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Research Article

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Research on Accuracy Calibration of Optical Interference Methane Analyzer

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Abstract: To address the inaccuracies in methane (CH_4) measurements by optical interference methane detectors in environments such as gas explosions, fires, and nitrogen injection for fire prevention, this study analyzed error patterns under varying temperature, pressure, and gas composition conditions. By examining the principles of interference fringe variations, error sources were identified, and a correction model was developed. The findings indicate that mine temperatures (10°C–30°C) and atmospheric pressure (97 kPa–99 kPa) have negligible effects on measurement results. However, gas components such as CO_2 CO, N_2, and O_2 significantly affect accuracy. Each 1% increase in CO_2 or CO raises methane readings by 1.12% and 0.3%, respectively, while N_2 and O_2 impact air's refractive index. CH4 measurements below 5% concentration remain accurate, but concentrations above 5% lead to underestimation.CO_2 and CO interference were mitigated using absorbents, while a correction model was proposed to address N_2 and O_2 effects. The corrected results align closely with gas chromatography readings, with discrepancies between 0% and 0.001%, demonstrating improved accuracy.

Keywords: mine gas detection; optical interference methane detector; refractive index; correction model.

1. Introduction

The frequency of gas accidents during coal mining is high [1], and the consequences are severe, often resulting in significant loss of life and property. Methane, the primary component of gas, is an explosive gas with an explosion concentration range of 5–15%. Optical interference methane detectors, due to their fast measurement and portability, are widely used in coal mines to detect methane concentrations. These detectors can efficiently measure the concentrations of CH_4 and CO_2 in rescue operations in fire zones of mines. However, after gas explosions, fires, or other accidents, coal and methane react with oxygen in the airflow, producing large amounts of CO_2 and CO gases. This causes optical interference methane detectors to produce significant deviations when measuring CH_4, which impacts the accuracy and analysis of methane concentration detection during post-disaster rescue and accident investigations [2]. For example, during the "8.4" suffocation accident at Xinfeng, Dengfeng Yulian Coal Industry, under a CO_2 concentration of 10%, the optical interference methane detector measured the gas concentration at about 2%, whereas the actual methane concentration was only 0.1%, severely affecting the judgment of the on-site situation and causing significant inconvenience in initiating rescue operations.

Currently, the methane detection equipment used in domestic coal mines mainly includes optical analysis methods, such as infrared absorption spectroscopy [3] and optical interference, as well as non-optical analysis methods, such as gas chromatography [4], ultrasonic methods, and carrier catalysis [5]. Non-dispersive infrared

spectroscopy [6] and tunable diode laser absorption spectroscopy [7] are also employed. The optical interference methane detector is an instrument that utilizes optical principles to detect gas concentrations [8]. Compared to traditional electrochemical and semiconductor sensors, optical interference methane detectors offer higher sensitivity and selectivity, and are less affected by changes in humidity and temperature, making them suitable for gas detection in complex environments [9]. Optical detectors typically have a longer service life and lower maintenance costs, making them an important instrument for manual methane detection in underground coal mines.

Zhang Shirong and Zheng Chuanming analyzed the principle of optical interference in methane detectors, laying the foundation for the study of the instrument's optical path and the generation of interference fringes [10,11]. Guo Cuiji analyzed the causes of errors in optical interference methane detectors and suggested that regular maintenance and temperature-pressure corrections, especially when the measurement site deviates significantly from standard conditions, can reduce measurement errors [12]. The composition of gases at the detection site can affect the accuracy of the results. Yin Xuntao studied experimental data from the Fushun Coal Research Institute and proposed that for every 1% reduction in oxygen concentration in the air, the methane concentration measurement result is approximately 0.2% higher [13]. Xue Xiaoyin and Jiao Zhongxing first calculated the refractive index conversion coefficient and found that in oxygen-deficient areas, for every 1% decrease in oxygen content, the baseline of the optical interference methane detector shifts 0.187% to the right [14], resulting in a reading that is higher than the actual concentration. Xing Yuzhong et al. measured methane concentrations in the upcorner and return ventilation tunnels of the Jiaozili 1105 coal mining face at Xinhua Coal Mine, where they found that increased nitrogen concentration caused the concentration readings to be higher [15]. Zhao Kun analyzed the gas components in the Ehuobulake coal mine and proposed a correction model for measuring CH_4 concentrations in the underground optical interference methane detector at Ehuobulake, along with a method for calculating the true value of CH_4 concentration [16]. Xu Enxiang compared the refractive index differences between CH_4 and air with those between hydrogen and air and found that their absolute values are nearly equal, one positive and one negative. By swapping the methane chamber with the air chamber, optical interference detection can be used to measure hydrogen concentration [17], indicating that optical interference detection results are closely related to the refractive index of the gases.

In summary, the above studies have proposed ideas for the measurement errors of optical interference methane detectors. However, these studies primarily focus on low-concentration gases, with limited discussion on the causes of inaccurate measurements when detecting high-concentration gases. Based on this, the author simulates different environmental conditions using the optical interference methane detector to measure methane (CH_4) concentrations at varying levels, comparing them with the actual concentrations. By analyzing the deviation patterns, the study provides a detailed explanation of the nature of errors occurring during incidents such as fires and gas explosions in coal mines. Additionally, a correction equation is proposed to improve the accuracy of high-concentration CH_4 measurements and reduce the detection errors of optical interference methane detectors.

2. Principle and Apparatus of Optical Interference Methane Detector

Measurement Principle

The optical interference methane detector is based on the principle of optical interference, with its core function being the determination of gas concentration by analyzing the position or change of interference fringes [18]. It is currently the primary instrument used in coal mines in China for detecting methane concentrations. The light emitted by the light source passes through a condenser lens and reaches a plane mirror. Before entering the gas chamber and the air chamber, the light undergoes amplitude splitting interference [19]. The light beam is first divided into two beams: the reference beam that enters the air chamber and the test beam that enters the gas chamber. The reference beam passes through the air chamber, where a refractive prism directs it back to pass through the air chamber again before returning to the plane mirror. After refraction, it reflects off the rear surface (coated with a reflective membrane) of the plane mirror and proceeds towards the reflection prism. After deflection, it enters the objective lens. The test beam refracts into the plane mirror, reflects off the rear surface, and then passes through the gas sample chamber and refractive prism, returning to the plane mirror. After reflection, the red beam converges with the reference beam and both enter the objective lens, where a white light interference phenomenon unique to these beams occurs at the focal plane of the objective lens. When gases such

as methane enter the gas sample chamber, the interference fringes produced by the two beams are displaced. Thus, by measuring the displacement of the interference fringes, the concentration of gases such as methane can be determined.

Experimental Setup

The optical interference methane detector consists of three main parts: the air intake balloon assembly, the absorption tube assembly, and the instrument itself, as shown in Figure 1.

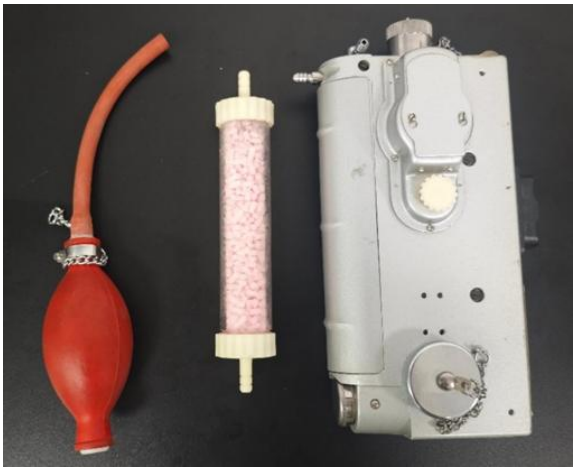

Figure 1: Composition and component names of detectors

The CJG-type optical interference methane detector used in this study has a plane mirror tilted backward by 55′ (other types of detectors, although they do not change the 45° vertical plane placement of the plane mirror, will alter the position of the prism) [20] .This leads to an asymmetry in the propagation paths of the reflected and refracted light beams in space, causing a slight angular deviation in the light as it passes through the system. Although the optical path difference inside the gas chamber remains the same, the path length difference of the light beams inside the plane mirror is inconsistent. The path lengths traveled by the two beams are not exactly equal, fulfilling the interference condition and generating initial interference fringes. The optical interference methane detector used complies with the relevant requirements of the "Optical Interference Methane Detector" (MT28—2005), and the equipment is in good condition.

The experiment uses the CG-4000A gas chromatograph, as shown in Figure 2, for the comparison of gas concentrations. Prior to the experiment, the gas chromatograph was calibrated, and the results of the standard sample measurements met the experimental accuracy requirements. The concentrations measured by the gas chromatograph were taken as the actual gas sample concentrations.

Figure 2: Gas Chromatography Instrument

3. Analysis of Sources and Causes of Errors in Gas Detection

Sources of Error in Gas Detection

The main factors affecting the accuracy of the optical interference methane detector include environmental factors such as atmospheric pressure, temperature, and humidity, as well as the composition of other gases, such as CO_2 and CO. Through experiments, the specific impact of changes in air pressure, temperature and humidity, and gas composition on the methane concentration detection results is analyzed.

(1) The impact of air pressure and temperature on the detection results. In the laboratory, a constant temperature and pressure chamber was used to conduct optical interference methane detection experiments (CH_4) under different pressures (constant temperature set to 20℃, which is a common temperature in coal mines) and different temperatures (constant atmospheric pressure set to 0.099 MPa, a typical atmospheric pressure in coal mines). The study investigates the effect of variations in air pressure and temperature on the accuracy of gas concentration measurements. The experimental results and their error data are presented in Figures 3 and 4.

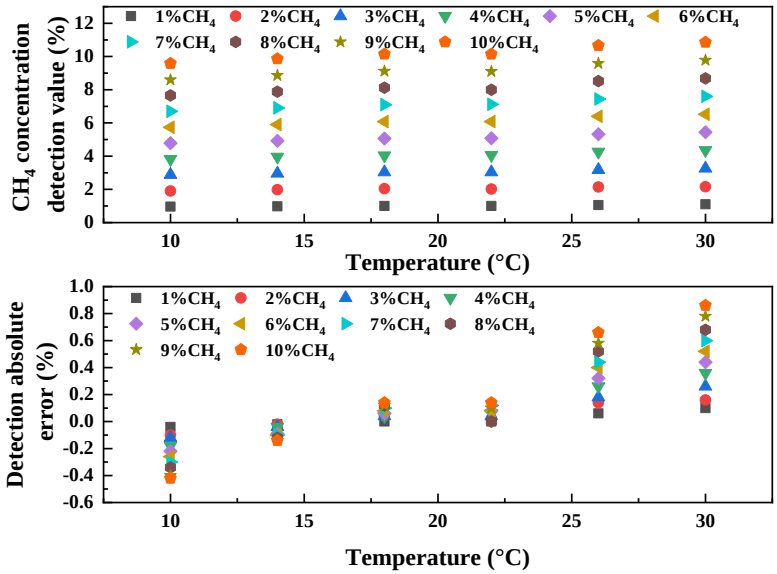

Figure 3: CH_4 detection results and errors at different temperatures

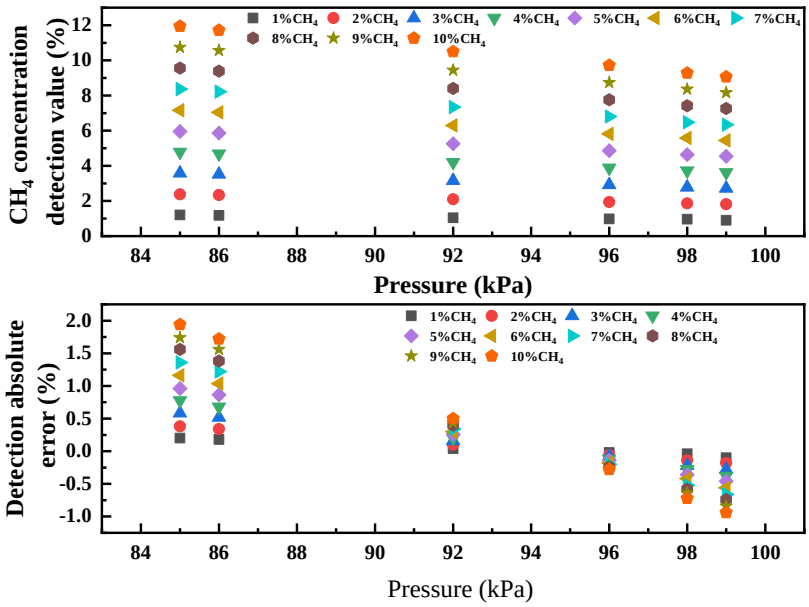

Figure 4: CH_4 detection results and errors at different pressures

As shown in Figures 3 and 4, the absolute error in the measurement results of the optical interference methane detector due to temperature (10°C to 30°C) does not exceed 0.11%, and the absolute error due to atmospheric pressure (97 kPa to 99 kPa) does not exceed -0.94%. These values are within the allowable error range of the instrument.

(2) The impact of CO_2 and CO gas composition on the detection results. Different concentrations of CO_2 and CO gases were mixed with methane (CH_4), and the results detected by the optical interference methane detector were compared with those detected by the gas chromatograph. The detection results and errors for methane at different CO_2 and CO concentrations are shown in Figure 5.

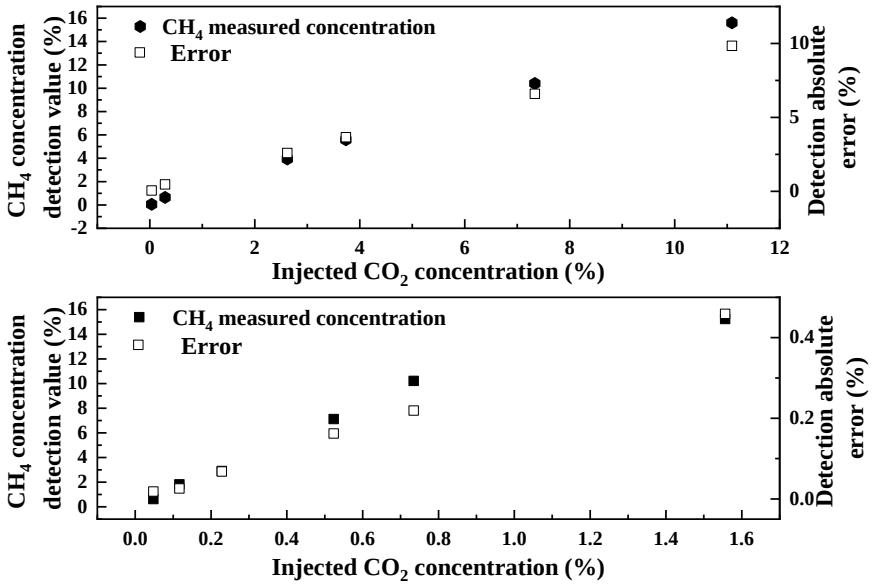

Figure 5: Results and errors of CH_4 gas detection by mixing CO_2 and CO optical interference methane detector

As shown in Figure 5, when using the optical interference methane detector to measure CH_4 in an environment containing carbon dioxide (CO_2) and carbon monoxide (CO), if the corresponding absorbent is not used to completely absorb CO_2 and CO, these gases will enter the gas sample chamber along with methane (CH_4), resulting in an overestimation of the measured CH_4 concentration. This significantly affects the accuracy of the methane detection results.

Table.1: Error of optical interference methane detector in detecting CH_4 at different CO_2 concentrations

Injected CO_2 concentration (%)	Detection absolute error (%)	Average absolute error (%)
11.09	9.83	0.89
7.34	6.60	0.90
3.74	3.66	0.98
2.62	2.59	0.99
0.29	0.46	1.58
0.04	0.05	1.40

Table 2: Error of optical interference methane detector when detecting CH4 at different CO concentrations

Injected CO_2 concentration (%)	Detection absolute error (%)	Average absolute error (%)
1.56	0.46	0.29
0.73	0.22	0.30
0.52	0.16	0.31
0.23	0.07	0.30
0.12	0.03	0.22
0.05	0.02	0.38

According to the data in Tables 1 and 2, for every 1% increase in CO_2 and CO concentration, the methane measurement results show a deviation of approximately 1.12% and 0.3%, respectively, causing the methane concentration to be overestimated. This error is particularly severe in high CO_2 concentration environments, especially in post-disaster environments such as coal mines, where fires or gas explosions may generate a large amount of CO_2, leading to distortion in the detection results.

(3) The impact of N_2 and O_2 gas components on the detection results. Nitrogen (N_2) and oxygen (O_2) are the main components of air. When the concentrations of CH_4 or CO_2 gases are high in the detection environment, the proportion of N_2 and O_2 in the air changes significantly, and the air is no longer fresh. As a result, the detection results may also show significant deviations. The test results are shown in Figure 6.

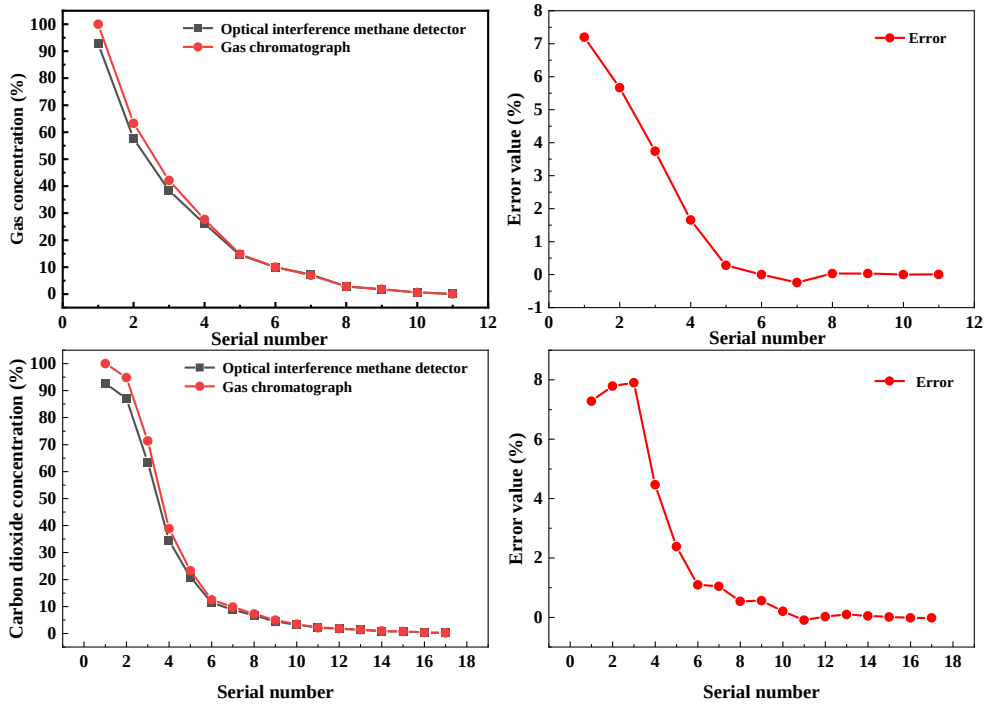

Figure 7: Precision of CO_2 and CH_4 detection by the optical interference methane detector at varying concentrations

When the optical interference methane detector measures CH_4 concentration, the deviation between the measured and actual concentration remains within 0.03% when the CH_4 concentration is below 5%. As the CH_4 concentration increases from 5% to 20%, the measured concentration gradually underestimates the actual value, with errors ranging from 0.2% to 1%. When the CH_4 concentration ranges from 20% to 100%, the deviation significantly increases, with the measured results underestimating by 1% to 7.2%. The detection accuracy decreases noticeably as the methane concentration increases.For CO_2 measurements, when the CO_2 concentration is below 10%, the deviation in the detected concentration is less than 1%. However, as the CO_2 concentration increases from 10% to 100%, the measured CO_2 concentration underestimates, with errors ranging from 1% to 7.89%. Therefore, at higher concentrations, the optical interference methane detector shows certain deviations in detection accuracy. For precise measurements, corrections to the results are necessary.

Analysis of Sources of Measurement Error

Interference of light is a phenomenon caused by the superposition of coherent light waves, and the optical path difference is the prerequisite for generating two correlated beams of light. Before using the instrument, fresh air is first used to clean the gas chamber. At this point, both the sample chamber and the air chamber are filled with fresh air, and no optical path difference is generated as the light passes through the gas chamber. The initial optical path difference is caused by the geometric bias of the plane mirror or prism, which results in a slight change in the incident angle of the light. The instrument used in this study is the CJG-type optical interference

gas detector, as shown in Figure 1. The tilt bias of the plane mirror (with an angle of $\Delta\theta$) creates the initial optical path difference. Let the incident angles of the light beams on the plane mirror be i_1 and i_2, respectively. Due to the tilt of the plane mirror, i_1 and i_2 are not exactly equal. For simplification, we introduce a unified incident angle ii, which is defined as the average of the two incident angles,

$$i_1 = i\text{-}\frac{\Delta\theta}{2}, \quad i_2 = i + \frac{\Delta\theta}{2} \tag{1}$$

In the equation, i represents the average angle between the light ray and the normal to the plane mirror, while $\Delta\theta$ describes the geometric angular deviation caused by the tilt of the plane mirror.

The initial optical path difference between the two incident light rays is given by：

$$\Delta\delta = \frac{d\sin\Delta\theta\sin 2i}{\sqrt{n^2 - \sin^2 i}} \tag{2}$$

In the equation, i represents the average angle between the light ray and the normal to the plane mirror; d is the thickness of the plane mirror, in meters (m); n is the refractive index of the plane mirror; and $\Delta\theta$ describes the geometric angular deviation caused by the tilt of the plane mirror.

Once the instrument is properly calibrated, the initial optical path difference remains constant, and the interference fringes stabilize. When the gas to be measured enters the instrument after calibration, it alters the refractive index of the gas chamber, changing the optical path difference. This leads to a change in the phase difference between the two light beams, and after stabilization, new interference fringes are formed. The difference in phase between the two sets of interference fringes is referred to as the spectral shift.

To describe the positional change of the interference fringes within the field of view and facilitate the direct measurement of the interference phenomenon, a new variable ε is introduced, representing the angular displacement of the light. In the instrument, the plane mirror is placed at a 45° angle, and the incident angle of the light can be written asi=45°+ε， epsilon. Since both $\Delta\theta$ and ε are very small, the initial position of the dark fringe angle is denoted as ε_1.

$$\varepsilon_1 = (2k+1)\ \lambda\sqrt{2n^2-1}\Big/\sqrt{2}\,d\Delta\theta \quad (\text{k=1,2,3..}) \tag{3}$$

In the formula， d is the thickness of the plane mirror, in meters (m); $\Delta\theta$ is the tilt angle of the plane mirror; n is the refractive index of the plane mirror; k is the order of the interference fringe; λ is the wavelength of the light, in nanometers (nm); ε_1 is the initial angular displacement of the fringe.

When the gas sample chamber is filled with the detection gas and stabilized, the angle position of the same interference fringe becomes ε_2.

$$\varepsilon_2 = (2\text{k}+1)\lambda - 2L\Delta N\sqrt{2n^2-1}\Big/\sqrt{2}d\Delta\theta \quad (\text{k=1,2,3..}) \tag{4}$$

In the formula, d is the thickness of the plane mirror in meters (m); $\Delta\theta$ is the tilt angle of the plane mirror; n is the refractive index of the plane mirror; L is the length of the gas chamber in meters (m); ΔN is the change in refractive index between the air chamber and the gas chamber; k is the order of the interference fringe; λ is the wavelength of light in nanometers (nm); ε_2 is the shift angle of the interference fringe.

The phase difference between the initial and measured interference fringes is given by $\Delta\varepsilon$.

$$\Delta\varepsilon = L\Delta N\cdot\sqrt{4n^2-2}\Big/d\Delta\theta \tag{5}$$

In the formula: Δε epsilon is the spectral shift of the interference fringes； L is the length of the gas chamber, in meters； ΔN is the refractive index difference between the air chamber and the gas chamber； n is the refractive index of the plane mirror； d is the thickness of the plane mirror, in meters；$\Delta\theta$ is the tilt angle of the plane mirror. According to the formula, the light shift varies linearly with the change in refractive index.

The refractive index nnn of a mixed gas can be calculated using the following equation n.

$$\text{n}_\text{m} = x_1 n_1 + x_2 n_2 + \cdots + \text{x}_\text{i} n_i \tag{6}$$

In the formula, nm is the refractive index of the mixed gas, n_1、n_2……n_i are the refractive indices of the different components in the mixed gas, x_1、x_2……x_i are the mole fractions (or concentrations) of the individual components in the mixture.

The spectral shift on the optical interferometric methane detector is linearly related to the refractive index of the gas in the sample chamber, with the shift corresponding directly to the refractive index of the sample chamber. The introduction of CO_2 and CO significantly increases the spectral shift, leading to measurement errors. During detection, gases other than the target gas are referred to as background gases (typically fresh air). In mine fire rescue environments, in addition to the generation of gases like CO_2 and CO, oxygen is consumed in large amounts, and inert gases (such as nitrogen injected into voids to prevent fires) are introduced. These conditions alter the background gas composition in the detection environment, changing the refractive index of the sample chamber. This change in refractive index is a key factor in generating measurement errors.

4. Correction of Measured Values by the Optical Interferometric Methane Detector

Changes in gas composition and concentration can severely affect the accuracy of measurements. During a gas explosion or fire, although the interference of gases like CO_2 and CO can be eliminated using absorbents, the nitrogen-oxygen ratio in the environment changes. This significant change in the composition of nitrogen and oxygen causes a shift in the refractive index of the air (since the primary components of air are N_2 and O_2, with other gases present in much smaller quantities). Compared to an environment filled with fresh air, this alteration in the refractive index of the sample chamber results in a spectral shift that deviates from the original shift. The resulting error is difficult to eliminate. The movement of interference fringes is caused by spectral shifts, and since there is a linear relationship between the refractive index and the spectral shift, the detection results can be corrected by adjusting for the refractive index changes.

Measured Value Correction Model

When the instrument detects gases in an environment with non-fresh air, where the nitrogen-oxygen ratio changes, the refractive index of the gas chamber containing x% of a gas can be expressed as

$$\mathrm{n}_c = x\%n_{\mathrm{q}} + n_{\mathrm{a}} \tag{7}$$

The formula is, n_c is the refractive index of the gas in the gas chamber; n_q is the refractive index of the detection gas; n_a is the refractive index of air under different nitrogen-oxygen ratios.

The calculation formula for gas concentration C_q and refractive index can be derived as follows.

$$\mathrm{Cq} = \frac{C_q^{'}\left(n_q - n_{\mathrm{a}}\right) + \Delta n_k}{n_q} \tag{8}$$

In the formula, C_q is the corrected concentration of the detected gas (unit: %); $C_q^{'}$ is the uncorrected concentration of the detected gas; nq is the refractive index of the detected gas; Δn_K is the refractive index difference between fresh air and non-fresh air; n_a is the refractive index of non-fresh air under different nitrogen-oxygen ratios.

Verification of the Accuracy of the Corrected Model

When measuring methane in a fire zone, the nitrogen-oxygen content changes. By using absorbents to absorb other gas components (CO_2, CO, etc.), the refractive index of air under the current nitrogen-oxygen ratio, nan_a, is calculated using formula (1) based on the oxygen and nitrogen content. Then, by substituting the actual concentration measured by the optical interference methane detector into formula (8), the optical interference methane detector data is corrected. The five gas samples were analyzed by gas chromatography, the actual measurements by the optical interference methane detector, and the corrected data are shown in Table 3.

Table 3: Gas Chromatograph Analysis, optical interference methane detector Measured and Corrected CH_4 Concentration Values

CH_4 concentration (gas chromatography) / %	**CH_4 concentration (light watts) / %**	**Corrected result (%)**	**Error / (%)**	**CH_4 concentration (gas chromatography) / %**	**CH_4 concentration (gas chromatography) / %**	**Corrected result (%)**	**Error / (%)**
100	92.8	99.9989	+0.001	6.9579	7.2	6.9578	+0.000

			1				1
63.2664	57.6	63.2655	+0.000	2.8319	2.8	2.8318	+0.000
			9				1
42.144	38.4	42.1434	+0.000	1.7941	1.76	1.7940	+0.000
			6				1
27.6585	26	27.6582	+0.000	0.6016	0.6	0.6015	+0.000
			3				1
14.781	14.2	14.7808	+0.000	0.0852	0.94	0.0852	0
			2				
10.001	10	10.0009	+0.000				
			1				

As shown in Table 3, with the decrease in the nitrogen-oxygen ratio, the refractive index of air decreases, leading to a smaller CH_4 concentration measured by the optical interference methane detector. This is because, in the high-concentration CH_4 region, the proportion of nitrogen and oxygen, the main components of air, significantly decreases. At this point, the background gas and methane mix, causing the refractive index of the gas chamber to be lower than normal. Due to the presence of the disc-shaped tube, the air chamber always contains fresh air, which results in a smaller refractive index difference between the two gas chambers. This leads to a smaller shift in the interference fringe and lower readings on the scale. As the nitrogen-oxygen ratio continues to decrease, the error gradually increases. It can also be seen that the error between the uncorrected results and the gas chromatograph measurements ranges from 0.58% to 7.2%, while the error after correction ranges from 0% to 0.001%. The error is extremely small, meeting the requirements for methane concentration monitoring in underground mines.

5. Conclusion

(1) The interference fringe shift of the optical interference methane detector varies linearly with the refractive index. Under the mining temperature range (10°C to 30°C) and atmospheric pressure range (97 kPa to 99 kPa), the absolute error in the measurement results of the optical interference methane detector does not exceed 0.11% and -0.94%, which is within the instrument's allowable error range and can be neglected. The presence of CO_2 and CO in the gas sample chamber will increase the refractive index difference between the gas sample chamber and the air chamber, leading to an increase in the spectral shift and causing the methane concentration readings to increase. For every 1% increase in CO_2 or CO, the methane concentration reading will increase by 1.12% and 0.3%, respectively.

(2) When measuring methane with the optical interference methane detector, changes in the nitrogen and oxygen proportions in the ambient air will cause the gas refractive index in the gas sample chamber to differ from the refractive index during normal measurements, resulting in errors. The greater the difference between the nitrogen and oxygen ratio in the ambient air and that of fresh air, the larger the error. It is necessary to simultaneously measure the nitrogen and oxygen ratios and use formulas to correct the measurement results. After correction, the error ranges from 0% to 0.001%, and the corrected results are more accurate.

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