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STUDY ON DAILY-SCALE EMISSION CHARACTERISTICS OF SPONTANEOUS COMBUSTION GASES IN SHALLOW SOIL OF COAL FIRE AREAS

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Abstract: *The development of coalfield fire areas not only leads to the wastage of coal resources but also results in the emission of a large quantity of spontaneous combustion gases, further exacerbating air pollution. Monitoring the spontaneous combustion gas products in coalfield fire areas is crucial. These gases are released to the surface through surface fissures and shallow soil layers. However, current monitoring methods for carbon emissions in coalfield fire areas often overlook the spontaneous combustion gas emissions from shallow soil regions. Therefore, this study focuses on CO2 and CO, which are the primary components in spontaneous combustion gases, and employs a self-developed multi-zone gas concentration monitoring system for coalfield fire areas. This system is used to capture the temporal variation patterns of spontaneous combustion gas concentrations and related parameters in shallow soil and fissure regions. The study further investigates the influence of surface meteorological factors on gas emissions in these areas, revealing the relationship between the gas emission patterns in shallow soil and fissure regions from both high-frequency and low-frequency data perspectives. The findings provide important theoretical insights for the rational assessment and improvement of carbon emission evaluations in coalfield fire areas.*

Keywords: *coalfield fire area; fissure area; shallow soil; spontaneous combustion gases; daily scale*

1. Introduction

Coal fires, a natural disaster caused by the spontaneous combustion of coal seams, typically occur in coal outcrops and shallow coal layers, often triggered by external activities such as coal mining. These fires are most commonly found in underground coal seams [1]. Currently, coal fire disasters are prevalent in countries such as China, India, the United States, and Australia [2-5]. In China, confirmed coalfield fire areas are primarily distributed in the arid and semi-arid regions of northern provinces, including Inner Mongolia, Xinjiang, Ningxia, Gansu, Qinghai, and Shanxi [2, 6-8]. Coal fires not only result in substantial losses of coal resources but also exacerbate atmospheric pollution in affected areas, seriously threaten the safety of mining operations, and pose significant health risks to residents [5, 9].

The formation and development of coal fires is a spontaneous, slow, and dynamic process that involves exothermic reactions, heat accumulation, and temperature rise, ultimately leading to coal seam combustion [10]. The combustion process of coal fires is generally divided into four stages: weathering and oxidation, natural ignition, combustion expansion, and fire area extinction [11]. Each stage of coal fire development generates various geophysical anomalies in the affected areas, such as thermal, gas, magnetic, and electrical conductivity anomalies [12-15].

In the early stages of coal fire combustion, which marks the precursor to fire spread and expansion [11], the coal oxidation rate accelerates, and its activity increases [16], releasing large amounts of spontaneous combustion gases such as CO_2 and CO [17]. Surface fissures, vents, and other openings serve as the primary pathways for the emission of gases from coal fires. For example, Litschke et al. [18] measured CO_2 levels in the smoke released from surface cracks in the Wuda coalfield fire area in Inner Mongolia. Ide et al. [19] estimated CO_2 emissions from a coal fire in Colorado, USA, through on-site monitoring, while Kuenzer et al. [20] estimated CO_2 emissions based on the amount of coal combustion.

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However, surface fissures and vents are not the only channels through which spontaneous combustion gases are emitted. Under pressure, buoyancy, and other forces, spontaneous combustion gases can migrate upward through fissures and pores in the rock layers, eventually being released into the surface space via shallow soil. Existing monitoring methods often overlook the emissions of spontaneous combustion gases from shallow soil areas in coal fire regions. Therefore, this paper proposes a multi-region spontaneous combustion gas concentration monitoring system and device for coalfield fire areas, which can collect spontaneous combustion gas emission data from shallow soil, surface space, and fissure areas on a daily scale. Using wavelet decomposition, the monitoring data are broken down into high-frequency and low-frequency components, which further reveal the relationship between gas emission patterns in shallow soil and fissure areas. This approach provides important theoretical support for the reasonable assessment of carbon emissions in coalfield fire areas.

2. Research systems and methods

2.1. Research area

The selected study area is a typical coal fire zone located within the boundaries of Fukang City, Xinjiang Autonomous Region. This fire zone is situated in an arid to semi-arid continental climate zone, characterized by hot and dry summers, cold and dry winters, with an average annual temperature of 6.7°C. The area receives an average annual precipitation of 205.0 mm, while evaporation reaches as high as 1578.7 mm. Windy periods are concentrated in April and May, with prevailing wind directions changing seasonally. The terrain is primarily composed of low hills and ridges, with higher elevations in the south and lower elevations in the north. The area is marked by the development of gullies and sparse vegetation. The region experiences significant wind speed variations and strong wind erosion, leaving coal seam outcrops in a persistently dry state or subjecting them to dry-wet cycles, where brief wetting is followed by rapid drying. These conditions make coal seam outcrops highly susceptible to spontaneous combustion [21].

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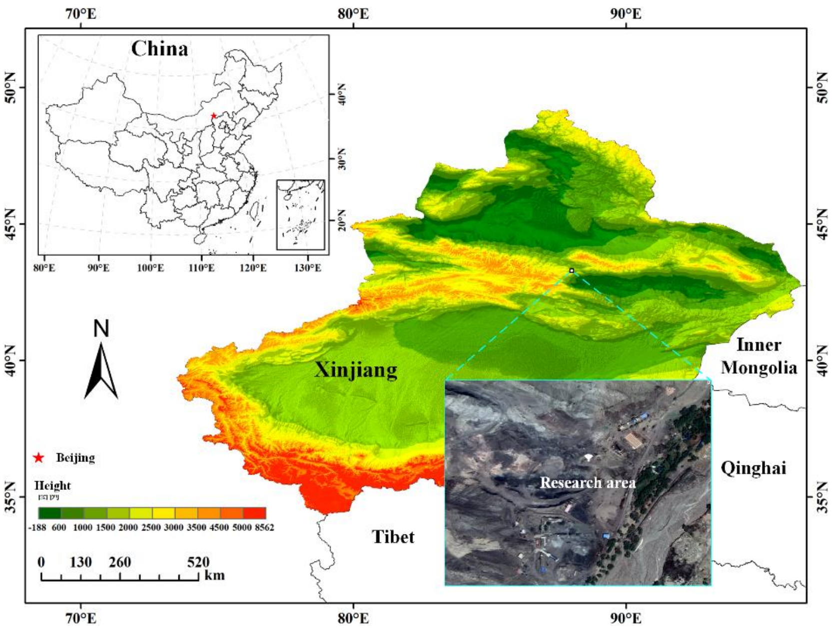

Fig.1. Location map of the study area

Field investigations revealed distinct signs of coal fires in this area, including prominent surface fractures, cracks, and subsidence pits. Monitoring points were established at locations with flat terrain, starting from surface fractures.

2.2. Monitoring platform

Based on the characteristics of different locations within coal fire areas, this study independently developed an integrated monitoring platform capable of continuously monitoring gas concentrations and their influencing factors at various locations in coal fire regions. The platform enables simultaneous online coupled monitoring of multiple parameters in surface areas, shallow soil areas, and fracture zones. The specific components of this platform are illustrated in Fig 2. The multi-region monitoring platform for the temporal characteristics of spontaneous combustion gas products in coalfield fire areas used in this study consists of four modules: surface monitoring module, shallow soil monitoring module, fracture monitoring module, and data acquisition and power supply module.

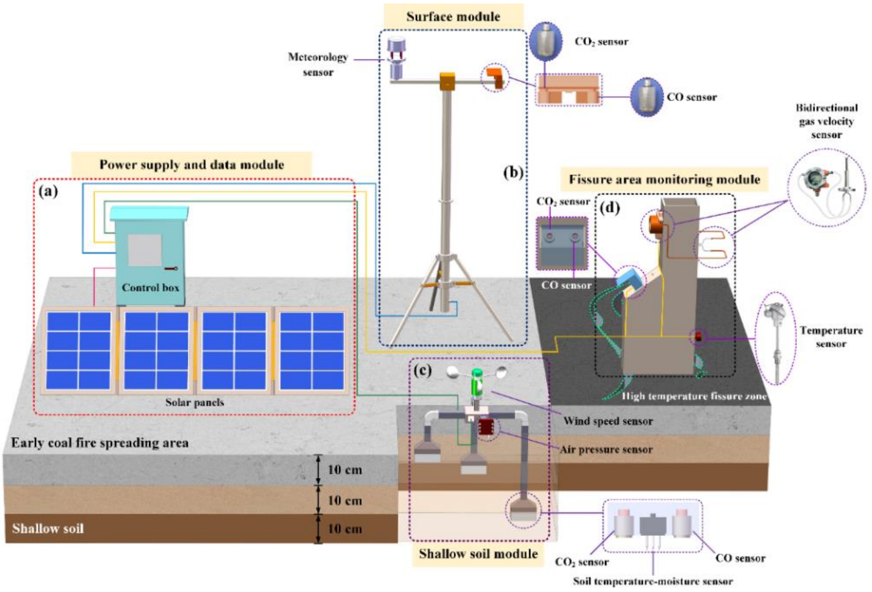

Fig.2. Schematic diagram of the monitoring platform for temporal characteristics of spontaneous combustion gas products in multi-regions of the coalfield fire area. (a) Power supply and data module; (b) Surface layer module; (c) Shallow soil module; (d) Fissure area module [22]

2.3. On-site monitoring

After determining the study area, the installation and commissioning process of the monitoring platform is as follows:

- Site selection

Based on the characteristics of surface fractures, cracks, and white smoke, the fracture zone was identified as the target monitoring area. Using the fracture zone as a reference point, surface temperature measurements were taken along the vertical direction of the fractures with temperature sensors. Locations with lower temperatures and flat terrain were selected as the installation sites for the data collection and power supply modules.

- Platform layout and assembly

First, the sensors and equipment components of the surface module, shallow soil module, and fracture module were assembled into an integrated system. Then, the fracture module, surface module, shallow soil module, and data collection and power supply module were laid out in the fracture and shallow soil regions. Finally, the solar panels were oriented toward sunlight, and the modules were connected with wires to ensure the complete assembly of the platform.

- Sensor calibration and debugging

The power for the data collection and power supply module was turned on, and the sensors in each module were powered and calibrated. This step ensured the sensors operated accurately and stably, and the monitoring error was kept within an acceptable range.

- Data collection and verification

After ensuring the sensors were functioning properly, a preliminary test lasting 5 minutes was conducted to check whether the collected data met the predefined monitoring standards. Once the system's stability was confirmed, the data reading and saving interval was set to 1 minute to ensure real-time data collection and storage.

- System monitoring and data continuity assurance

Based on the stable operation of the system, regular checks of the system's operational status were scheduled, with 10:00 am as the observation time, in accordance with the daylight hours in Xinjiang. This was to prevent monitoring interruptions or sensor malfunctions, ensuring the continuity and completeness of the data collection.

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2.4. Data Preprocessing

- Data Preprocessing

In order to improve the validity of the data, preprocessing was conducted on the data obtained from the system monitoring. First, missing (null) and abnormal values in the monitoring data were handled by either removal or imputation. Next, the arithmetic mean of the data for each minute was calculated to obtain the average data for every 30 min. Finally, the data from different modules were summarized in chronological order to form a complete system monitoring dataset.

- Pearson Correlation

The Pearson correlation coefficient is a measure of the linear relationship between two sets of variables, typically denoted by r. It is expressed as:

$$r = \frac{\sum_{i-1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (1)$$

where, n is the sample size, x_i and y_i are the i-th single sample point and are the sample means. The Pearson correlation coefficient ranges from [-1, 1], where 1 indicates a perfect positive linear correlation, 0 indicates no linear correlation (non-linear correlation), and -1 indicates a perfect negative linear correlation.

- Discrete Wavelet Decomposition

Discrete wavelet decomposition is a process that decomposes a signal into high-frequency and low-frequency components [23]. The high-frequency part of the signal represents the abrupt changes and fluctuation intensity of the sequence, while the low-frequency part reflects the trend characteristics of the sequence, usually representing the approximation of wavelet coefficients. As the decomposition scale increases, the high-frequency components are progressively removed, and the low-frequency part is retained, which captures the overall variation pattern of the time series.

3. Research systems and methods

3.1 Surface area

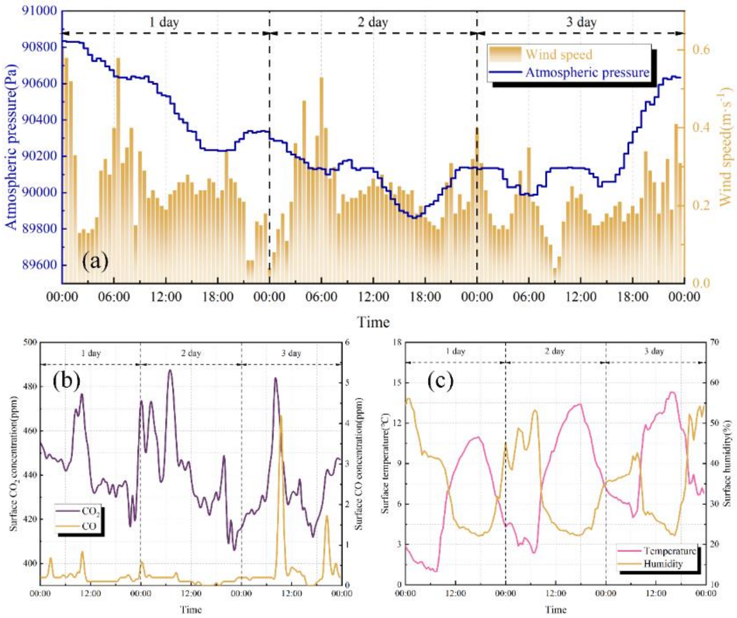

Fig.3. Temporal variation of environmental factors and gas concentrations in the near-surface region. (a) Average surface wind speed and atmospheric pressure; (b) Surface CO_2 and CO concentrations; (c) Surface temperature and humidity

The temporal variation of environmental factors and gas concentrations in the near-surface region is shown in Fig 3. According to Fig 3(a), from April 20 to April 22, the atmospheric pressure at a height of 2 m in the near-surface region shows an overall trend of first decreasing and then increasing. During the daily period from 04:00 to 08:00, the wind speed exhibits noticeable fluctuations. According to Fig 3(b), the temperature and humidity at 2 meters in the near-surface region show an inverse overall trend. The

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temperature and humidity fluctuate in a curve, with the temperature reaching its maximum value and the humidity reaching its minimum value between 12:00 and 14:00 each day. According to Fig 3(c), the concentrations of CO_2 and CO at 2 m in the near-surface region exhibit random fluctuations. Over the three-day period, the overall trend shows a decrease followed by an increase in their concentrations.

3.2. Shallow soil

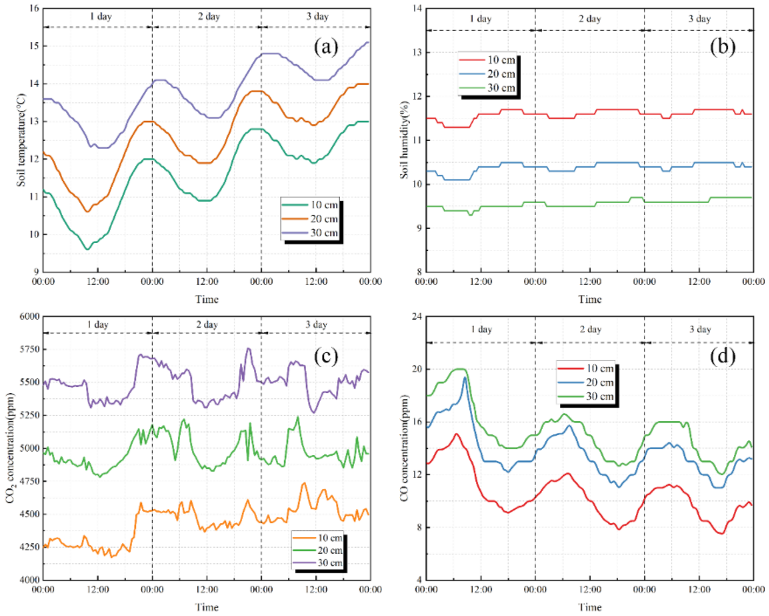

Fig.4. Temporal variation of soil factors and gas concentrations in the shallow soil region.
(a) Soil temperature; (b) Soil moisture; (c) Soil CO_2 concentration; (d) Soil CO concentration

The temporal variations of soil factors and gas concentrations in the shallow soil region are shown in Fig 4. According to Fig 4(a) and (b), the temporal changes in soil temperature and humidity at different soil depths in the shallow soil region are observed. The soil temperature exhibits an "S"-shaped fluctuation pattern over time, generally decreasing first and then increasing throughout the day. The soil humidity, on the other hand, shows a relatively stable trend over time. As the soil depth increases, both the soil temperature and humidity gradually increase. According to Fig 4(c) and (d), the temporal changes in CO_2 and CO concentrations at different soil depths in the shallow soil region are observed. The CO_2 concentration at 10 cm, 20 cm, and 30 cm depths exhibits fluctuating patterns, with a decrease in CO_2 concentration observed around 10:00 every day. At around 19:00, CO_2 concentrations generally show an increasing trend. The temporal variations in CO_2 concentrations at the 10 cm, 20 cm, and 30 cm depths demonstrate regular sinusoidal fluctuations, where the trend follows a pattern of increasing, decreasing, and then increasing again daily. As the depth increases, both soil CO_2 and CO concentrations gradually increase.

3.3. Fissure area

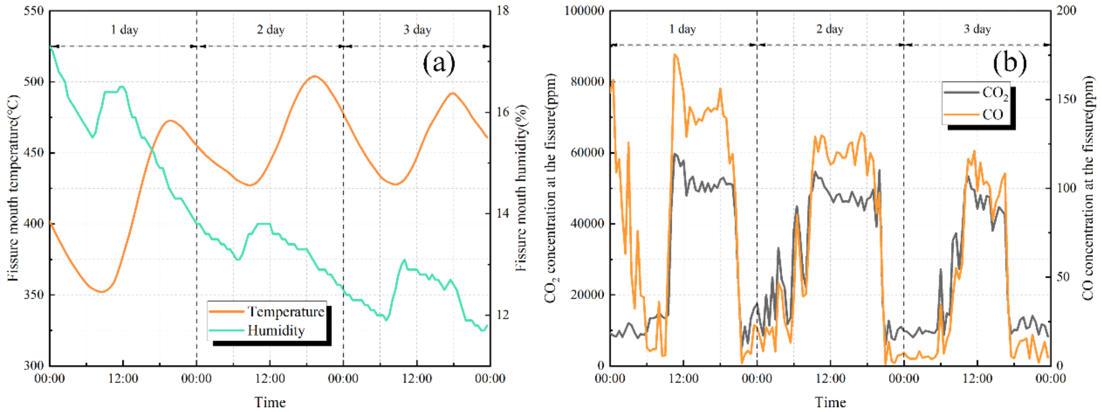

Fig.5. Temporal variation of physical factors and gas concentrations in the fracture zone.
(a) Fracture mouth temperature and humidity; (b) Fracture mouth CO_2 and CO concentrations

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The temporal variations of physical factors and gas concentrations in the fracture region are shown in Fig 5. According to Fig 5(a), the physical factors in the fracture region exhibit the following temporal patterns. The fracture temperature generally increases over time, with a daily fluctuation in the shape of an "S" curve, decreasing initially and then increasing. The fracture humidity, on the other hand, shows a decreasing trend overall, but with a daily fluctuation pattern also resembling an "S" curve, decreasing initially, then increasing, and finally decreasing again. Between 06:00 and 12:00, the fracture temperature reaches its minimum value, while the fracture humidity shows an increasing trend. From 08:00 to 19:00, the fracture temperature shows an increasing trend. According to Fig 5(b), the temporal variation in gas concentrations in the fracture region follows a similar pattern for both CO_2 and CO. From 00:00 to 10:00, the concentrations of CO_2 and CO increase. Between 10:00 and 20:00, both CO_2 and CO concentrations fluctuate steadily without significant changes. From 20:00 to 24:00, the concentrations of CO_2 and CO show a decreasing trend.

3.4. Comparison analysis of gas concentrations in different regions

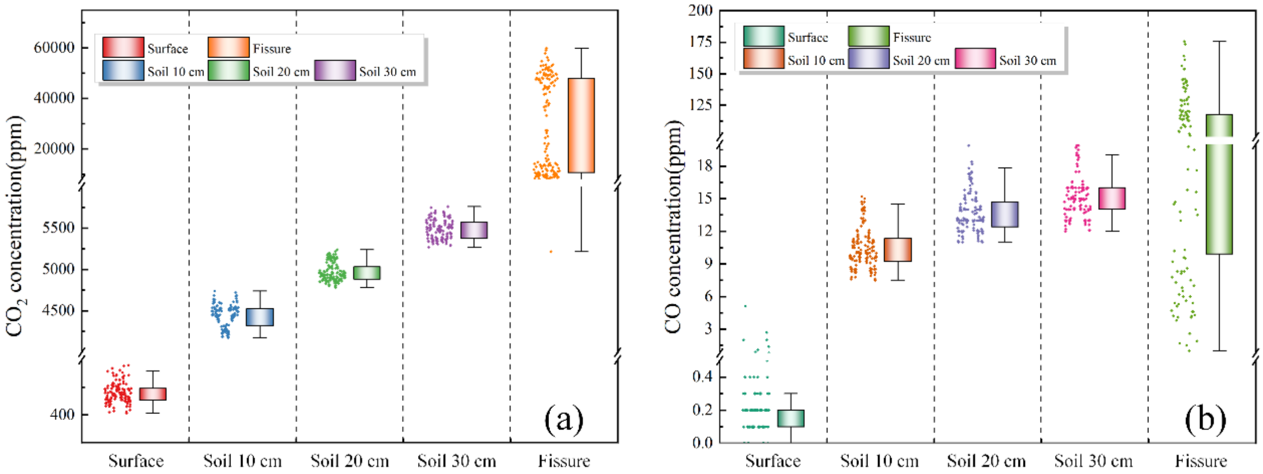

Fig.6. Comparative analysis of gas concentrations in different regions
(a) CO_2 concentration; (b) CO concentration

The comparative analysis of CO_2 and CO concentrations across different regions is shown in Fig 6. According to Fig 6(a), the CO_2 concentration at 2 m in the near-surface region ranges from 403 to 490 ppm, with an average of approximately 440 ppm. In the shallow soil region, as the depth of the soil layer increases, the CO_2 concentration also increases. The CO_2 concentration at a depth of 10 cm ranges from 4174 to 4739 ppm, with an average of approximately 4437 ppm. At 20 cm depth, the CO_2 concentration ranges from 4782 to 5239 ppm, with an average of approximately 4965 ppm. At 30 cm depth, the CO_2 concentration ranges from 5268 to 5760 ppm, with an average of approximately 5488 ppm. In the fracture region, the CO_2 concentration ranges from 5217 to 59827 ppm, with an average of approximately 28906 ppm. According to Fig 6(b), the CO concentration at 2 m in the near-surface region ranges from 0 to 5.1 ppm, with an average of approximately 0.28 ppm. In the shallow soil region, as the soil depth increases, the CO concentration also increases. The CO concentration at 10 cm depth ranges from 7.2 to 15.2 ppm, with an average of approximately 10.5 ppm. At 20 cm depth, the CO concentration ranges from 11 to 19.9 ppm, with an average of approximately 13.7 ppm. At 30 cm depth, the CO concentration ranges from 12 to 20 ppm, with an average of approximately 15.2 ppm. In the fracture region, the CO concentration ranges from 1 to 175.5 ppm, with an average of approximately 67.5 ppm. These results indicate that the CO_2 concentration is consistently higher than the CO concentration across all regions. The CO_2 and CO concentrations in the fracture region are significantly higher than those in the shallow soil and near-surface regions. In both the near-surface and shallow soil regions, the CO_2 and CO concentrations increase progressively with depth. The CO_2 and CO concentrations in the shallow soil region are lower than those in the fracture region but are still notably higher than those in the near-surface region. Since the CO concentration in the near-surface region is lower and more influenced by surface meteorological factors, while the CO_2 concentration in the shallow soil region is higher and less influenced by surface factors, the CO_2 concentration in the shallow soil region can serve as an exploration indicator for coal fire areas.

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4. Discussion and analysis

4.1. Analysis of time series data of spontaneous combustion gas concentration in different areas

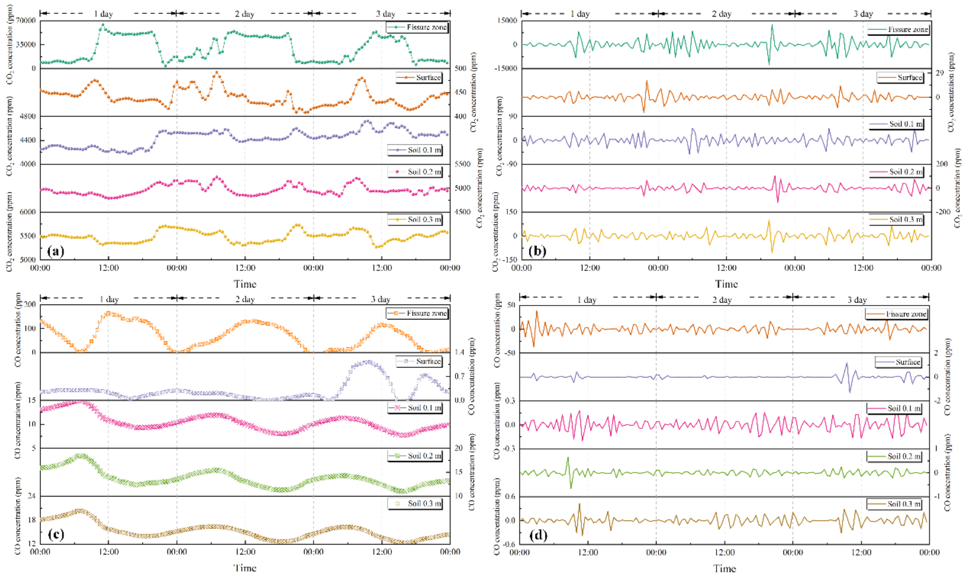

Fig.7. Low-frequency and high-frequency data analysis of CO_2 and CO concentrations in different regions (a) Low-frequency CO_2 concentration data; (b) High-frequency CO_2 concentration data; (c) Low-frequency CO concentration data; (d) High-frequency CO concentration data

The time series data of CO_2 and CO concentrations monitored in different regions were decomposed using the discrete wavelet transform (DWT), and the results are shown in Fig 7. According to Fig 7(a), the low-frequency data reflects the continuous trend of CO_2 concentration changes in different regions. The CO_2 concentration changes in shallow soil exhibit a continuous variation pattern similar to that of the surface and fracture regions, primarily showing periodic fluctuations on a daily scale. The trend on a single day shows a decrease followed by an increase. According to Fig 7(b), the high-frequency data reflects the fluctuation trend of CO_2 concentration changes in different regions. The high-frequency fluctuations in the CO_2 concentration of the fracture region are significantly greater than those in the shallow soil and surface regions. Particularly, data fluctuations are observed between 00:00 and 12:00 of each day. According to Fig 7(c), the continuous trend of CO concentration changes across different regions shows a wave-like periodic trend, characterized by an increase, followed by a decrease, and then an increase again. According to Fig 7(d), the fluctuation trend of CO concentration changes across different regions is mainly concentrated in the time interval from 00:00 to 12:00 of each day. From this analysis, it can be concluded that the emission trends of spontaneous combustion gases in the shallow soil region and fracture region are generally consistent. However, due to the direct connection of fracture channels to the surface space, the emission process in the fracture region is significantly affected by surface meteorological factors. In contrast, the shallow soil, as a porous medium with a porous structure, shows a relatively weaker response to surface meteorological factors. Therefore, the emission characteristics of spontaneous combustion gases in the fracture region exhibit a certain degree of lag.

4.2 Correlation analysis between meteorological factors and spontaneous combustion gas concentrations

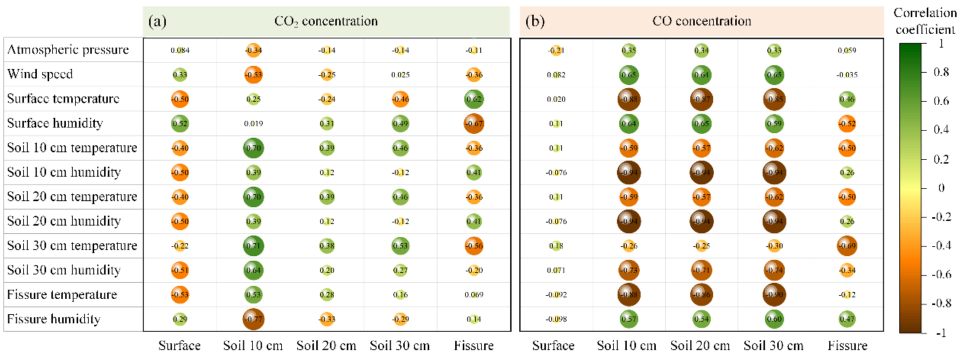

Fig.8. Correlation analysis of near-surface meteorological factors and CO_2, CO concentrations in different regions (a) CO_2 concentration; (b) CO concentration

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According to Fig. 8, meteorological factors near the surface have a certain influence on the CO_2 concentration in different regions. The average wind speed shows a significant negative correlation with the CO_2 concentration at a depth of 10 cm in the soil. The average air pressure also has a significant negative correlation with the CO_2 concentration at 10 cm, while exhibiting a strong positive correlation with the CO_2 concentration at 2 m, and a strong negative correlation with the CO_2 concentration in the fractures. Temperature shows a significant positive correlation with the CO_2 concentration in the fractures, but a strong negative correlation with the CO_2 concentrations at 2 m and at a depth of 10 cm in the soil. Humidity, in contrast to temperature, exhibits a significant negative correlation with the CO_2 concentration in the fractures, but a strong positive correlation with the CO_2 concentrations at 2 m, 10 cm, 20 cm, and 30 cm in the soil. According to Fig. 8, meteorological factors near the surface also have a certain impact on the CO concentration in different regions. The average wind speed shows a significant positive correlation with CO concentrations at 10 cm, 20 cm, and 30 cm in the soil, but a negative correlation with the CO concentration at 2 m. The average air pressure exhibits a significant positive correlation with CO concentrations at 10 cm, 20 cm, and 30 cm in the soil. Temperature shows a significant positive correlation with the CO concentration in the fractures, but a strong negative correlation with CO concentrations at 10 cm, 20 cm, and 30 cm in the soil. Humidity, in contrast to temperature, shows a significant negative correlation with the CO concentration in the fractures, but a strong positive correlation with CO concentrations at 10 cm, 20 cm, and 30 cm in the soil.

4.3. Analysis of time series data of spontaneous combustion gas concentration in different areas

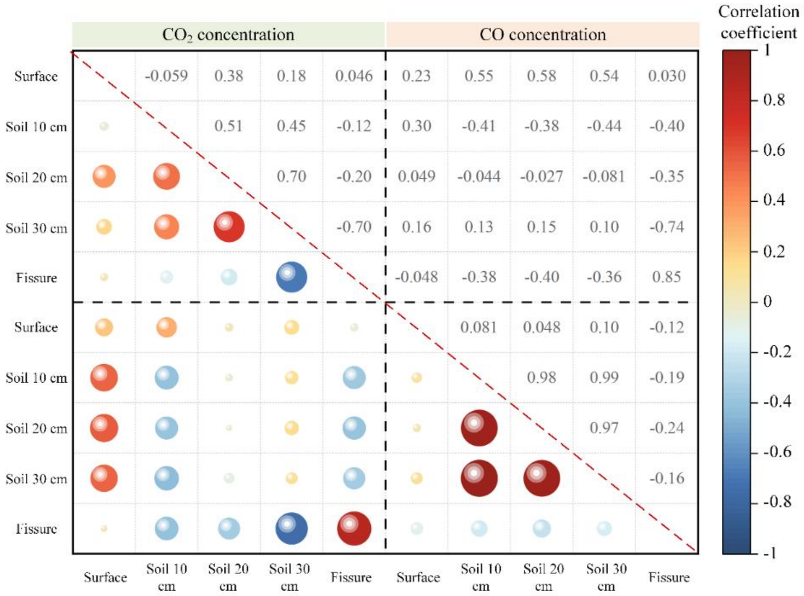

Fig.9. Correlation analysis of gas concentrations between different regions

Based on the data from Fig 9, the relationship between CO_2 and CO concentrations in different regions can be summarized as follows. In the near-surface region, there is a weak negative correlation between CO_2 and CO concentrations. In the shallow soil region, the CO_2 concentration at a depth of 10 cm shows a negative correlation with CO concentration. However, the correlation coefficients between CO_2 and CO concentrations at depths of 20 cm and 30 cm are very small. In the fracture region, there is a significant positive correlation between CO_2 and CO concentrations. In the near-surface region, there is a relatively strong positive correlation between CO_2 concentrations and CO_2 concentrations at a depth of 20 cm, as well as between CO_2 concentrations at depths of 10 cm to 30 cm. In the shallow soil region, CO_2 concentrations exhibit a negative correlation with both CO_2 and CO concentrations in the fracture region. These results indicate that in the near-surface meteorological factors, temperature and humidity have the most significant influence on CO_2 and CO concentrations in different regions. Average wind speed and atmospheric pressure also exert some impact on the concentrations in these regions. In the shallow soil region, the impact of meteorological factors on CO_2 and CO concentrations differs with depth, and as depth increases, the effect gradually diminishes. Moreover, there is a certain relationship between the CO_2 and CO concentrations in the shallow soil region and those in the fracture region. Therefore, the changes in gas concentrations in the shallow soil region can reflect the variation patterns in the fracture region's gas concentrations, which in turn may indicate the combustion state of coal fire areas. Combined with other detection results, this provides further evidence that the monitoring location lies within the combustion zone of a coalfield fire.

5. Conclusions

To investigate the combustion characteristics in coal fire areas, this study utilized a multi-region spontaneous combustion gas product time-series monitoring system. The system collected data on near-surface meteorological factors (such as temperature, humidity, wind speed, and atmospheric pressure), as well as variations in spontaneous combustion gas concentrations. It also monitored the physical properties and gas concentration changes in different soil layers of shallow soil, along with the thermal and physical characteristics and gas concentration changes in fissure areas. The key findings are as follows:

- In the surface space, shallow soil, and fissure areas, the concentration of CO_2 in the spontaneous combustion gas products consistently exceeds that of CO. Gas concentrations in the fissure areas are significantly higher than those in shallow soil and surface space.
- The emission trends of spontaneous combustion gases in shallow soil generally align with those in the fissure areas. The low-frequency data from both shallow soil and fissure areas exhibit similar continuous trends. However, due to the greater influence of meteorological factors in the fissure areas, there is a certain degree of lag in the data from these regions. Simultaneously, high-frequency data from both areas show similar fluctuating trends.
- Among the near-surface meteorological factors, temperature and humidity have the most significant impact on the concentrations of CO_2 and CO in different areas. Wind speed and atmospheric pressure have a relatively weaker effect on concentration changes. There is a discernible relationship between the spontaneous combustion gas concentrations in shallow soil and fissure areas. Consequently, changes in gas concentrations in shallow soil can reflect the variation characteristics of gas concentrations in fissure areas, thereby providing insights into the combustion state of the coal fire area.

Acknowledgements

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References

[1] **Shaofeng W., Xibing L., Deming W.,** 2016
Mining-induced void distribution and application in the hydro-thermal investigation and control of an underground coal fire: A case study, Process Saf Environ, 102, 734-756

[2] **Jinchang D., Shaokun G., Haining Q., Fubao Z., Bobo S.**, 2021
Underground coal fire emission of spontaneous combustion, Sandaoba coalfield in Xinjiang, China: Investigation and analysis, Science of the Total Environment, 777

[3] **Dindarloo S., Hood M.M., Bagherieh A., Hower J.C.,** 2015
A statistical assessment of carbon monoxide emissions from the Truman Shepherd coal fire, Floyd County, Kentucky, Int J Coal Geol, 144, 88-97

[4] **Luhar A.K., Emmerson K.M., Reisen F., Williamson G.J., Cope M.E.** 2020
Modelling smoke distribution in the vicinity of a large and prolonged fire from an open-cut coal mine, Atmos Environ, 229

[5] **Riyas M.J., Syed T., Kumar H., Kuenzer C.**, 2021
Detecting and Analyzing the Evolution of Subsidence Due to Coal Fires in Jharia Coalfield, India Using Sentinel-1 SAR Data, Remote Sens-Basel, 13

[6] **Haiyan W., Xiyang F., Feng D., Bo T., Lang Z., Yanchuan L., Changfu X.**, 2021
Three-dimensional distribution and oxidation degree analysis of coal gangue dump fire area: A case study, Science of the Total Environment, 772

[7] **Bin D., Yuntao L., Fuchao T.,** 2021
Detecting concealed fire sources in coalfield fires: An application study, Fire Safety J, 121

[8] **Kus J.**, 2017
Impact of underground coal fire on coal petrographic properties of high volatile bituminous coals: A case study from coal fire zone No. 3.2 in the Wuda Coalfield, Inner Mongolia Autonomous Region, North China, Int J Coal Geol, 171, 185-211

[9] **Melody S.M., Johnston F.H.,** 2015
Coal mine fires and human health: What do we know?, Int J Coal Geol, 152, 1-14

[10] **Jun L., Pengbin F., Qiren Z., Yandong M., Cheng Y.,** 2018
A lab-scale experiment on low-temperature coal oxidation in context of underground coal fires, Appl Therm Eng, 141, 333-338

[11] **Zhang J., Guan H., Cao D.,** 2008
Underground coal fires in China: origin, detection, fire-fighting, and prevention, China Coal Industry Publishing House

[12] **Civeira M.S., Pinheiro R.N., Gredilla A., Fernandez Ortiz de Vallejuelo S., Oliveira M.L.S., Ramos C.G., Taffarel S.R., Kautzmann R.M., Madariaga J.M., Silva L.F.O.,** 2016
The properties of the nano-minerals and hazardous elements: Potential environmental impacts of Brazilian coal waste fire, Science of the Total Environment, 544, 892-900

[13] **O'Keefe J.M.K., Henke K.R., Hower J.C., Engle M.A., Stracher G.B., Stucker J.D., Drew J.W., Staggs W.D., Murray T.M., Hammond III M.L., Adkins K.D., Mullins B.J., Lemley E.W.,** 2010
CO_2, CO, and Hg emissions from the Truman Shepherd and Ruth Mullins coal fires, eastern Kentucky, USA, Science of the Total Environment, 408, 1628-1633

[14] **Zhenlu S., Deming W., Yanming W., Xiaoxing Z.,** 2014
Theory and application of magnetic and self-potential methods in the detection of the Heshituoluogai coal fire, China, J Appl Geophys, 104, 64-74

[15] **Zhijie W., Xiao W., Lianjun C., Guan L.,** 2017
Size Effect on Acoustic Emission Characteristics of Coal-Rock Damage Evolution, Adv Mater Sci Eng.

[16] **Biao K., Zenghua L., Yongliang Y., Zhen L., Daocheng Y.,** 2017
A review on the mechanism, risk evaluation, and prevention of coal spontaneous combustion in China, Environ Sci Pollut R, 24, 23453-23470

[17] **Liming Y., Smith A.C.,** 2011
CO and CO_2 emissions from spontaneous heating of coal under different ventilation rates, Int J Coal Geol, 88, 24-30

[18] **Litschke T., Wiegand J., Schloemer S., Gielisch H.,** 2008
Detailed mapping of coal fires in combination with in-situ gas flow measurements to estimate mass flow balance and fire development

[19] **Taku Ide S., Orr Jr. F.M.,** 2011
Comparison of methods to estimate the rate of CO_2 emissions and coal consumption from a coal fire near Durango, CO, Int J Coal Geol, 86, 95-107

[20] **Kuenzer C., Jianzhong Z., Tetzlaff A., van Dijk P., Voigt S., Mehl H., Wagner W.,** 2007
Uncontrolled coal fires and their environmental impacts: Investigating two arid mining regions in north-central China, Applied Geography, 27, 42-62

[21] **Haiyan W., Cheng F., Lei C., Xiao C., Junzhao Z., Hongbin Z.,** 2024
Research on early identification of burning status in a fire area in Xinjiang based on data-driven. Case Studies in Thermal Engineering, 104685

[22] **Haiyan W., Cheng F., Jinglei L., Yanwei Z., Xingdun S., Shiyue X.,** 2023
Dynamic characteristics of near-surface spontaneous combustion gas flux and its response to meteorological and soil factors in coal fire area. Environmental Research, 217, 114817

[23] **Wan-Ju C., Yuan-Chien L.,** 2021
Investigation of the main PM2. 5 sources and diffusion patterns and corresponding meteorological conditions by the wavelet analysis approach. Atmospheric Pollution Research, 12, 101222