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RESEARCH

Effect of periodic wide atmospheric pressure change on CO emission in closed goaf

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Abstract

Atmospheric pressure fluctuation is one of the most important factors affecting the climate environment and gas emission in the fire area. To obtain the influence rule of the surface atmospheric pressure change on the gas sampling and abnormal emission in the mine closed goaf, the No. 1 coal mine in Dananhu was taken as the research object. Using Fourier transform and Fisher harmonic analysis and other statistical methods, the influence of the periodic variation of atmospheric pressure on the gas leakage and outflow in the closed goaf was studied. The results showed that there were three atmospheric pressure periods of 15.2 d, 1 d and 182.2 d, and the probability was greater than 95%. The time period with the highest number of atmospheric pressure peaks was 7:00–8:00, which accounted for 20.2% of total occurrence number in a day. And the time periods with the highest number of atmospheric pressure trough were 2:00, 15:00 and 16:00, accounting for 27.4%. The peak-to-trough transition time was mainly concentrated around 6 h, and the diurnal variation curve of atmospheric pressure was mainly bimodal. The atmospheric pressure change rate was mostly concentrated in 10–50 Pa/h. It was determined that the distance that the gas sampling pipe was pre-laid into the inner side of the closed wall should be greater than 44.4 m, and the CO concentration and atmospheric pressure in the closed goaf were both periodic and negative with atmospheric pressure. The research results have important guiding significance for the monitoring, early warning and environmental protection of the goaf.

Keywords Atmospheric pressure · Periodic variation · Closed goaf · CO emission · Coal mine

1 Introduction

Mine fires have the characteristics of long-term and dynamic changes, and will induce gas (dust) explosions and cause more secondary disasters. CO is the most commonly used symbol gas to predict the coal spontaneous combustion (Więckowski et al. 2020; Adamus et al. 2011; Charrière et al. 2010; Shao et al. 2020). However, in addition to the coal spontaneous combustion, there is also a phenomenon of CO emission in the normal temperature environment, which seriously restricts the accuracy and scientificity of coal spontaneous combustion accident prediction (Deng et al. 2021; Shao et al. 2018; Wang et al. 2021). Under normal temperature conditions, the reasons for the CO emission in the goaf are divided into internal reasons and external reasons. The internal reasons include: (1) Factors such as negative pressure drainage and periodic air pressure lead to aggravation of air leakage and oxygen supply in the goaf, resulting in accelerated oxidation reaction of the residual coal and the generation of CO (Zheng et al. 2021). (2) Factors such as coal and rock fragmentation, friction and impact in the goaf lead to a sudden increase in CO (Liu et al. 2013). (3) The residual coal in the goaf is slowly oxidized at room temperature, resulting in an increase of CO in the goaf (Tang 2015). External reasons include: (1) Gas drainage, nitrogen injection, periodic pressure and other factors have caused

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disturbances and changes in the ventilation system in the goaf, resulting in abnormal CO concentration in the air leakage collection (Zheng et al. 2021). (2) Changes in the resistance of the surrounding rock of the roadway, periodic changes in air pressure and temperature from morning to night, and sudden changes in the ground environment can damage the external ventilation system of the goaf, resulting in abnormal CO concentration in the air leakage collection (Zhu et al. 2017). It is particularly important to exclude the abnormal CO emission information caused by the periodic change of atmospheric pressure, and to obtain the information of CO emission caused by coal spontaneous combustion from the abundant monitoring information.

In recent years, many casualties have occurred due to excessive CO in coal mines. On September 27, 2020, a carbon monoxide excess accident occurred at Songzao mine in Chongqing, China. An abnormal emission of CO occurred in Yangdong mine, Hebei Province, China. Finally, it was found that there was no abnormal phenomenon of coal seam spontaneous combustion at the field, but the CO concentration at the field was as high as 3340 ppm, which seriously endangered normal safe production activities. This may be due to the fact that the periodic changes of surface atmospheric pressure and temperature cause gas migration in mine closed area, causing the gas to exhibit "expansion–contraction" periodic fluctuations, which is also known as the phenomenon of "breathing"(Shen 2016).

Many scholars focus on the influence of surface atmospheric pressure and temperature changes on the mine state. Lolon et al. (2017) believed that in the process of longwall mining, the fluctuation of atmospheric pressure would destroy the pressure balance between the goaf and the ventilation work area, resulting in the phenomenon of goaf breathing. And through the simulation, it was found that the change of atmospheric pressure directly affected the formation of air outlet, air inlet and gas explosion area in goaf. Bin et al. (2019) took Zhengli coal mine 14-1103 closed goaf as the research object, and analyzed the variation law of air pressure inside and outside the closed goaf and the gas volume fraction outside the closed goaf under different atmospheric parameters. It was obtained that the "breathing" phenomenon in the closed goaf was the result of the combined effect of the surface atmospheric parameters, the air flow parameters of the wells, the characteristics of the wells and the gas state parameters in the goaf. Wu et al. (2022) established a multi-parameter mathematical model of gas emission in goaf by continuously monitoring the concentration of CH_4 and monitoring and analyzing the atmospheric pressure on the ground. The results showed that the model can accurately reflect the influence of goaf atmospheric pressure on gas emission. Yang et al. (2018) adopted pressure-equalizing fire-fighting technology such as plugging the air leakage channel, adjusting the ventilation direction to change the pressure difference, and injecting nitrogen into the goaf for fire-fighting measures to prevent spontaneous combustion in large areas of old gobs in Wangtai mine. Yu et al. (2013) proposed a quantitative analysis method for optimal ventilation energy distribution coupled with atmospheric pressure fluctuations, which prevented harmful gas leakage in goaf.

The above scholars found from field tests that atmospheric pressure had a significant impact on the change of mine pressure and the generation and migration of gas concentration in the fire zone, and discovered the phenomenon of "breathing cycle". However, the influence mechanism of atmospheric pressure change on the fire area pressure and gas migration is not fully understood, especially the problems of fire area prediction and gas sampling under the action of periodic wide amplitude or abrupt fluctuation of atmospheric pressure remains to be further studied. Therefore, the author takes the Dananhu No. 1 mine in Xinjiang, China as the research object, and analyzes the mathematical characteristics such as the periodicity and trend of atmospheric pressure and temperature, as well as influence rule of CO concentration in closed area by observing the atmospheric pressure, temperature and gas concentration data in closed area from 2016 to 2017. The research results have important guiding significance for monitoring and early warning of fire areas and improving the management level of fire areas and environmental protection.

2 Data and method

2.1 Data acquisition source

The atmospheric pressure and temperature data are from the National Meteorological Information Center (http://data.cma.cn/), and the measurement point information of Hami weather station in Xinjiang is shown in Table 1 and Fig. 1. The data collection time was from January 1, 2016 to December 31, 2017. The data collection interval was 1 h, the atmospheric pressure resolution was 10 Pa, and the temperature resolution was 0.1 °C.

Table 1 Geographical location information of measuring points of Hami weather station

Location	Station number	Latitude (°)	Longitude (°)	Observation field altitude (m)
Hami, Xinjiang	52203	42.82	93.52	739

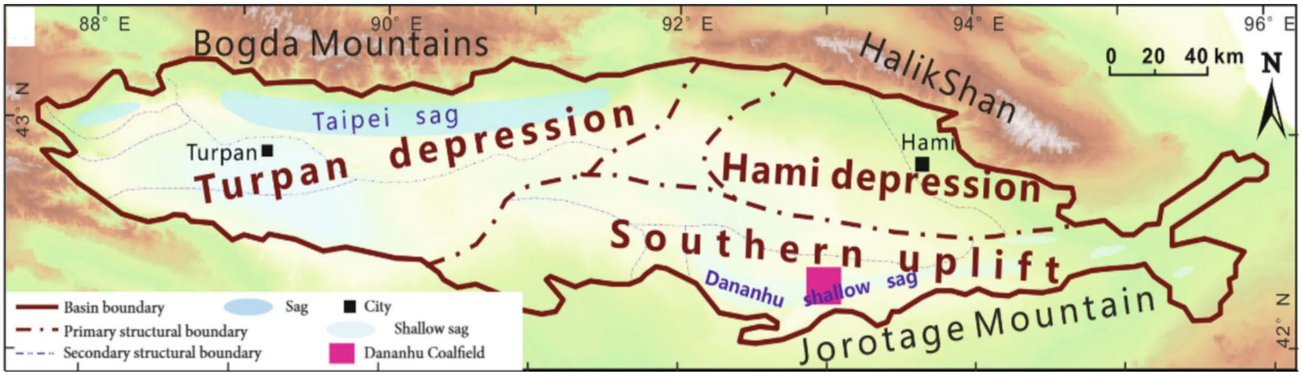


Fig. 1 Location of Hami weather station and Dananhu mine

2.2 Methods

2.2.1 Standard Fourier transform

Since the standard Fourier transform only has the ability to analyze locally in the frequency domain but does not exist the ability in the time domain, thus, the short-time Fourier transform introduced by Dennis Gabor in 1946 is used to analyze the atmospheric pressure and temperature spectrum in the paper. The method is illustrated in Eq. (1) (Atakishiyev and Klimyk 2018).

$$S(n,p) = \int_R f(t)g^*(\overline{n} - p)e^{-jnt}\mathrm{d}t \tag{1}$$

where * denotes complex conjugate, $g(\overline{n},p)$ is a function with compact support, and $f(t)$ is the signal entering the analysis. In this transformation, e^{jnt} plays the role of frequency limit, $g(\overline{n},p)$ plays the role of time limit. As time τ changes, the "time window" determined by $g(\overline{n},p)$ moves on the t-axis and $f(t)$ is "gradually" analyzed. Therefore, $g(\overline{n},p)$ is often called a window function, $S(n,p)$ roughly reflects the relative content of $f(t)$ at time τ with a frequency n of the "signal component".

2.2.2 Theoretical analysis of influence of atmospheric pressure on air leakage in closed fire area

Taking the closed area of Dananhu mine 1304 working face as the research object, the influence of the ground atmospheric pressure change on the air leakage law in mine closed area is studied. The closed area is a U-shaped working face (Fig. 2), the roadway section is rectangular (4.5 m × 3 m), the thickness of the coal seam H is 3 m, and the working face is fully mined at one time. The surrounding rock around the sealing wall is complete, and masonry is used to build the closed wall with a thickness of 1 m. The permeability coefficient of the closed wall is 0.0012, and the wind resistance value R is 583.33 (Song 2002). The length of the roadway in closed area is: $l_1 = 120$ m, $l_2 = 450$ m, $l_3 = 200$ m, $l_4 = 4.5$ m.

It is assumed that the air leakage in the mine closed area is only affected by the change of atmospheric pressure under the action of pressure equalization measures, the air leakage between closed area and external environment is laminar flow, and the initial air leakage direction is from the external environment to the closed area. The air leakage quantity is calculated based on Eq. (2).

$$Q = \sqrt{\frac{1}{R}\left(p_{\mathrm{out}} - p_{\mathrm{in}}\right)} \tag{2}$$

where Q is the air leakage volume, m^3/s, p_{out} is the atmospheric pressure outside the closed wall, Pa, p_{in} is the air pressure inside the airtight wall, Pa, R is the air resistance of the closed wall, N s/m^5.

With the change of air quality in closed area, the gas pressure in closed area reaches p_{in} from the initial value p_{init} after time t, then the change in air leakage during this period is calculated based on Eq. (3).

$$\mathrm{d}Q = \frac{Q\mathrm{d}T}{V}p_{\mathrm{init}} = \frac{\sqrt{\left(p_{\mathrm{out}} - p_{\mathrm{in}}\right)\frac{1}{R}}}{V}p_{\mathrm{init}}\mathrm{d}T \tag{3}$$

It is assumed that the surface atmospheric pressure changes periodically with time, then Eq. (4) can be obtained.

$$p_{\mathrm{out}} = p_{\mathrm{aver}} - \Delta p_{\mathrm{out}} \cos\left(2\pi\frac{T}{\Delta T}\right) \tag{4}$$

where V is the volume of mine closed area, m^3, p_{aver} is the average pressure, Pa, ΔT is the cycle period, s, Δp_{out} is the pressure change amplitude, Pa. Equation (3) can be converted into Eq. (5):

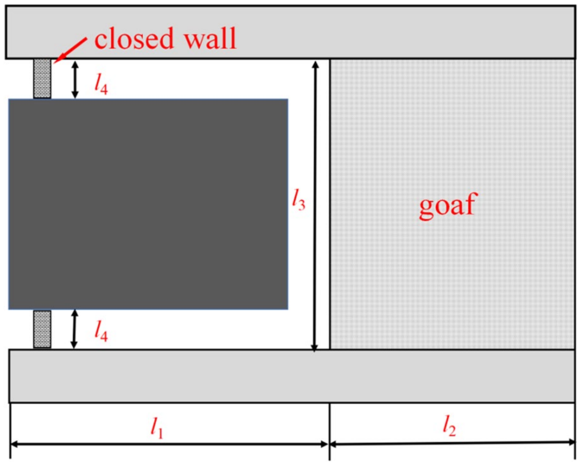


Fig. 2 Schematic diagram of closed area of mine

$$dQ = \frac{1}{R}\left[\Delta p_{out}\frac{2\pi}{\Delta T}\sin\left(2\pi\frac{T}{\Delta T}\right) - \frac{Qp_{init}}{V}\right]dT \tag{5}$$

By solving Eq. (5), it can be known that the maximum air leakage caused by the change of surface atmospheric pressure within a single period is calculated based on Eq. (6) (Zhou and Wu 1996).

$$Q_{max} = \frac{\frac{2\pi\Delta p_{out}}{\Delta TR}}{\left[\left(\frac{p_{init}}{RV}\right)^2 + \left(\frac{2\pi}{\Delta T}\right)^2\right]^{\frac{1}{2}}} \tag{6}$$

From the analysis of Eq. (6), it can be seen that the air leakage in closed area caused by the change of the surface atmospheric pressure is proportional to the change rate of the atmospheric pressure, but has nothing to do with the absolute value of the atmospheric pressure change. In other words, when the atmospheric pressure increases rapidly, the air leakage from external environment to closed area is large. When the atmospheric pressure drops rapidly, the gas in closed area expands rapidly, and the amount of gas emission of closed area increases. At this time, gas sampling and analysis can better reflect the gas state in closed area. The longest distance that external environment air leaks into closed area can be obtained by Eq. (7).

$$L = \frac{Q_{max}}{nA} \tag{7}$$

where L is the longest distance that air leaks into closed area, m, n is the number of closed roadways, A is the section area of the closed roadway, m^2.

2.2.3 Theoretical analysis of the influence of atmospheric pressure periodic change on CO emission in closed area

In order to study the influence of atmospheric pressure changes outside closed area on the CO emission in closed area, the following basic assumptions are made in this paper.

(1) CO is gushing out in closed area, and CO can be quickly and evenly mixed with the original gas.
(2) The environment temperature is normal and constant, the downhole gas is an ideal gas, and there is no chemical reaction between the components of the gas.
(3) The resistance between the closed area and external environment is R_S, and the wind resistance of the roadway outside the closed area is ignored.
(4) The total volume of the closed area is constant.
(5) The surrounding environment of the closed area has no adsorption of gas.
(6) The gas in the closed area is not compressible.
(7) The concentration of CO emission is 100%, and the concentration after mixing with other gases is C.

Then the change of CO concentration in the closed area can be expressed in Eq. (8).

$$dC = \frac{dt}{V}\left(q_{in} - q_{out}C\right) \tag{8}$$

where C is the CO concentration in the closed area, %, t is time, s, q_{in} is the CO emission amount in the closed area, m^3/s, q_{out} is the mixed gas flow rate out of the closed area, m^3/s.

If the pressure in the closed area remains unchanged, the pressure outside the closed area changes periodically with time, which satisfies Eq. (8). The pressure inside the closed wall is greater than that of the outside ($p_{in} > p_{out}$). In other words, it is in the gas outlet state. The initial conditions are $t=0$, $C=C_0$, and Eq. (9) can be obtained as following.

$$q_{out} = \frac{1}{R_S}\left(p_0 + \Delta p_{out}\cos\left(2\pi\frac{t}{\Delta t}\right) - p_{in}\right) \tag{9}$$

Then Eq. (10) can be obtained.

$$dC = \frac{dt}{V}\left(q_{in} - \frac{1}{R_S}\left(p_0 + \Delta p_{out}\cos\left(2\pi\frac{t}{\Delta t}\right) - p_{in}\right)C\right) \tag{10}$$

After scoring, Eq. (11) can be obtained.

$$C = \exp\left[\frac{\left(q_{\text{in}} - p_{\text{in}} - \frac{p_0}{R_S}\right)t - \frac{\Delta p_{\text{out}}\cdot\Delta t}{2\pi\cdot R_S}\cdot\sin\left(2\pi\frac{t}{\Delta t}\right) + V\ln C_0}{V}\right] \tag{11}$$

It can be seen from Eq. (11) that when the gas pressure outside the closed area changes periodically, the CO concentration in the closed area also changes periodically.

3 Results and discussion

3.1 The annual variation of atmospheric pressure

There are 252 missing data in the Hami atmospheric pressure hourly data, with a completeness rate of more than 99.6%. Since the missing data is single-point data, the missing data is filled with the linear interpolation method, and then the hourly change curve of atmospheric pressure in the Dananhu mine is drawn from January 1, 2016 to December 31, 2017. And first-order Fourier series fitting is performed to obtain the Fourier series fitting coefficients and fitting curves, which are shown in Table 2 and Fig. 3a. The analysis indicates that the first-order Fourier series fitting can well describe the annual variation of atmospheric pressure. The annual period of atmospheric pressure is 357.78 d, which is less different from 360 d per year. The average atmospheric pressure in Hami area is 930.8 hPa, the annual periodic fluctuation amplitude is 10.8 hPa, and the standard deviation is 9.2 hPa. Therefore, the hourly change in atmospheric pressure data fluctuates greatly, and the data is very scattered. Due to the violent hourly fluctuation of atmospheric pressure data, the sum variance and mean square error in the fitting process are large, and it is difficult to analyze the daily fluctuation law of atmospheric pressure by fitting equation (Lagny 2014).

By analyzing Table 2 and Fig. 3a, it can be seen that the annual temperature period in Hami area is 364.83 d. The average temperature in Hami area is 12.2 °C, the annual periodic fluctuation amplitude is 18.31 °C, and the standard deviation is 14.18988. Thus, the hourly temperature fluctuation is small, and the data distribution is more concentrated than that of the atmospheric pressure change.

Pearson correlation analysis is performed on Hami's atmospheric pressure and temperature fluctuation curves using SPSS software (see Table 3). The Pearson correlation coefficient of Hami's atmospheric pressure and temperature is − 0.432, and the hourly change data of atmospheric pressure and temperature are significantly correlated at the 0.01 level. However, the Pearson correlation coefficient is small, indicating that the linear correlation between atmospheric pressure and temperature is poor.

3.2 Analysis on the law of diurnal periodic variation of atmospheric pressure

In order to accurately analyze the diurnal characteristics of the annual hourly variation data of atmosphere and temperature, it is necessary to eliminate the annual trend term of the original data, and obtain discrete points of atmospheric pressure and temperature without the annual period data (Fig. 3b, Fig. 4b). The discrete data periods of atmospheric pressure after eliminating the annual trend term are mainly 15.2 d, 1 d and 182.2 d. Fisher's harmonic analysis significance test is used to make judgment. Since there is no case with period number 3 in Fisher's critical value table, indirect analysis is performed by logical means. Take the significant level as 0.05, because g0.05 (1000,3) is greater than g0.05 (1000,5), so when the spectral density is less than g0.05 (1000,5), it means that the spectral density is also less than g0.05(1000,3). The spectral density is calculated by Fourier transform, the Fisher critical value of harmonic analysis is found, and the significance test is performed on its period, which is shown in Table 4. The analysis shows that the probability of atmospheric pressure with periods of 15.2 d, 1 d and 182.2 d is greater than 95%. The main frequency of atmospheric pressure data changes is near 0, and the daily fluctuation period (frequency is 0.0417 Hz) amplitude is 0.1050, indicating that there is a diurnal periodicity in atmospheric pressure changes and it is significant. Similarly, it is obtained that the temperature only has a period of 1 d, and the probability is greater than 95% to be judged by the significance test of Fisher harmonic analysis.

Table 2 Fourier series coefficient fitting

Data type	Fit coefficient				Sum variance	Sum of squared deviations	Adjusted sum of squared deviations	Mean square error
	a_0	a_1	b_1	w				
Atmospheric pressure	930.8	10.8	− 0.91	0.007217	4.4543×10^5	0.6934	0.6934	5.077
Temperature	11.92	− 18.31	1.363	0.0007158	6.134×10^5	0.8238	0.8238	5.9574

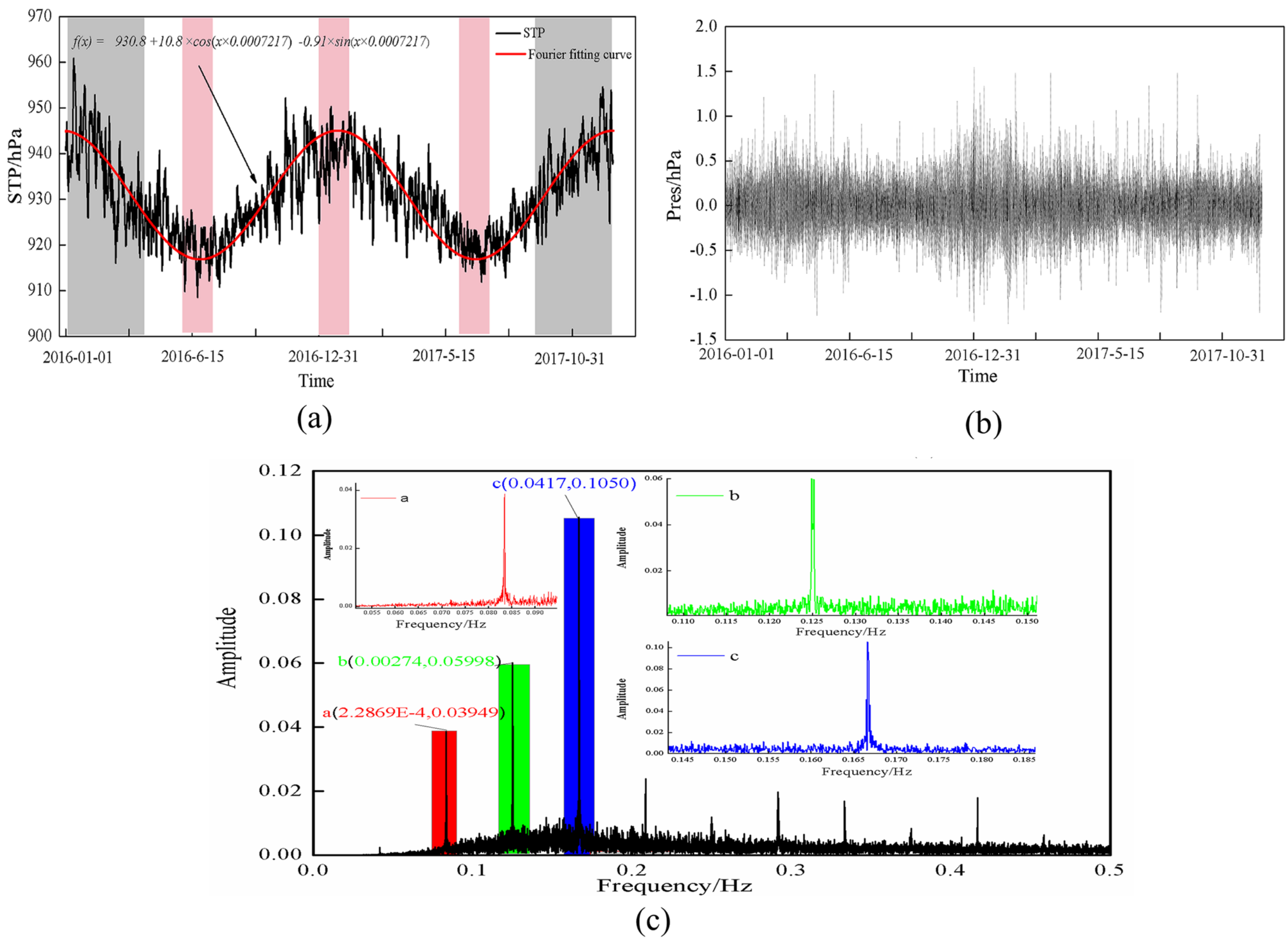


Fig. 3 Atmospheric cycle change analysis **a** Atmospheric pressure 1st order Fourier series fitting curve; **b** Distribution map of discrete points of atmospheric pressure elimination annual trend; **c** Atmospheric pressure spectrum analysis

Table 3 Pearson correlation analysis of atmospheric pressure and temperature

Correlation			
		VAR00001	VAR00002
VAR00001	Pearson correlation coefficient	1	−0.432**
	Sig. (two-tailed)		0.000
	cases number	17,288	17,288
VAR00002	Pearson correlation coefficient	−0.432**	1
	Sig. (two-tailed)	0.000	
	cases number	17,288	17,288

**Is at the 0.01 level (two-tailed), and the correlation is significant

3.3 Analysis of atmospheric pressure peak trough distribution and change rate

The time period with the highest number of atmospheric pressure peaks is 7:00–8:00, which accounts for 20.2% of the total occurrence number in a day. Secondly, the time periods with the highest number of atmospheric pressure troughs are 2:00, 15:00 and 16:00, accounting for 27.4%.

Through the statistical analysis of the two-year hourly data of atmospheric pressure, a histogram of the peak and trough values of atmospheric pressure changes is drawn, which is presented in Fig. 5a. The time period with the highest number of atmospheric pressure troughs are number of atmospheric pressure peaks is 7:00–8:00, which accounts for 20.2% of the total occurrence number in a day. Secondly, the time periods with the highest number of atmospheric pressure troughs are 2:00, 15:00 and 16:00, accounting for 27.4%. Matlab is used to perform statistical analysis on the atmospheric pressure change data in Fig. 1, and different amplitude intensities statistical histogram and peak-to-trough transition time statistical histogram are plotted (see Figs. 5b, c). Most of the amplitudes in the hourly data fluctuation of atmospheric pressure are within 1000 Pa, of which 500–1000 Pa is the most, and very few amplitudes exceed 1000 Pa. In addition, the transition time between the peak

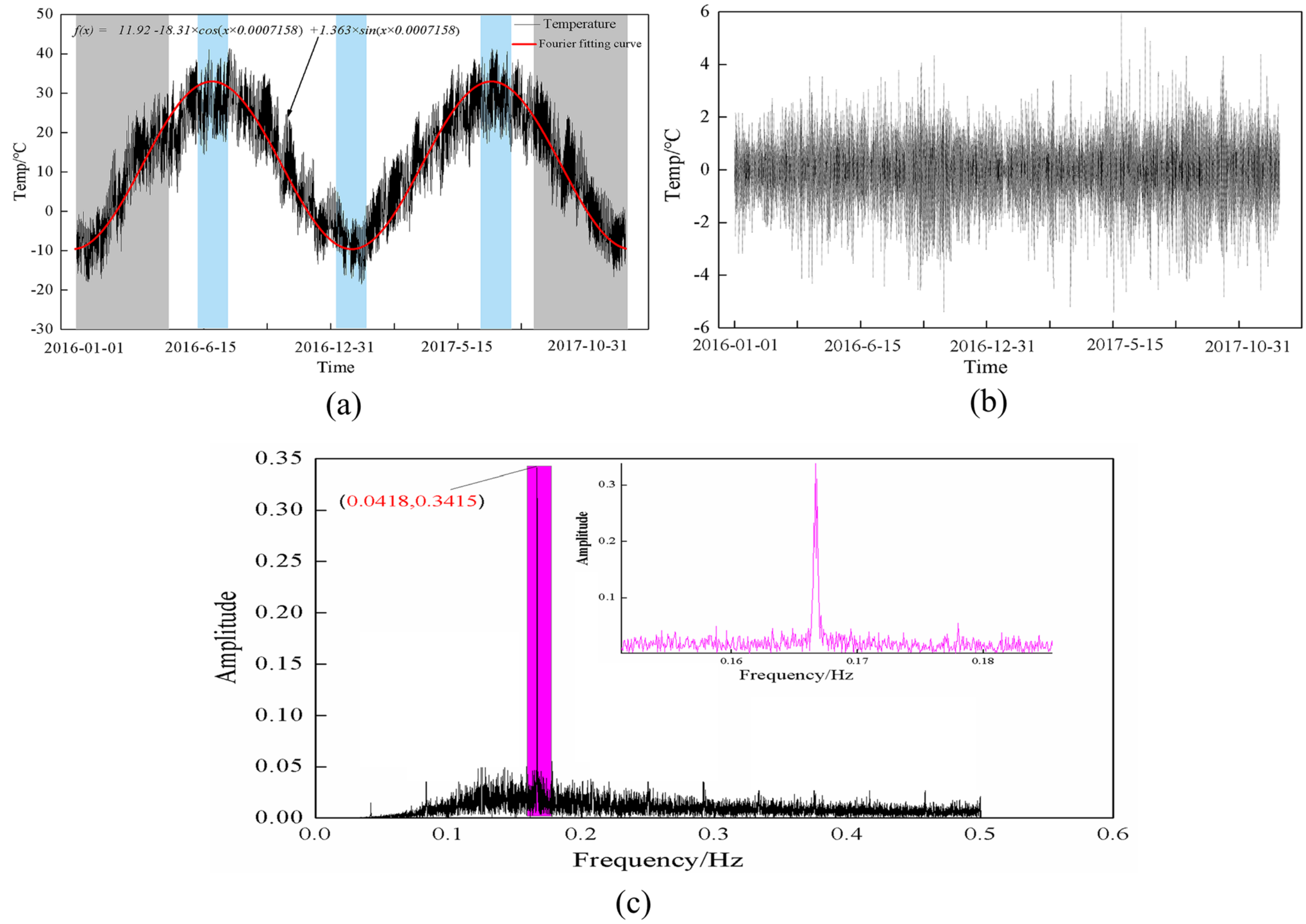


Fig. 4 Temperature cycle change analysis **a** Temperature 1st order Fourier series fitting curve; **b** Distribution map of discrete points of temperature elimination annual trend; **c** Temperature spectrum analysis

Table 4 Fisher test for significance analysis

Period (d)	Spectral density	Fisher critical value
15.2	0.0267	$g_{0.05}(1000,1)=0.00984$
1	0.0263	$g_{0.05}(1000,2)=0.00790$
182.2	0.0255	$g_{0.05}(1000,5)=0.00790$

and trough of atmospheric pressure is mainly concentrated in 2–12 h, accounting for 70.9% of the total, and the conversion time of 1 h accounts for 28.4. Because the time is very short, this may be the noise in the process of atmospheric pressure fluctuation. Combined with the diurnal variation of atmospheric pressure, the hourly fluctuation of atmospheric pressure has diurnal periodicity, and the peak-to-trough transition time is mainly concentrated around 6 h, so the curve shape of the diurnal variation of atmospheric pressure is mainly bimodal. In addition, as shown in Fig. 5d, the atmospheric pressure change rate is mostly concentrated in range of 10 to 50 Pa/h, and a few of them are greater than 100 Pa/h. This is mainly due to the influence of abnormal weather such as cold wave outbreak and thunderstorm process (Lei et al. 2020). For example, a rainstorm occurred at 20:00 on August 1, 2017 in Hami (http://data.cma.cn/).

4 Field application

4.1 Basic situation

The Dananhu No. 1 Mine of Shenhua Group is located about 84 km south of Hami City, Xinjiang Uygur Autonomous Region. The main coal-bearing strata is the Xishanyao Group of Jurassic, which contains 29 coal-bearing layers (groups). The content of silk char in the coal rock composition of each coal seam is relatively high. The coals are mostly low-metamorphic lignite and long-flame coal with thin overburden layers, and they are easily weathered. The structure of the mine field is relatively simple, it is a wide and gentle fold that strikes near east–west, and there are no faults and no influence

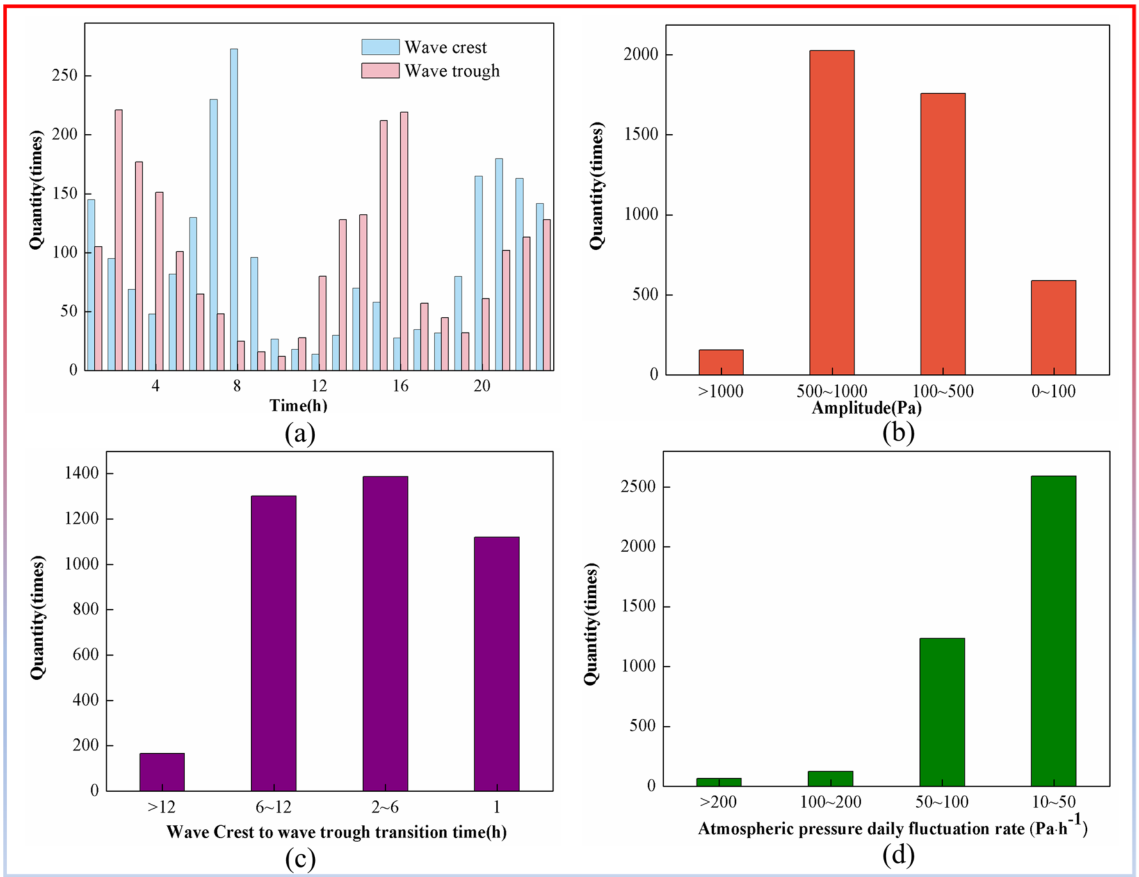


Fig. 5 Statistics of atmospheric pressure peaks and troughs: **a** Distribution period of atmospheric pressure peaks and troughs; **b** Quantitative statistics of different amplitude intensities; **c** The statistics of peak and trough transition time; **d** Statistics of daily fluctuation rate of atmospheric pressure

of magmatic rocks. The attitude of stratum is gentle, the dip angle of the stratum is generally 3° to 13°, and the stratum in some sections is nearly horizontal. The mining depth is about 250 m below the ground, the coal dust is explosive, the spontaneous combustion tendency grade is Class I, and the shortest spontaneous combustion ignition period is 37 days (Chang 2017). In recent years, during the coal mining operation of Dananhu mine, it is found that the phenomenon of CO exceeding the limit often occurs in the working space. According to the CO monitoring data of the 1304 working face during the mining process of Dananhu mine, the source of the excessive CO is carefully analyzed and studied.

4.2 Analysis on the change law of air leakage in closed area

Taking the conditions of the closed area in Fig. 2 as the research object, using the atmospheric pressure data in Fig. 3a and Eq. (6), the influence of the ground atmospheric pressure change on the maximum air leakage in the closed area under the action of no mechanical wind pressure is analyzed. The calculation results are depicted in Fig. 6.

As shown in Fig. 6, the direction of air leakage between closed area and external environment is affected by the atmospheric pressure and presents a positive and negative change from time to time. Even when the sealing quality of the closed wall is good, the air volume exchange between closed area and external environment is still large, up to 900 m^3/h. If the air leakage direction is from external environment to closed area, according to Eq. (7), it can be calculated that the minimum distance that the air leakage enters closed area is 44.4 m. Therefore, if the distance between the gas sampling pipe and the inner side of the closed wall is less than 44.4 m, the gas sampling result may be affected by air leakage and cannot truly reflect the gas composition in closed area.

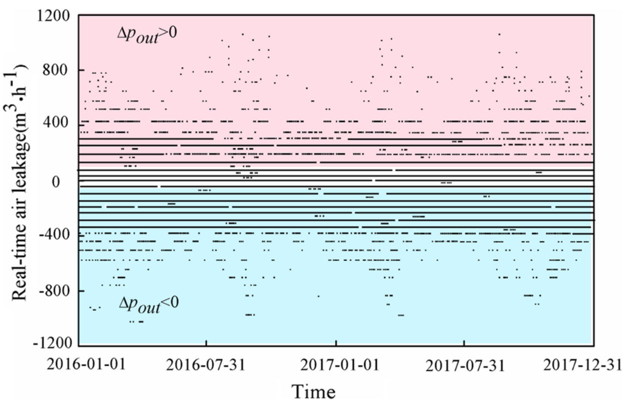


Fig. 6 Scatter distribution of real-time air leakage between closed area and external environment

4.3 Field monitoring data analysis

According to the above analysis results, the length of the sampling pipe pre-laid into the inner side of the closed wall of the 1304 working face is greater than 44.4 m. From December 22, 2016 to January 23, 2017, and from February 23, 2017 to March 23, 2017, the CO concentration and surface atmospheric pressure in the goaf are continuously monitored hour by hour. As shown in Fig. 7 and 8, when the surface atmospheric pressure increases, the CO concentration in the goaf decreases. On the contrary, when the surface atmospheric pressure decreases, the CO concentration increases. This is mainly because surface atmospheric pressure is one of the main influencing factors on the change of underground atmospheric pressure, and the trend of the two is similar. When the surface atmospheric pressure decreases, the absolute pressure of the tunnel airflow also decreases. When the atmospheric pressure sharply decreases, the absolute pressure of the tunnel airflow also decreases rapidly. The underground atmospheric pressure and surface atmospheric pressure show monotonic increasing changes or decrement, Periodic changes in atmospheric pressure can cause similar trends in closed goaf.

Therefore, when the surface atmospheric pressure increases, the absolute static pressure of the working face increases rapidly, while the average absolute pressure of the goaf does not change. Therefore, the emission of CO from the goaf to the working face is reduced. Similarly, when the atmospheric pressure decreases, the emission

Fig. 7 Variation trends of atmospheric pressure and CO concentration from December 22, 2016 to January 23, 2017

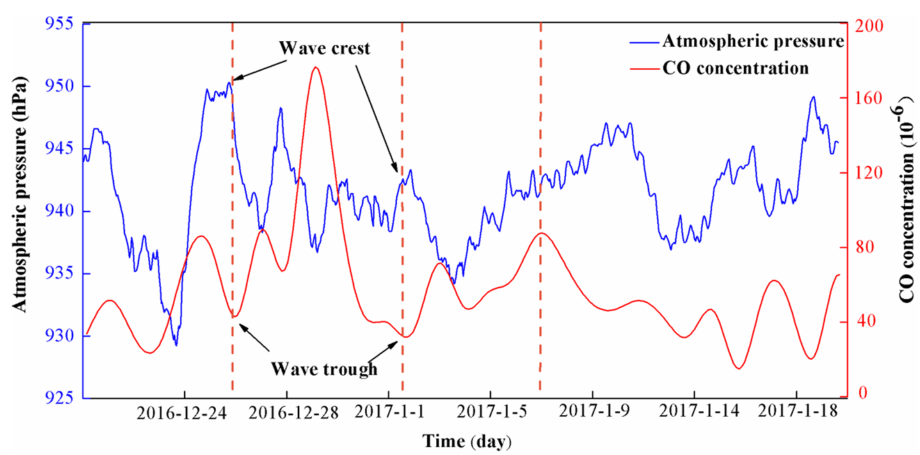
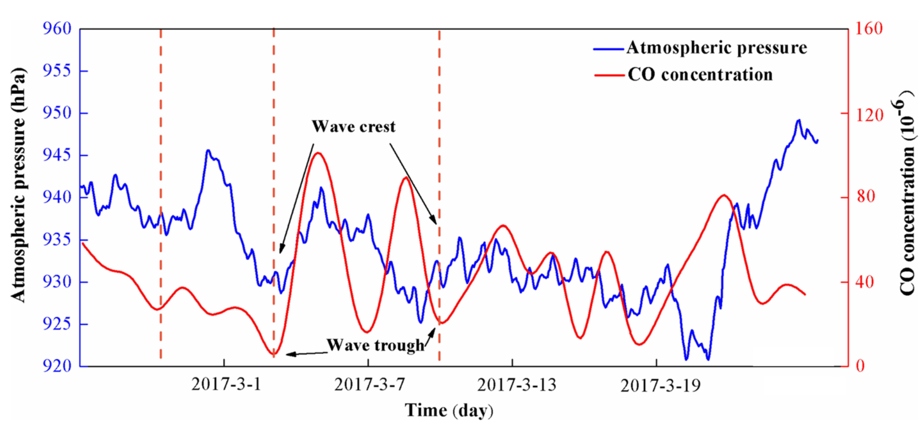


Fig. 8 Variation trends of atmospheric pressure and CO concentration from February 23 to March 23, 2017



of CO from the goaf to the working face increases, eventually leading to an inversely proportional relationship between the CO concentration monitored in the return airway and atmospheric pressure (Wu et al. 2022; Zhu et al. 2014).

In order to further analyze the influence of the diurnal periodic characteristics of atmospheric pressure on CO concentration, the atmospheric pressure and CO concentration on March 10, June 9, September 10 and December 9, 2017 were extracted for specific analysis. As shown in Fig. 9, the surface atmospheric pressure is negatively correlated with the CO emission in the goaf. The CO concentration is the minimum from 12:00 to 14:00 every day, on which atmospheric pressure reaches its peak value. And the CO concentration is the maximum from 19:00 to 21:00 every day, on which atmospheric pressure reaches its trough value. This is consistent with the above results.

5 Conclusions

The change of surface atmospheric pressure has an important impact on the air leakage in the mine closed area and the external environment. Through the analysis and calculation of the hourly change data of atmospheric pressure and CO monitoring data from 2016 to 2017 in the Dananhu No. 1 mine in Hami area, the following main conclusions are obtained.

(1) The periodic variation of atmospheric pressure is analyzed by Fourier transform, and it is found that the variation of atmospheric pressure has an annual periodicity. There are three periods of 15.2 d, 1 d and 182.2 d, and the probability is greater than 95%. The time period with the highest number of atmospheric pressure peaks is 7:00–8:00, which accounts for 20.2% of the total occurrence number in a day. And the time periods with

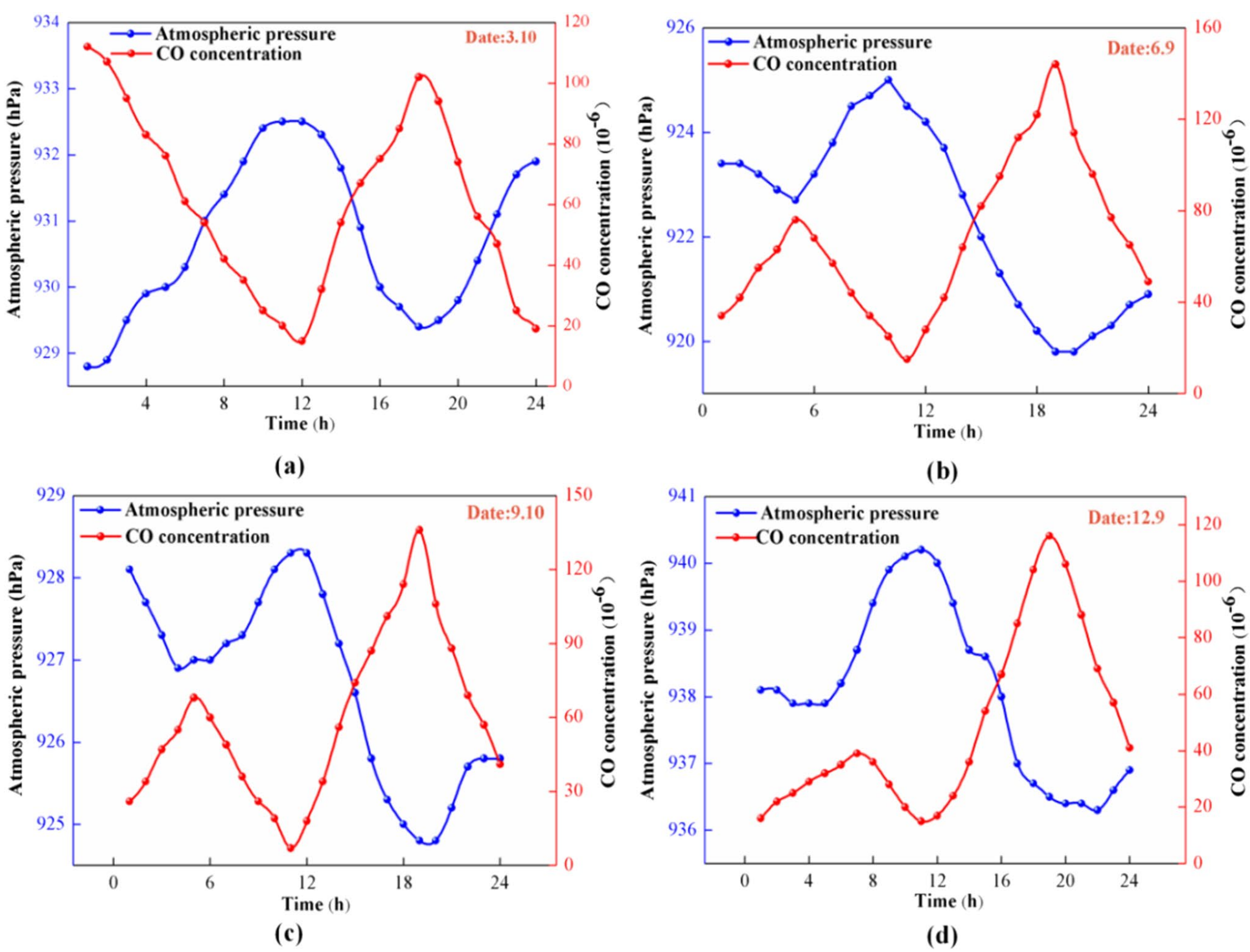


Fig. 9 Diurnal trends of atmospheric pressure and CO concentration

the highest number of atmospheric pressure troughs are 2:00, 15:00 and 16:00, accounting for 27.4%. The peak-to-trough transition time is mainly concentrated around 6 h, the diurnal variation curve of atmospheric pressure is mainly bimodal, and the atmospheric pressure change rate is mostly concentrated in 10–50 Pa/h.

(2) Using SPSS software to analyze the Pearson correlation of Hami's atmospheric pressure and temperature fluctuation curve, it is obtained that the Pearson correlation coefficient of Hami's atmospheric pressure and temperature is -0.432. And the change relationship between atmospheric pressure and temperature is significantly correlated, but not significantly linear correlated.

(3) By analyzing the influence of atmospheric pressure periodic changes on CO emission in the closed area, it is found that when the gas pressure outside the closed area changes periodically, the CO concentration in closed area also changes periodically, and the field verification is carried out. The theoretical model of the influence of atmospheric pressure on the air leakage in the closed fire area is established. And it is determined that the distance that the gas sampling pipe of the Dananhu 1304 working face is pre-laid into the inner side of the closed wall should be greater than 44.4 m. In addition, the bundled tube system should be preferentially used for real-time continuous sampling and analysis, so as to eliminate the influence of atmospheric pressure fluctuations on the gas migration.

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Availability of data and materials The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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