Field Study on Correlation between CO₂ Concentration and Surface Soil CO₂ Flux in Closed Coal Mine Goaf

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ABSTRACT: Self-heating of coal mine goaf or shallow coal seams can release an outbreak of unimaginable pollution disaster under suitable circumstances. As an indicator gas, CO₂ is always used to determine the coal spontaneous combustion state during the self-heating process. Based on this, the paper investigated the influence of abandoned coal mine goaf CO₂ on the surface environment by measuring the CO₂ concentration in the borehole connected to the goaf and CO₂ flux on the soil surface. Furthermore, rainfall and atmospheric temperature effects are discussed to illustrate the correlation between the CO₂ concentration and surface soil CO₂ flux in the closed mine goaf. Subsequently, the tracer gas experimental method is employed to analyze the effect of air leakage from an open-pit slope on CO₂ flux. The experimental results demonstrated that the distribution of CO₂ concentration in the borehole confirms the continuous diffusion of goaf CO₂ onto the surface. The value of CO₂ flux in the goaf is significantly higher than that of a normal area. Temperature is one of the primary factors that affect the CO₂ flux on the field. Air leakage from the slope promotes the surface soil-overlying goaf CO₂ diffusion. The study provides important reference data for the assessment of the mining area field environment and the determination of the spontaneous combustion risk of the residual coal in the goaf.

1. INTRODUCTION

Coal has been the primary energy resource in China. For a long time, the large-scale exploitation of coal resources has led to an increase in the area of goaf created by underground mining. At the same time, the influence of the underground mined-out area has gradually emerged on the surrounding environment. On the one hand, the toxic and harmful gases are generated by the spontaneous combustion of residual coal remained in the closed goaf and then diffused to the surface, which affects the surface flora, fauna, and shallow microbes, thereby affecting the ecological environment of the area. On the other hand, by the action of high temperature and high pressure in the deep, the CO₂ gas in the closed goaf migrates to the surface. During this process, CO₂ gas can dissolve the shallow groundwater that affects its characteristics by changing the pH and directly or indirectly affect the surface soil–plant ecosystem.1–3 Therefore, the research on correlation between the underground coal-generated CO₂ concentration and surface soil CO₂ flux has become more and more important.

At present, the study on the characteristics of spontaneous combustion in the goaf mainly includes the beam tube monitoring method, tracer gas method, infrared thermometer method, temperature sensor method, etc.4 There are many factors, such as high cost, complex implementation, and difficult installation, and so on, which make it difficult to carry out. Meanwhile, the research on the influence of the harmful gases generated by spontaneous combustion in the goaf on its overlying surface and the analysis of spontaneous combustion characteristics in the goaf by the change in surface CO₂ emission concentration has not been carried out. Based on this, on the premise of analyzing the spontaneous combustion characteristics and the gas diffusion law in the closed goaf, the emission law of CO₂ from the overlying surface of the goaf and its influencing factors were measured and analyzed by the intelligent soil gas monitoring system combined with tracer gas monitoring equipment. Then, the effects of CO₂ concentration in the closed goaf on the changes of surface CO₂ flux and fluctuation laws were discussed in the paper.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1. Outline of Measurement. Surface CO₂ flux measurement is mostly used in environmental science studies to investigate respiration characteristics of surface soil, vegetation, and soil microorganisms.5–7 Previous studies show that, during the whole process from coal low-temperature oxidation to high-temperature pyrolysis, the reaction that produced CO₂ takes up a large proportion in each stage.8–11 Therefore, it is feasible to take CO₂ as an indicator gas to determine the...
oxidation state of goaf residual coal or shallow coal seam. The dynamic factors that promote the goaf surface soil CO2 diffusion process are as follows: (i) Mining process destroyed the original geological structure and formed a large number of fissures, which is conducive to the CO2 diffusion; (2) the goaf residual coal oxidized or smoldered to generate heat, making the goaf ambient temperature increase benefitting the gas emission; (3) overlying strata collapse increases the goaf pressure, which is conducive to the CO2 emission. In addition, the respiration of microorganisms and plant roots on the surface, some of CO2 will dissolve in the underground aquifer; microorganisms and plants near the surface; and most of CO2 produced by spontaneous combustion in the goaf will directly reflect the oxidation state of underground coal. In this study, the surface soil CO2 flux can directly reflect the oxidation state of the normal area.

However, surface CO2 flux overlying the goaf is dominated mainly by the oxidation of residual coal remaining in the goaf. The results show that, in the process of CO2 diffusion to the surface, some of CO2 will dissolve in the underground aquifer; a small amount of CO2 will be fixed by the rock medium or by microorganisms and plants near the surface; and most of CO2 produced by spontaneous combustion in the goaf will diffuse to the surface. Therefore, the flux change of surface CO2 can indirectly reflect the spontaneous combustion state of the goaf. Studying the variation law of surface CO2 flux can effectively analyze the spontaneous combustion process of residual coal in the goaf.

The surface soil CO2 flux is the amount of CO2 gas emission per unit area and unit time, which is defined as

\[
F = \frac{1000\rho \cdot C_s \cdot V \cdot P \cdot P_0}{\Delta t \cdot A \cdot P_0} \cdot 10^{-6}
\]

where \(F\) is the gas flux (mol·m^{-2}·s^{-1}), \(\rho\) is the standard state gas density (kg·m^{-3}), \(C_s\) is the gas chamber volume (m^3), \(A\) is the surface area of CO2 emission (m^2), \(M\) is the gas molecular weight (g·mol^{-1}), \(C_i\) is the linear increase in CO2 concentration in parts per million (10^{-6}), \(\Delta t\) is the time step (s), \(g\) is the gravitational acceleration (m·s^{-2}), \(P\) is the absolute pressure of the measuring point (Pa), \(P_0\) is the standard atmospheric pressure, \(T\) is the temperature of the measuring point (K), and \(T_0\) is the standard state temperature (K).

The characteristics of CO2 emission were monitored by the closed chamber method in the field measurements. In this study, a constant volume automatic ventilation chamber (HL-1017B) was used to measure the gas exchange flux between the soil and the atmosphere environment. By drilling holes on the surface of the goaf to monitor the distribution of CO2 concentration in the borehole with a multichannel gas analyzer (SKY2000-M3), the emission and diffusion characteristics of CO2 in the goaf are analyzed. The tracer gas technique was used to find out the source and route of air leakage in the slope of the test area and verify the influence of air leakage on the variation of goaf surface CO2 flux.

2.2. Field Measurement Methodology. The targeted field is located on the overlying surface of the mined-out area including goafs on the east side, about 150 m away from the Haizhou Open-Pit Mine, as shown in Figure 1. The Haizhou Open-Pit Mine is 3 km away from the Fuxin City center. The mining area is 4 km long from east to west and 2 km wide from north to south. The Haizhou Open-Pit Mine 250 m deep and involves a total area of 30 km^2 was closed and stopped its production. The average annual rainfall in this area is 539 mm, and the evaporation is 1800 mm. It is a semi-arid continental monsoon climate zone in the north temperate zone. The soil type in the mining area is composed mainly of cinnamon soil; the sandy soil layer is about 3.0–5.5 m in thickness. The content of the organic matter is 1.2–1.5%, and the soil pH value is between 7.1 and 7.5.

As shown in Figure 1, the measurement locations on the surface area are as follows: the #0 point on normal soil in an unmined area, #2 and #3 points are on the surface over the goaf, and the #1 point is a wellbore 80 m in depth, which connects to the goaf. Also, the diameter of the wellbore upper part \((H \leq 6 \text{ m})\) is 27 cm. The layout of monitoring points in the borehole is shown in Figure 2. There are six coal seams in the location. From the bottom to the top are Gaode 3, Gaode 2, 1.0 m, 2.5 m, 1.5 m, and 1.3 m coal seams, respectively. Among them, the 1, 1.5, and 2.5 m coal seams are not mined, and the coal seam elevation is between −75 m and −30 m (ground elevation is about +180 m). About 70 m on the west side of the measuring point is the Gaode 2 chasm. The geological condition of the monitoring points and surface soil

Figure 1. Map of measurement locations.
properties and atmospheric parameters of the measuring area are shown in Tables 1 and 2, respectively.

In this study, the long-term monitoring method of the surface CO₂ flux was carried at #0, #2, and #3 points (Figure 3). The surface CO₂ fluxes at #0, #2, and #3 points were measured by the closed chamber method. The effect of spontaneous combustion in the goaf was investigated by continuous monitoring of the soil surface CO₂ flux.

Furthermore, the short-term measurement of the CO₂ concentration versus the depth of the borehole at the #1 point was carried out using the open measuring principle. The relationship between air leakage into the goaf and CO₂ flux changes was studied using the SF₆ laser leak detector (KARAT LLD-100) to verify the effect of air leakage at the #3 point. SF₆ as a tracer gas was released continuously from the surface at the lower part of the open-pit mine slope. The vertical distance from the monitoring point is 30 m, and the horizontal distance is 120 m. The locations of the releasing and monitoring points are shown in Figure 4. To avoid the data contingency caused by the single point measurement, two test points and two blank points were selected to measure the SF₆ concentration. The test points I and II for the measurements were located over the fracture zone, and the blank points (points III and IV) for measurements are 30 cm away from the test points. The

| serial number | altitude (m) | adjacent fault | coal seam name | coal seam elevation (m) | mined out area (Y/N) | distance from slope (m) |
|---------------|-------------|----------------|----------------|------------------------|----------------------|-------------------------|
| #0            | +183        | no. 2 fault    | Gaode 2        | 0 to +25               | Y                    | about 150               |
|               |             |                |                | 1.3 m                  |                      |                         |
|               |             |                |                | 1.5 m                  |                      |                         |
|               |             |                |                | 1.5 m                  |                      |                         |
| #1            | +179        | no. 1 fault    | Gaode 2        | 0 to +25               | Y                    | about 100               |
|               |             |                |                | 1.3 m                  |                      |                         |
|               |             |                |                | 1.5 m                  |                      |                         |
| #2            | +180        | nos. 1 and 2 faults | Gaode 2 | 0 to +25               | Y                    | about 23                |
|               |             |                |                | 1.3 m                  |                      |                         |
|               |             |                |                | 1.5 m                  |                      |                         |

Table 2. Surface Soil and Atmospheric Parameters

| serial number | relative humidity (%) | volume weight of soil (g·cm⁻³) | soil porosity (%) |
|---------------|-----------------------|---------------------------------|-------------------|
| #0            | 20–80                 | 1.85                            | 29                |
| #1            | 44–67                 | 1.70                            | 32                |
| #2            | 54–70                 | 1.95                            | 26                |
| #3            | 40–64                 | 1.90                            | 27                |
was observed that the CO$_2$ flux of the #0 measuring point is high in the daytime and low at night. The reason is basically consistent with the change in soil temperature. The surface soil of the measurement area is composed of sandstone and coal powder. The soil is relatively dry, and there is no vegetation on the surface. The measured surface CO$_2$ flux between 0.1 and 0.2 μmol·m$^{-2}$·s$^{-1}$ is mainly emission from the respiration of microorganisms in the soil. A low temperature inhibits soil microbial respiration, and high soil moisture prevents the diffusion of CO$_2$. Therefore, the lowest surface flux emission in the daytime occurs around 6 a.m. with the lowest temperature and relatively high humidity. In this monitoring area, the soil is dry. Accordingly, the CO$_2$ flux increased sharply during the period of rainfall. According to the measurement results, the appropriate rainfall will lead to a large increase in the surface CO$_2$ flux. This kind of increase does not occur immediately but starts approximately 2 h after rainfall. This is a process in which rainwater penetrates into the soil and causes decomposition and buffering of the microorganisms and organic matter in the soil. The elapsed time of the CO$_2$ flux starts to rise up until the peak value is about 3 h. With continuous rainfall, the soil water content on the surface will inhibit CO$_2$ emission.

### 3.2. Analysis of Surface CO$_2$ Flux over Goaf

The CO$_2$ fluxes measured at #2 and #3 points are shown in Figures 6 and 7, respectively. The CO$_2$ flux at the #2 point is about 0.25–1.25 μmol·m$^{-2}$·s$^{-1}$, which is 5–10 times larger than that of the normal area (about 10% of #3 point test data). The goaf under the #2 point was created about 30 years ago, and the surface has subsided due to free collapse. The goaf is in a closed state and does not have coal spontaneous combustion; therefore, the measured value of the surface flux is relatively low.

The spontaneous combustion phenomenon in the goaf under the #3 point is obvious. Due to the short distance, air leakage from the slope to the goaf may induce residual coal spontaneous combustion. The test results of the CO$_2$ flux at the #3 point are shown in Figure 7. The surface CO$_2$ flux range is 10–15 μmol·m$^{-2}$·s$^{-1}$. The variation of CO$_2$ flux is still correlated with the daily temperature changes, and the fluctuation of CO$_2$ flux is much larger than that of the normal area. These results indicate that the daily variation of CO$_2$ flux is not only affected by the biological activity but also related to the air leakage intensity caused by diurnal temperature differences.

Figure 8 shows the temperature and CO$_2$ flux curves of the day and night (24 h). It can be seen that the CO$_2$ flux of the normal area (#0 measuring point) has the same trend as the temperature changes (see Figure 8a). The CO$_2$ flux increases with increasing atmospheric temperature. However, Figure 8b,c shows that the CO$_2$ flux on the surface over the goaf is negatively correlated with the atmospheric temperature. The #2 point is located over the goaf but does not include the spontaneous combustion of coal. However, the CO$_2$ flux is still 5–10 times larger than that of the normal area, indicating that, due to the influence of internal and external temperatures and pressure differences, there is still existing goaf CO$_2$ continuous emission to the surface. The mined-out area of this measuring point was created for a long time and collapsed freely. The goaf interior is approximately confined, the air leakage is weak, and the temperature is constant.

During the summer period, the temperature difference between the goaf and the outside reduces with increasing atmospheric temperature. So, it weakens the diffusion of CO$_2$ due to less buoyancy force on the gas. Therefore, surface CO$_2$ flux increases as the temperature decreases. CO$_2$ emission
of the #3 point is significantly higher than that of the #2 point and affected by the temperature change. The change in air leakage intensity caused by the temperature difference has a significant effect on the oxidation reaction of residual coal in the goaf and the gas diffusion intensity from the goaf to the surface. These relations indicate that the oxidizing reaction intensity of residual coal in the goaf affects indirectly the value of surface soil CO₂ flux.

3.3. Seasonal Changes in Surface CO₂ Fluxes over Goaf. The surface soil CO₂ emission under different seasonal conditions is measured as shown in Figures 9 and 10. The same time period (9:00 a.m. to 12:00 p.m. in sunny daytime),
winter (December), and summer (July) monitoring results were selected to compare the effect of season changes on CO² flux.

The soil animals, plants, soil microflora, and other soil organisms show significant differences in the living conditions due to the temperature difference between winter and summer (the average temperature difference is about 40 °C). In summer, the measured CO² flux in the goaf-overlying surface contains both CO² released by soil fauna and soil microflora activities and the CO² diffused from the goaf. However, in winter, the life activities of surface soil fauna and microflora are almost stopped since the atmospheric temperature drops below the freezing point. Based on this, it has become apparent that the oxidation state of the underground coal can be indirectly determined by monitoring the change in the surface CO² flux.

Due to the seasonal changes, the fluctuation law of CO² flux on the surface of the #2 point shows quite different trends. Comparing Figures 9 and 10 can conclude that, in the same test period, the CO² flux fluctuation range is small, and the variation curve is relatively flat in summer; however, the CO² flux increases with temperature in winter. In summer, the atmospheric temperature is high, and the metabolic activities of soil animals, plants, soil microflora, and other soil organisms in the surface soil are frequent. The slow oxidation stage of the residual coal in the goaf accelerates the release of CO²; therefore, the total measured CO² flux is relatively high. Consequently, the measured CO² flux is about 1 time larger than that in winter. However, during the summer monitoring period, due to the small relative temperature difference between the goaf and the outside, the surface CO² flux varies slightly (as shown in Figure 9), which is not conducive to the diffusion of CO² to the surface. Therefore, when the temperature is at the highest level, the change in surface CO² flux is not obvious. In winter tests, the measured CO² flux range is 0.2 to 0.3 μmol·m⁻²·s⁻¹, much lower than the measured summer data. In a cold environment, the soil fauna and soil microflora activities almost stopped, and there is no extra CO² emission. The measured CO² flux is only from the goaf diffusion. Additionally, the #2 point underground goaf is closed; the temperature is higher than that of the outside atmosphere, resulting in a large temperature and pressure difference between the goaf and the outside, which accelerates the CO² release to the surface. So, the surface CO² flux increased with increasing outside atmospheric temperature, as shown in Figure 10. From the discussion, one may conclude that the difference in environmental conditions such as temperature and soil characteristics is the main reason for the different trends of CO² flux on the surface soil. By measuring the CO² flux overlying the goaf, the conditions of underground coal can be indirectly reflected, which lays a data foundation for more accurately predicting and warning the residual coal in the abandoned goaf and the spontaneous combustion state of the shallow buried coal seam.

3.4. Tracer Gas Measurement for Air Leakage Pass.

To confirm the air leakage to the goaf from the open-pit mine slope, the tracer gas measurement was carried out. Before the release of SF₆, the background concentrations of the points (test points I and II and blank test points III and IV) were determined. After the values were stabilized, SF₆ was continuously released. The wind velocity is measured every 5 min. The change in SF₆ concentration and the distribution of wind velocity are shown in Figures 11 and 12.

As shown in Figure 11, the measured SF₆ background concentration is in the range of 5–18 ppb. The elapsed time of test point I that detected the SF₆ concentration rise was 50 min, and the peak value reached 110 ppb. According to the measured wind velocity, the stronger the wind velocity, the higher the measured SF₆ concentration. Since SF₆ is released in the slope, to eliminate the influence of diffusion in the atmosphere, the blank test point III is simultaneously measured, and the concentration change is also illustrated in Figure 11. When moved to the blank test point III, the concentration of SF₆ instantaneously drops below 18 ppb, returning to the background concentration measured before release.

Figure 9. Monitoring results at the #2 point in summer.

Figure 10. Monitoring results at the #2 point in winter.

Figure 11. Relationship between the SF₆ concentration and wind velocity at points I and II.
As can be seen from Figures 4 and 12, the crack position at the test point II is relatively wide, and a peak concentration value of 230 ppb appears when the wind velocity is up to the maximum. When the wind velocity drops, the concentration value also decreases. Finally, the SF$_6$ concentration in the test point II is stable at about 120 ppb. Once the monitoring probe to the blank test point IV was moved, the SF$_6$ concentration drops below 18 ppb.

Combining the results of Figures 11 and 12, we can see that a certain concentration of SF$_6$ can be detected at the surface crack of the goaf. The measured SF$_6$ concentration is directly proportional to the wind velocity, indicating that the goaf has air leakage in the slope and the stronger the wind velocity, the more air leakage to the goaf. Air leakage promotes the oxidation of residual coal in the goaf, which increases the concentration of internal CO$_2$ and speeds up its diffusion to the surface. According to the comparative analysis of the measured results of test points I and II and blank test points III and IV, it can be seen that most of SF$_6$ released from the slope penetrates into the goaf with the air leakage. The surface cracks connect to the goaf, and the air leakage on the slope promotes the CO$_2$ emission from the overlying surface.

3.5. Correlation Analysis of Surface CO$_2$ Emission and Goaf Spontaneous Combustion. To study the diffusion process of CO$_2$ from the goaf to the surface and fully understand the variation of the underground CO$_2$ concentration, the emission characteristics of CO$_2$ from the borehole connecting to the goaf were measured by infrared gas monitoring equipment. In the measurement, nine monitoring positions were set at the #1 point (see Figure 2). Each monitoring takes 6 min and operates 11 cycles throughout the day.

Summarizing the data measured in Figure 13, the CO$_2$ concentration in the borehole deeper part is higher than that in the upper part. However, when $H > 1$ m, the CO$_2$ concentration almost remains constant. Meanwhile, the larger the depth, the smaller the fluctuation of the monitored CO$_2$ concentration. According to Fick’s law and the measured climate data, atmospheric temperature is the most important reason for this phenomenon. Moreover, it also points out that the CO$_2$ concentration in the borehole below 1 m depth is not affected by changes in atmospheric temperature. The measurement results indirectly prove the existence of CO$_2$ diffusion from the goaf to the surface. When the region exceeds 2 m in depth, the CO$_2$ concentration has a decreasing trend with increasing depth, as shown in Figure 13.

The change in the CO$_2$ concentration is positively correlated with the ambient temperature, as shown in Figure 13. The higher the ambient temperature, the stronger the CO$_2$ diffusion ability. Therefore, the existed deeper part of CO$_2$ in the wellbore is easier to diffuse to the top area.

As shown in Figures 13 and 14, the surface microbial activity is enhanced as the atmospheric temperature increases. Due to
the influence of air leakage from the open-pit slope to the goaf, the surface CO₂ flux increases. From the changes in CO₂ concentration in the borehole, it can be found that with increasing temperature, a large fluctuation in the CO₂ concentration was measured near the surface of the borehole (within a depth of 1 m) due to the increase in CO₂ emission. It is important to point out that the atmospheric temperature and slope leakage affect the goaf CO₂ diffusion and promote the emission of CO₂ on the surface. Note that the concentration of CO₂ in the \( H \geq 3 \) m area becomes smaller. Meanwhile, the CO₂ concentration in the borehole is influenced not only by the goaf but also the diffusion of the surrounding stratum.

The above preliminary analysis has provided important information that there is a certain amount of CO₂ in the upper stratum and the CO₂ diffusion from the goaf to the surface.

### 3.6. Surface Soil CO₂ Fluxes Related to Spontaneous Combustion in the Goaf

The coal mines have (#3 point location area) already closed the mine shafts, roadways around goafs 2 years ago. There is a smoking belt fissured from the north to the south on the surface. Therefore, air leakage from the slope surface provides oxygen to residual coal in the goaf and may induce spontaneous combustion in the goaf.

As shown in Figure 15, the value of CO₂ flux at the #3 point overlying the goaf is roughly 10 times larger than that of the #2 point on the normal soil surface due to spontaneous combustion of the residual coal. We expect that the main environmental and topographic factors to induce spontaneous combustion at the goaf are atmospheric temperature, wind velocity, and wind direction at the pit slope surface.

According to the environmental monitoring data at the site, the influence of wind velocity on the surface CO₂ flux over the goaf is discussed, because the wind direction of the monitoring area is mainly west wind. Figure 16 shows the relation between the wind velocity and surface soil CO₂ flux. The trend of CO₂ flux is sensitive to the wind velocity. The reason may be that the goaf air leakage induces with increasing wind velocity, and it promotes the coal oxidation and producing CO₂ gas. This phenomenon is attributed to the increase in the surface CO₂ flux.

Figures 17 and 18 show the relationships between the goaf surface soil CO₂ flux, temperature, and wind velocity for \( V \leq 2 \) m·s\(^{-1}\) and \( V > 2 \) m·s\(^{-1}\), respectively. Under the influence of the wind velocity, the CO₂ flux increases significantly. This is because the wind promotes the oxygen supply to the residual coal in the goaf, which induces the oxidation reaction and produces CO₂. This phenomenon is further confirmed by the monitoring data presented in Figure 18.

***Figure 14.*** Surface CO₂ flux curve.

***Figure 15.*** Relationship between the CO₂ flux and temperature at the #3 point.

***Figure 16.*** Relationship between the CO₂ flux and wind velocity at the #3 point.

***Figure 17.*** Relationship among the surface CO₂ flux, temperature, and wind velocity at the #3 point \((V \leq 2 \) m·s\(^{-1}\)): (a) surface CO₂ flux versus temperature and (b) surface CO₂ flux versus wind velocity.
the normal area increases with increasing atmospheric temperature, while the CO$_2$ flux over the goaf decreases with increasing atmospheric temperature.

3. The CO$_2$ concentration in the borehole is basically constant when the depth is higher than 1 m. The difference in the concentration at different depths indicates the presence of CO$_2$ diffusion in the stratum.

4. The tracer gas method proved the air leakage in the goaf. The air leakage intensity is proportional to the magnitude of wind velocity. It was found that the fracture in the area of the #3 point is connected to the goaf. The air leakage from the open-pit slope was expected to promote the surface CO$_2$ emission over the goaf.

**CONCLUSIONS**

In this study, the CO$_2$ concentration in the borehole connected to the goaf and CO$_2$ flux in the soil surface was carried out to investigate the influence of abandoned coal mine goaf CO$_2$ on the surface environment. The present study is summarized as follows:

1. The surface CO$_2$ flux over the goaf is obviously higher than that of the normal area. The measured CO$_2$ flux over the goaf is mainly provided from the oxidation reaction of residual coal. The present measurement results are useful for early warning to prevent hazards related to spontaneous combustion in the goaf or shallow coal seams.

2. Both surface CO$_2$ fluxes over the goaf and the normal area are affected by the soil characteristics and atmospheric temperature. However, the CO$_2$ flux in the surface soil CO$_2$ flux over the goaf decreases with increasing atmospheric temperature.

3. The CO$_2$ concentration in the borehole is basically constant when the depth is higher than 1 m. The difference in the concentration at different depths indicates the presence of CO$_2$ diffusion in the stratum.

4. The tracer gas method proved the air leakage in the goaf. The air leakage intensity is proportional to the magnitude of wind velocity. It was found that the fracture in the area of the #3 point is connected to the goaf. The air leakage from the open-pit slope was expected to promote the surface CO$_2$ emission over the goaf.

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