop line of the upper mined-out area was ruptured, and serious air leakage occurred. The oxygen concentration spread to the upper mined-out area, resulting in a high oxygen concentration there. This diffusion gradually weakened upon increasing the diffusion distance; therefore, the farthest distance from the stop line, that is, near the lower working face, had the lowest O₂ concentration, which was about 6%. The CH₄ concentration increased from 0.05% to about 0.3%, while the CO₂ concentration increased from 3% to about 6% and then remained stable before rapidly decreasing to

about 3.5%. Due to the weakening of the air leakage dilution effect of the coal pillar stop line, as well as mining of the lower coal seam, the rock fissures in the upper goaf increased, more CH₄ was gradually released from the residual coal, and the CH₄ concentration gradually increased. The secondary oxidation of the floating coal and the release of the original CO₂ in the coal seam increased, and the CO₂ concentration gradually increased. A rapid decrease in CO₂ was caused by the migration of a high concentration of CO₂ from the upper goaf to the lower coal seam. The change in the CO concentration in the overlying goaf was closely related to the migration in the upper and lower goafs and the secondary oxidation of floating coal. Due to the influence of the oxygen concentration, the changing trend of the CO concentration was basically the same as that of O₂, from about 27 to 10 ppm. The measured concentrations of CH₄ and O₂ at the return air corner of the working face were 0.2 and 17%,

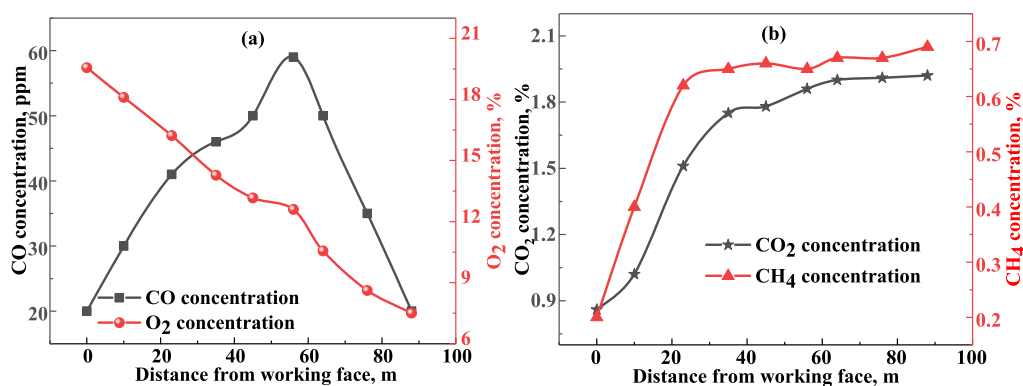


Figure 4. (a) CO and O₂ and (b) O₂ and CH₄ distribution in the goaf at the return air side of the 1818 working face.

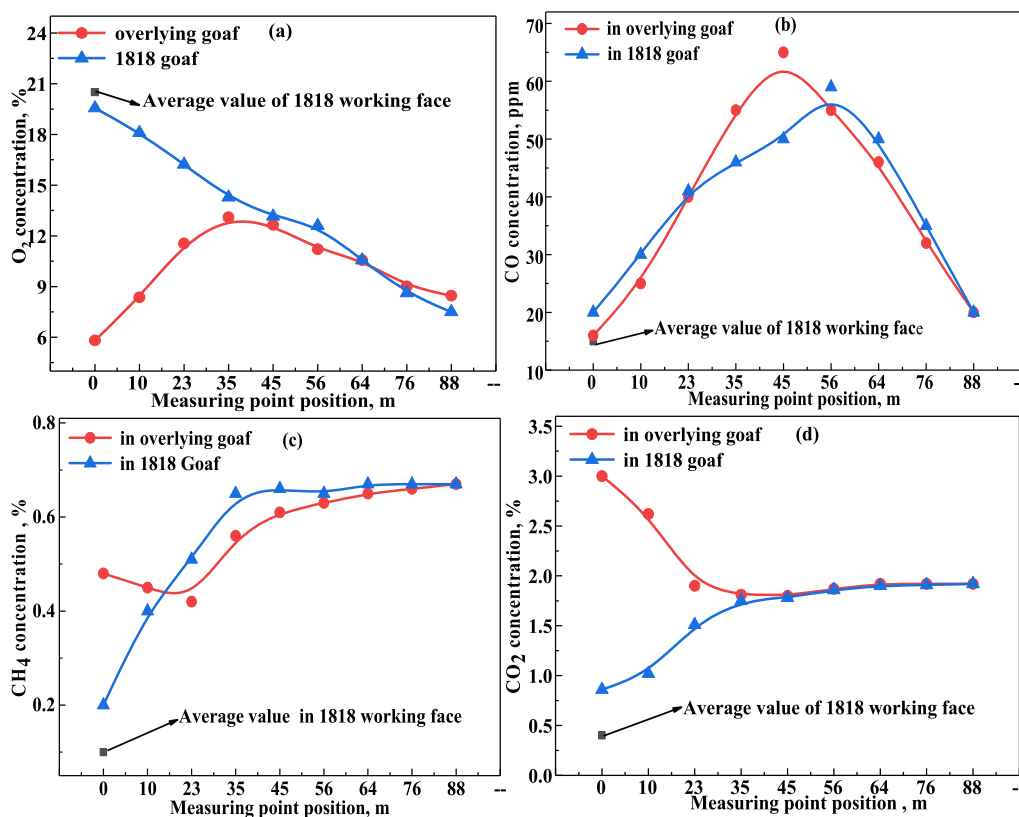


Figure 5. Variation law of (a) O₂, (b) CO, (c) CH₄, and (d) CO₂ concentrations in 1818 goaf and upper goaf.

respectively, which are quite different from those at the upper coating goaf. This indicates that before mining the close-distance coal seam, the goaf behind the working face was not completely connected to the upper coating goaf. The mining effect was mainly caused by the mutual migration of gases between the working face goaf and the upper coating goaf.

3.2. Dynamic Gas Distribution Law in the Goaf of the Lower Coal Seam. Figures 3 and 4 respectively, represent the distribution map of each gas in the goafs of the intake and return air side behind the 1818 working face. The distance between the measurement point and the 1818 working face was expressed by the abscissa, the concentration of each gas was expressed by the ordinate, and the distribution trend of each gas in the goaf behind the 1818 working face was expressed in the curve. It can be seen from Figures 3a and 4a that the oxygen concentration on the intake and return sides gradually decreased from the working face to the deep part of the goaf upon the advance of the working

face. The CO concentration showed an inverted “V” trend of increasing first and then decreasing. On the return side, the oxygen concentration decreased to less than 10% in the goaf 70 m from the working face, while on the intake side, the oxygen concentration decreased to less than 10%, 140 m from the working face. The average concentration of O₂ in the goaf on the intake side was much higher than that on the return side, indicating a serious air leakage on the intake side, and the airflow was influenced by diffusion. This indicates an obvious “rear movement” of the oxidation zone in the goaf.

Figures 3b and 4b show that at the inlet side, from the working face to 160 m away from the 1818 working face, the CH₄ concentration increased from 0.01 to 0.15%, and the CO₂ concentration increased from 0.2 to 1.2%. Beyond 150 m, the CH₄ and CO₂ concentrations remained relatively stable. On the return air side, within 85 m from the working face to the 1818 working face, the CH₄ concentration increased from 0.2 to

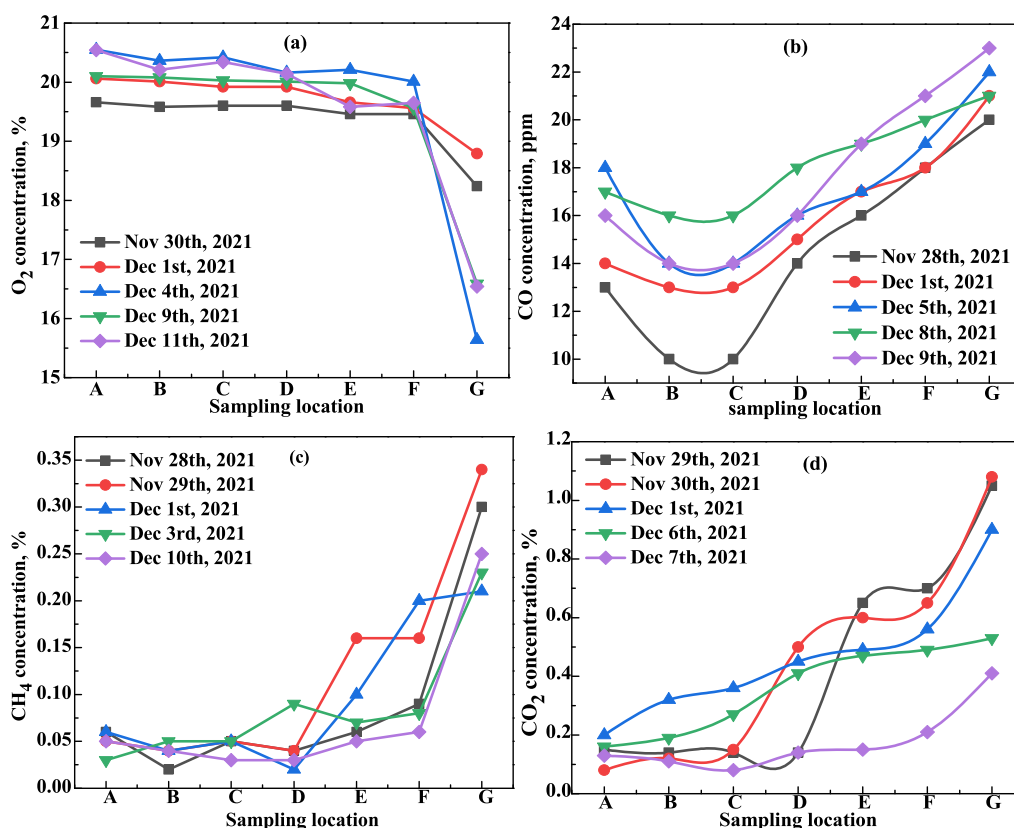


Figure 6. (a) O_2 , (b) CO, (c) CH_4 , and (d) CO_2 concentration distribution map of the 1818 working face.

0.68%, and the CO_2 concentration increased from 0.8 to 2%. Beyond 85 m, the CH_4 and CO_2 concentrations remained stable.

The above results show that with the advance of the working face, along the depth direction of the goaf in the 1818 working face, the concentrations of CH_4 and CO_2 in the return air side and the inlet air side gradually increased from the working face to the deep part of the goaf. From the inlet side to the return air side, the concentrations of CH_4 and CO_2 gradually increased. Within 30 m of the working face in the deep part of the goaf, there was a natural accumulation area and a load-affected area of the goaf. The fallen rock was not compacted, and the porosity and permeability were large. Here, CH_4 and CO_2 were diluted and transported by the air leakage flow in the goaf and the air leakage from the upper goaf to the lower coal seam goaf, so the concentrations of CH_4 and CO_2 were relatively low. When the distance from the working face was greater than 30 m, the fallen rock in the goaf was gradually compacted, and the air leakage had a small dilution effect on the concentrations of CH_4 and CO_2 . The accumulation degree of CH_4 and CO_2 increased upon increasing the distance from the working face. From Figures 3b and 4b, it can also be clearly seen that the concentrations of CH_4 and CO_2 in the goaf at the return side were significantly higher than that at the inlet side within 150 m of the deep part of the goaf at the inlet and return sides of the working face. Along with the oxygen and CO concentrations, it is shown that the air leakage mainly flowed into the goaf from the inlet trough side, carrying large amounts of CH_4 and CO_2 to the goaf at the return side. A small amount of gas migrated to the working face along the air leakage channel of the working face, and most of the gas flowed out of the corner of the return air from the goaf at the return side. In this process, the airflow mainly diluted the CH_4 and CO_2 concentrations in the intake side goaf, while it

increased the CH_4 and CO_2 concentrations on the return side goaf due to the migration of CH_4 and CO_2 . CO generated in the goaf was also carried by the airflow to the corner of the return air, resulting in a high CO concentration there.

3.3. Gas Dynamic Distribution Law in the Upper Goaf.

Figure 5 shows the dynamic distribution of gas in the 1818 goaf and upper goaf during mining. The horizontal coordinate represents the distance between the measured point and the 1818 working face, the ordinate represents the gas concentration at the measured point, and the curve represents the changes in the gas concentrations in the upper and lower goafs. It can be seen from Figure 5 that from the 1818 working face to 90 m from the lower coal seam (corresponding to the upper goaf), the concentrations of O_2 and CO showed an inverted V-shaped trend in which they first increased and then decreased. The CH_4 concentration first decreased and then increased and then remained stable, and the CO_2 concentration first decreased and then stabilized.

The goafs in the upper coal seam interacted with each other during the mining of the lower coal seam. In the goaf 35 m from the working face, the caving rock was not compacted, the porosity and permeability were high, and the upper and lower gases began to exchange; therefore, the O_2 concentration in the goaf of the upper seam reached the maximum of 35 m from the working face. The floating coal in the goaf was oxidized, and the CO concentration reached the maximum at about 45 m from the working face. The high concentration of CO in the goaf of the lower coal seam also migrated upward to the goaf, and the high concentrations of CO_2 and CH_4 in the upper goaf also migrated to the lower coal seam; therefore, the concentration of CH_4 in the upper goaf gradually decreased from the working face to 25 m from the working face. After that, the rock falling in the goaf

was gradually compacted, and the gases in the upper and lower coal seams permeated with each other. The high concentration of CH_4 released by mining the coal seam migrated to the upper goaf. Finally, in the goaf more than 45 m from the working face, the accumulation degree of CH_4 and CO_2 in the upper coal seam increased upon increasing the distance from the working face, and the concentrations of O_2 and CO decreased gradually. Moreover, due to the mutual migration of gases in the upper and lower goafs, the concentrations of CH_4 , CO_2 , O_2 , and CO in the upper and lower goafs gradually became consistent and then remained stable.

3.4. Gas Dynamic Distribution Law of the Working Face. Figure 6 shows the distribution of O_2 , CO , CH_4 , and CO_2 on the 1818 working face. The abscissa A–G in the figure represents the seven measuring points from the intake side of the 1818 working face to the return air corner. The ordinate represents the concentration of each gas at different dates, and the curve represents the concentration distribution of each gas at different times in the 1818 working face. From Figure 6a, it can be seen that the O_2 concentration of the 1818 working face decreased slowly at first and then rapidly from the inlet to the return corner, and the O_2 concentration decreased from a maximum of about 20.6% to the lowest value of about 18%. From Figure 6b, it can be seen that the CO concentration of the 1818 working face generally decreased first and then increased from point A near the inlet side to point G at the return corner, from about 15 ppm to about 22 ppm. As shown in Figure 6c,d, the 1818 working face CH_4 concentration and the CO_2 concentration from the inlet side to the corner of the return air first stabilized and then gradually increased. The CH_4 concentration increased from about 0.05% to about 0.30%, while the CO_2 concentration increased from 0.15% to about 0.80%.

From the middle of the working face to the return air corner, because the gas behind the goaf migrated to the working face, the concentrations of CO , CH_4 , and CO_2 increased, and the concentration of O_2 decreased. This shows that a small part of CO , CH_4 , and CO_2 generated by the oxidation of residual coal in goaf 1818 was carried by the airflow and flowed out of the working face along the air leakage channel of the working face. Most of the generated CO , CH_4 , and CO_2 also migrated through the goaf to the return air corner due to ventilation and wind pressure. The previous analysis showed that the air leakage in the upper goaf also carried high concentrations of CH_4 and CO_2 from the lower coal seam working face near the return air corner. CH_4 , CO_2 , and CO generated by air leakage from the rear goaf in the working face also converged at the return air corner with the airflow, and an airflow vortex appeared near the return air corner. The mass transfer of airflow in the working face and goaf was weak, which caused the concentration of toxic and harmful gases in the return airflow to become too high, preventing them from being discharged from the return air roadway on time. This resulted in the accumulation of toxic and harmful gases in the return corner and the occurrence of hypoxia.

4. MIGRATION MECHANISM OF TOXIC AND HARMFUL GASES

The relationship between the gas concentration distribution in the overlying goaf and the working face distance is shown in Figure 7. During mining, the gas concentration in the goaf is affected by air leakage diffusion, migration between the upper and lower goafs, and coal oxidation. Therefore, there were different changes. From 180 to 25 m in front of the 1818 face, the

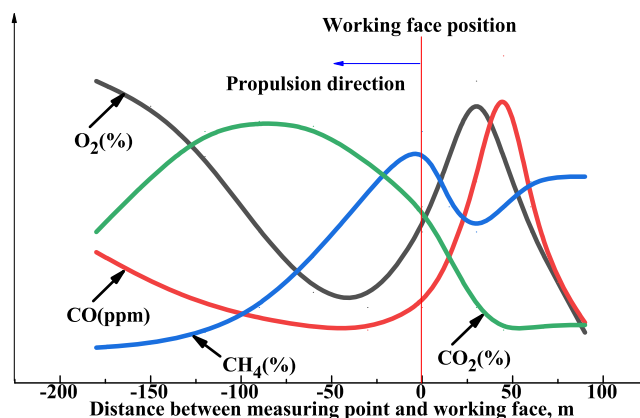


Figure 7. Relationship between gas distribution in the overlying goaf and the working face distance.

oxygen concentration in the goaf showed a decreasing trend. From 25 m in front of the working face to the working face's position, the O_2 concentration was affected by the mining of the working face, and the air leakage gradually increased. When the measuring point entered the rear of the working face, 35 m behind the working face, due to the blending of the gases in the upper and lower goafs, the O_2 concentration increased rapidly. From 35 m to 100 m behind the working face, the rock falling in the upper goaf was gradually compacted; the interactions between the upper and lower goafs were weakened and gradually entered the oxidation zone. The coal oxidation was accelerated, and the O_2 concentration decreased rapidly.

Changes in the CO concentration in the overlying goaf were closely related to the gas migration in the upper and lower goafs and the secondary oxidation of floating coal. Due to the influence of oxygen concentration, the change in the CO concentration was consistent with that of oxygen, that is, from 180 m in front of 1818 to 100 m behind it, the CO concentration decreased slowly, then increased rapidly, and then decreased rapidly. Different from the O_2 concentration distribution, the peak position was slightly delayed, which was closely related to the coal oxygen reaction.

Changes in the CO_2 concentration in the overlying goaf were related to the gas migration in the upper and lower goafs, the oxidation of floating coal, and the release of CO_2 in the original coal seam. The CO_2 concentration in the upper grazing goaf first increased and then decreased before slightly increasing and stabilizing. From 180 to 125 m in front of the working face, the air leakage dilution effect of the stop line of the upper coal seam was weakened, while the secondary oxidation of the floating coal and the release of the original CO_2 in the coal seam were strengthened, and the CO_2 concentration increased gradually. From 125 to 75 m in front of the working face, CO_2 reached saturation due to the oxidation of the float coal and the release of the coal seam, and the CO_2 concentration maintained a stable trend. From 75 m in front of the working face to the working face, due to mining of the rear working face, the high concentration of CO_2 here migrated to the lower coal seam return airway, and the CO_2 concentration decreased rapidly. From the working face to the rear 35 m range, the upper and lower goaf gases blended, the high-concentration CO_2 in the upper goaf accelerated discharge, and the concentration decreased rapidly. From 35 to 100 m behind the working face, blending of the upper and lower goaf gases was gradually

completed, and the CO_2 concentration in the goaf increased slowly and finally stabilized due to the oxidation of floating coal.

Changes in the CH_4 concentration in the overlying goaf were related to the release of the original CH_4 from the coal seam, the strength of air leakage in the goaf, and the migration of gases in the upper and lower goafs. From 180 m in front of the 1818 working face to the working face, due to the weakening of the air leakage dilution effect of the coal pillar stop line and mining of the lower coal seam, the rock fissures in the upper goaf increased. More CH_4 was released, which increased the CH_4 concentration.²⁷ When the measuring point entered 35 m behind the working face, the vertical fissures in the upper and lower goafs were connected, and the gases in the upper and lower goafs began to blend, and the concentration of CH_4 rapidly decreased. From 35 to 100 m behind the working face, the residual coal oxidation in the lower goaf and the CH_4 concentration released by the mining increased, and the gases in the upper and lower goafs continued to blend. The CH_4 concentration in the upper goaf began to increase gradually. Upon complete gas blending in the upper and lower goafs, the CH_4 concentration stabilized.

By studying the gas distribution laws of the upper and lower goafs, combined with the gas distribution and concentration changes of the working face and return air corner, four aspects of the gas migration mechanism between the upper and lower goafs in the no. 8 coal seam of the Shaping Mine were obtained.

First, gas migration occurred between the upper and lower mined-out areas. Upon mining the lower coal, the separation cracks and vertical fracture cracks formed in the overlying strata interacted with each other. At about 25 m behind the working face, because the surface atmospheric pressure was greater than the air pressure at the return side of the lower working face, under the action of wind pressure, the surface air leakage introduced high concentrations of CH_4 , CO_2 , and CO generated by the oxidation and accumulation of residual coal in the upper mined-out area into the return side of the goaf of the lower working face. The high concentration of O_2 in the lower coal seam also migrated to the upper mined-out area.

Second, the gas migration occurred in the goaf on the intake and return sides of the lower coal seam, and there was a large pressure differential between the intake and return sides. Figures 4 and 5 show high concentrations of CH_4 and CO_2 on the return side of the goaf. The average concentration of oxygen on the intake side of the goaf was much higher than the average concentration of oxygen on the return side. It can be seen from the analysis that there was serious air leakage flow on the intake side of the working face, and the airflow moved to the middle of the goaf and the return side. Most CH_4 , CO_2 , and CO generated by the oxidation of the floating coal in the goaf and the coal seam were transported to the goaf on the return side.

Third, gas migration occurred between the lower coal seam goaf and the working face due to a pressure difference between the working face near the return air side and the goaf. Figure 5 shows that low concentrations of CH_4 , CO_2 , and CO were measured in the working face, indicating that the leakage airflow in the lower goaf carried small amounts of CH_4 , CO_2 , and CO generated by the oxidation of the floating coal in the goaf or the presence of the coal seam along the cracks of the working face to the mining face near the return air channel.

Fourth, the oxidation of residual coal affected the gas concentration distribution, including the secondary oxidation of floating coal in the upper goaf and the primary oxidation of residual coal in the lower goaf. The floating coal in the overlying goaf was affected by the surface air leakage. The oxygen

concentration near the coal pillar of the stopping line in the overlying goaf was high, and the floating coal was oxidized again to generate a large amount of CO_2 and a small amount of CO. As the falling rocks in the goaf were gradually compacted, the air leakage weakened, the oxidation of the floating coal weakened, and the production of CO_2 and CO decreased. Within 50 m in front of the working face, a vertical conduction crack was generated due to the influence of mining, and the airflow of the lower coal seam penetrated the overlying goaf, resulting in the oxidation of the floating coal in the overlying goaf; therefore, a high concentration of CO_2 accumulated in the overlying goaf and migrated to the lower coal seam along the top cracks of the lower return airway. Behind the working face, the high concentration of CO_2 in the overlying goaf continued to migrate to the lower coal seam until the gases in the upper and lower goaf reached equilibrium. During mining, in the goaf of the lower coal seam, there was air leakage on the intake side of the working face due to interlayer conduction cracks behind the working face, which created conditions suitable for the oxidation of floating coal in the goaf. The violent oxidation of floating coal in the rear goaf released large amounts of CH_4 and CO_2 , which migrated to the goaf on the return side under the action of leakage airflow in the goaf.

The pressure at the return air corner of the working face was lower than that in the upper goaf area and also smaller than that in the lower goaf area and surface pressure; therefore, the toxic and harmful gases generated by the oxidation of the floating coal in the upper and lower goafs and the existing toxic gases in the coal seam and the toxic gases that diffused from the working face were imported into the return air corner under the action of the wind pressure gradient difference. This resulted in the accumulation of toxic gases and the occurrence of hypoxia in the return air corner. At the same time, the overall distribution of oxygen concentration in the goaf of the lower coal seam was affected and controlled by the air leakage and oxygen consumption rate. Due to diffusion, the oxidation zone of the lower coal seam displayed an obvious "backward movement" phenomenon. Based on the above research, the gas migration mechanism of the upper and lower goafs of no. 8 coal seam in the Shaping Coal Mine was obtained, and the schematic diagram is shown in Figure 8. This migration mechanism provides a theoretical basis for preventing the release of toxic gases in the overlying goaf and determining the influence of gas flow in the lower coal seam goaf on the working face and return air corner.

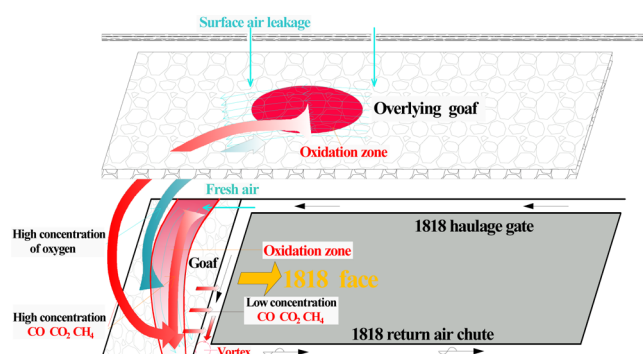


Figure 8. Schematic diagram of the gas migration mechanism in a close-distance coal seam.

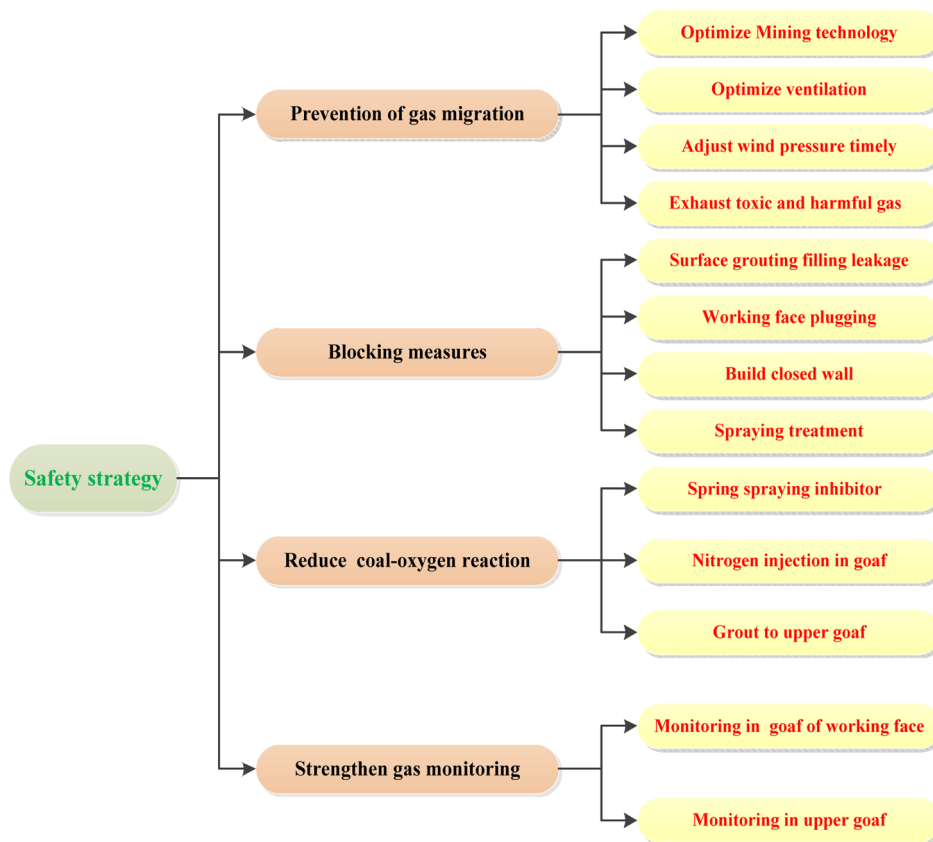


Figure 9. Safe strategies for controlling toxic and harmful gas emission.

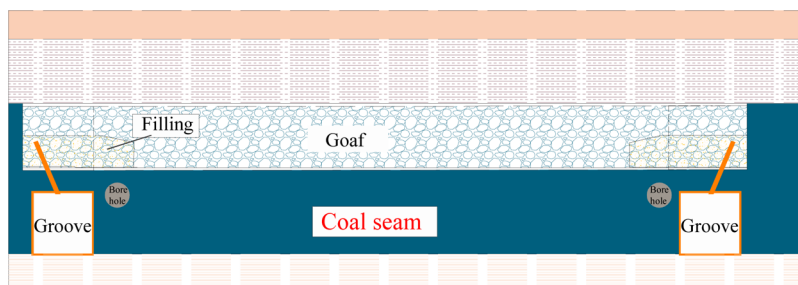


Figure 10. Profile of grouting from the lower coal groove to the top.

5. SAFETY STRATEGY FOR CONTROLLING TOXIC GASES

Through the above analysis, the emission and accumulation of toxic gases in close-distance coal seams were mainly affected by three factors, that is, air leakage diffusion from the earth's surface and working face to the goaf, gas migration in the upper and lower goafs, and the coal–oxygen reaction. Due to these factors, four countermeasures were proposed, as shown in Figure 9.

5.1. Plugging Measures. Plugging measures should be adopted on the surface promptly. Field measurements and analysis showed that serious air leakage occurred between the upper goaf, the lower goaf, and the earth's surface. First, treatment measures of surface fissure filling should be formulated as soon as possible to reduce the threat of spontaneous combustion of coal in the goaf of a close-distance coal seam mine. Next, the enterprise should take plugging measures in the working face.^{28,29} To prevent air leakage from the inlet end to the goaf during the mining of the working face, it is necessary to construct an isolation wall at the end of the goaf.

The main function of the closed wall at the inlet side was to block air leakage, and the closed wall at the return side increased the air leakage resistance of the working face to the goaf. At the same time, the outside and surrounding coal walls of the separation wall should be sprayed with slurry, with a thickness of at least 100 mm. Third, the enterprise should build a closed wall. To prevent airflow from the goaf and to isolate the goaf from the working face, the end closure and the construction of a closed wall should be used to isolate the airflow. A closed wall was established behind the protective coal pillar to prevent airflow from entering, and the sealing effect was improved by grouting with fly ash colloids and other materials.

5.2. Reducing Coal–Oxygen Reaction Opportunities. The coal–oxygen reaction is an important contributor to the emission of toxic gases. To reduce the oxidation time of the residual coal in goaf, inhibitory measures can be adopted. Inhibitor spraying is commonly used to prevent coal oxidation by forming a dense oxygen-insulating film on the outer surface of the residual coal, which blocks the air supply paths. The

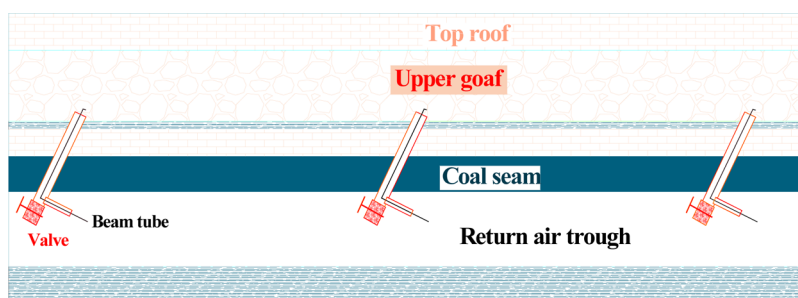


Figure 11. Schematic diagram of borehole construction in the upper goaf.

enterprise should also optimize the nitrogen injection process. Due to the negative ventilation pressure, the upper goaf is always in a state of air leakage, and oxygen can be supplied during the mining of the lower coal seam. Continuous nitrogen injection is adopted, and the nitrogen injection flow rate and the end position of the nitrogen injection pipeline are reasonably adjusted, which ensures fire prevention and that high-concentration nitrogen does not flow out into the cooling zone or working face and that it is always in the oxidation zone of the goaf. The enterprise should also inject slurry into the upper goaf through drilling. Because there is loose coal remaining in the upper goaf, a large amount of loose coal easily accumulates at the cross-heading of the upper goaf. To prevent its spontaneous combustion, grouting to the goaf at the top of the roadway is proposed to cover the roof of the lower coal roadway to form an isolation layer. The schematic diagram of grouting from the lower coal groove to the top goaf is shown in Figure 10, in which a borehole was constructed every 50 m from the lower coal working face to the top goaf. The angle between the borehole and the coal seam was about 45° , and the final borehole was 0.2–0.5 m above the bottom plate of the upper goaf.

5.3. Strengthening the Monitoring. The toxic gas concentrations should be monitored in the working face and return air corner. First, for the working face, a monitoring point should be placed at the return air corner, and the gas can be sampled from the goaf at the top of the return air corner and analyzed weekly. This will help focus on whether there is an index gas of coal self-heating, as well as its changes. If an index gas appears and its concentration rises, timely fire prevention and extinguishing measures should be implemented. The gas in the working face should be monitored every day, focusing on checking whether there is an index gas of coal self-heating at the back of the support. If there is an exception, it should be reported quickly enough to take appropriate measures.

Second, to monitor the top goaf, a borehole can be constructed in the upper goaf from the lower return roadway every 100 m. A relatively complete section of the roadway should be selected to construct the monitoring borehole in the top goaf. The bottom of the hole should reach the top goaf. A schematic diagram of the borehole formed in the upper goaf is shown in Figure 11. A drivepipe should be set in the drilling hole, and the valve should be set at the end. The miner should inspect all boreholes once a week and sample the gas composition with a gas chromatograph, record the monitoring results, and analyze the changes.³⁰

5.4. Prevention of the Migration of Toxic Gases. Enterprises should prevent the migration of toxic gases from the upper and lower goafs to the working face and return air corner. First, the enterprise should optimize the mining connection, balance the layout of the mining area and working face, and try

to alternate the mining method of one mining area with one working face. It is suggested that when there are more than three goafs at the working face, the coal pillar should be isolated from the adjacent working face to prevent the formation of a large goaf area. This will increase the emissions of harmful gases in the goaf when the length of the working face, the mining height, the air volume of the working face, or the pressure difference between the inlet and outlet channels of the working face increases. The length and height of the working face should be optimized, the recovery rate of the working face should be optimized, and the top coal should be retained as little as possible.

Second, the enterprise should adjust the regional ventilation pressure and change the goaf gas flow field. Reducing the air volume of the working face can reduce the air leakage in the goaf to reduce the concentration of toxic gases produced by the oxidation of floating coal in the goaf.³¹ According to the above analysis, the emitted toxic gases in the goaf above the working face flowed into the air return corner and the air return roadway of the working face under the negative pressure of ventilation; therefore, after the booster measures are adopted in the initial stage of mining, the emissions of harmful gases in the goaf above the working face can be inhibited. The air pressure in the goaf is higher than that in the working face, which is the main reason for the occurrence of hypoxia;³² therefore, a reasonable reduction in the goaf pressure is an effective means to prevent hypoxia. The borehole pressure relief can be used to reduce the pressure of the goaf to reduce the outflow of toxic gases to the corner of return air.^{33–35} At the same time, the ventilation duct can be set at the return air corner. Third, toxic and harmful gases should be discharged on time. A drainage system can be used to extract the toxic gases in the corner of the return air, and the negative pressure of the gas drainage system can be used to change the gas flow field in the corner of the return air. The negative pressure of the main fan can be used to drain the low-concentration oxygen in the corner of the return air through the duct into the return air channel. This will reduce the occurrence of the hypoxia phenomenon in the return air corner.

6. CONCLUSIONS

By constructing boreholes and arranging bundle pipes in two parallel grooves of the working face and the upper goaf, the gas concentration changes in the upper and lower goafs were monitored timely. Further, the gas migration mechanism of the goaf during close-distance coal seam group mining was explored. The main conclusions are as follows.

- (1) The field test results showed that from 180 m in front of the 1818 working face to 90 m behind the working face, the O_2 concentration first gradually decreased, then gradually increased, then increased rapidly, and finally decreased gradually. The change in the CO concentration

was consistent with that of O₂, but there was a lag period at the peak compared with O₂. The CH₄ concentration increased gradually, then decreased rapidly, then increased gradually, and finally stabilized. The CO₂ concentration increased first, then decreased, and then slightly increased before finally being stabilized.

- (2) The migration mechanism of gas emissions in the upper and lower goafs can be summarized into four aspects: First, gas migration occurred between the upper and lower mined-out areas. Second, the gas migration occurred in the goaf on the intake and return sides of the lower coal seam, and there was a large pressure differential between the intake and return sides. Third, gas migration occurred between the lower coal seam goaf and the working face due to a pressure difference between the working face near the return air side and the goaf. Fourth, the oxidation of floating coal affected the gas concentration distribution, including the secondary oxidation of floating coal in the upper goaf and the primary oxidation of residual coal in the lower goaf.
- (3) The migration mechanism of gas emissions during close-distance coal seam mining was explored based on the temporal and spatial distribution characteristics of gases in the compound goaf. During close-distance coal seam mining, the gas distribution and migration in goafs were affected by air leakage diffusion, migration in the upper and lower goafs, and the coal–oxygen reaction. Finally, feasible safety strategies were proposed to control toxic and harmful gas emissions.

■ AUTHOR INFORMATION

Corresponding Author

Yulong Zhang – College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China; orcid.org/0000-0002-5087-6524; Phone: +86 15135154673; Email: zhangyulong@tyut.edu.cn

Authors

Dapeng Wang – School of Mines, China University of Mining and Technology, Xuzhou 221116, China; Shanxi Jinshen Shaping Coal Industry Company Limited, Xinzhou 036500, China

Pengming Zhang – College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China

Shihao Tu – School of Mines, China University of Mining and Technology, Xuzhou 221116, China

Junfeng Wang – College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China

Zijing Hao – College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China

Complete contact information is available at:
<https://pubs.acs.org/10.1021/acsomega.2c00339>

Notes

The authors declare no competing financial interest.

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