Methane concentration detection system based on differential infrared absorption

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Abstract: The infrared absorption method for methane concentration detection is an ideal way to detect methane at present. However, it is difficult to spread this method due to its high cost. In this paper, by using a wideband infrared light emitting diode (LED) accompanied with a PIN photo electric diode, a low-cost methane detection system was designed. To overcome the shortcomings caused by the wide working band, a differential light path was designed. By means of a differential ratio algorithm, the stability and the accuracy of the system were guaranteed. Finally, the validity of the system with the proposed algorithm was verified by the experiment results.

Key words: methane detection; infrared absorption; differential light path; differential ratio algorithm

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0 Introduction

Methane, a kind of combustible gas without color and taste, is one of the major energy gases[1-2] and a principal component of biogas, natural gas and tunnel gas[3-4], etc., being distributed widely over the nature. The application of methane is so widespread that the research about methane detection was implemented early, from the anti-explosion detection in the traditional mine to the leakage detection of natural gas transmission pipeline, and so on.

According to the operating principle, the methods of methane detection are mainly classified into four types: catalytic combustion, semi-conductive gas-sensing response, fiber leak-checking and infrared absorption[5-6]. The catalytic combustion method is widely used in the mines, and its main disadvantage is the need of periodic calibration, meanwhile, it is likely to be poisoned in high-concentration methane, which makes workers unable to work[7-8]. The semi-conductive gas-sensing response system is the most common handheld testing equipment, which is widely used because of its high sensitivity, compact structure and high portability. Nevertheless, this method is susceptible to interference gases, and is strict in environment temperature and moisture[9]. The fiber leak-checking method has the advantages of wide detection area and high precision, but has poor capability to distinguish different gases, which makes it usually applied to detect single gas[10-13]. The infrared absorption method can achieve methane detection by using the spectral absorption characteristic of gas molecule, which has the advantages of rapid testing speed, strong capability of gas identification, continuous operation, and so on. However, the accuracy of this method depends mainly on the spectrum purity of light source, so that the main way to improve the accuracy depends on using expensive laser with narrow band, which greatly limits its wide application.

In view of the facts, a low-cost methane detection system based on infrared absorption method was designed in this paper. By using a wideband light source, the cost of the system is decreased. Some efforts were made to achieve a warrantable accuracy and stability by means of special light path with dif-

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ferential radio algorithm.

1 System architecture

1.1 Basic principle

The basis of the infrared absorption method is the theory of characteristic spectrum absorption. Therefore, methane detection can be achieved based on the characteristic that only the infrared radiation at specific wavelength can be absorbed by the methane molecule[11]. This method can meet the requirements of gas identification and quantitative analysis well due to its good selectivity, even in mixed environment with interference gases. The Beer-Lambert law[12-13] is the theoretical basis of quantitative calculation for methane concentration. According to the law, if the intensity of incident light I_i and the intensity of transmitted light I_t can be measured, the methane concentration C_m can be represented as

$$C_m = \frac{1}{\alpha_\lambda L} \ln \frac{I_i}{I_t}, \tag{1}$$

where L is the length of absorption path; α_λ is the absorption coefficient to be calculated.

1.2 Selection of characteristic wavelength

The methane molecule has four natural vibration frequencies, corresponding to four characteristic absorption wavelengths with strongest absorption capacity, including 3.31 μm, 3.43 μm, 6.52 μm and 7.66 μm, all of which are in mid-infrared band. There are several combined absorption bands and multiple frequency absorption bands in near-infrared band, and the absorption capacity in 1.33 μm and 1.65 μm are the strongest among them. The absorption capacity in mid-infrared band is stronger than that in near-infrared band. However, the laser working in mid-infrared band is expensive and needs to be refrigerated when working. Therefore, light source working in near-infrared band is adopted in this paper and the selected center wavelength is 1 650 nm.

1.3 Differential light path

After the characteristic wavelength is selected, the light path that embodies the differential radio algorithm is designed. Fig. 1 shows the principle of differential light path.

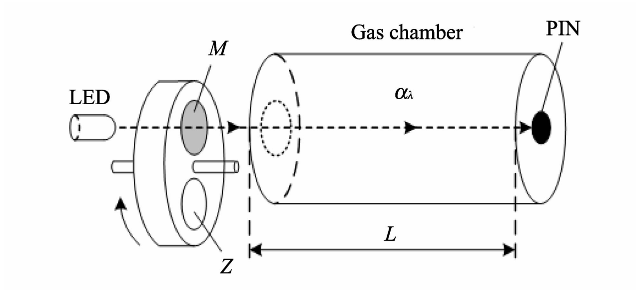

Fig. 1 Differential light path

The light path consists of near-infrared light source, switch window, gas chamber and infrared detector. An infrared light emitting diode (LED) typed as L1650-06 is selected as the light source, and a PIN photoelectric diode typed as LSIPD-1 is selected as the detector to match with the light source. The switch window is the key unit of the light path and consists of two optic windows: one is filled with air named as Z window, and the other is filled with high concentration methane named as M window. The gas chamber is the detection place of methane with two states: one is idle state with no methane, and the other is detecting state with methane filled in. The differential detection for methane can be achieved through the cooperation between the switch window and the gas chamber.

2 Differential ratio algorithm

As the two windows (Z or M) switch to each other, combined with the two states (idle or detecting) switched, four measurement processes are generated, accompanied with four values of detected light intensity.

For the first measurement process, Z window is aligned with the gas chamber being in idle state, and the detected light intensity is represented as I_{Z0}. For the second measurement process, M window is switched to being aligned with the gas chamber which is still in idle state, and the detected light intensity is represented as I_{M0}. The third measurement process, Z window returns to be aligned with the gas chamber, which is filled with methane gas, and the detected light intensity is represented as I_{ZX}. For the last measurement process, M window is aligned with the gas chamber again, which is still filled with methane gas, and the detected light intensity is represented as I_{MX}. So far, one time of measurement is finished.

The absorbed light intensity can be acquired exactly through ratio calculation between the four values of the detected light intensity, with no need for exact wavelength (radiated by modulated light source with narrow band), and then the methane concentration can be calculated exactly. The ratio calculation above mentioned is named as differential ratio algorithm, which is implemented as follows:

1) Take a finite amount of methane with known concentration as gas sample, and then implement one time of measurement. The light intensities of I_{Z0}, I_{M0}, I_{ZX} and I_{MX} can be acquired.

2) If the difference between I_{M0} and I_{MX} is distinct, increase the methane concentration in M window until $I_{M0} \approx I_{MX}$ (relative error is less than 1%).

3) Calculate $I_{Z0} - I_{M0}$, the result represents the total light intensity at methane characteristic absorption wavelength in light source, which can be used to replace I_i in Eq. (1) with more accuracy. Similarly, the result of $I_{ZX} - I_{MX}$ is the residual light intensity at methane characteristic absorption wavelength in light source, which can be used to replace I_t in Eq. (1), with more accuracy. Then the absorption coefficient α_λ can be calibrated in accordance with Eq. (1) and rewritten as

$$\alpha_\lambda = \frac{1}{C_m L} \ln \frac{I_{Z0} - I_{M0}}{I_{ZX} - I_{MX}}, \tag{2}$$

where C_m and L are known.

4) Implement a new measurement for the methane with unknown concentration. A new set of light intensities of I_{Z0}, I_{M0}, I_{ZX} and I_{MX} can be acquired.

5) Calculate the concentration of methane according to Eq. (1), which is rewritten as

$$C_m = \frac{1}{\alpha_\lambda L} \ln \frac{I_{Z0} - I_{M0}}{I_{ZX} - I_{MX}}, \tag{3}$$

where α_λ was calibrated just now.

It is shown that, with the differential radio algorithm, the concentration of the methane can be measured exactly.

3 Experiment and analysis

Under the condition of normal temperature and pressure, fill the gas chamber with methane gas with certain concentration, and then implement the differential detection for methane. At the same time, the methane gas is measured by gas analyzer typed as TDL-500. Since the TDL-500 has a good detection accuracy of 10^{-6}, the measured data can be used as the truth value of methane concentration. The measured data with the calculated results are shown in Table 1.

Table 1 Experiment results

Truth value ($\times 10^{-6}$)	Measured value ($\times 10^{-6}$)	Error (%)
100	91	9.0
300	282	6.0
500	491	1.8
1 000	989	1.1
2 000	1 974	1.3
3 000	2 958	1.4
4 000	3 953	1.2
5 000	4 921	1.6

As can be seen from Table 1, when the methane concentration is lower, the relative error is higher. The possible reason is that the concentration is low and the methane molecule cannot react adequately with the transmitted light at characteristic wavelength, so the absorbed light intensity is too low to suppress the interference causes by noise. As the concentration increases, the error decreases obviously. When the concentration exceeds 5×10^{-4}, the relative error tends to be stable. Table 1 only lists the data at low concentration. When the concentration exceeds 5×10^{-3}, the relative error will increase again. Therefore, the application range of this method can be confirmed as 5×10^{-4}—5×10^{-3} with good stability and accuracy.

4 Conclusion

Under the guidance of spectral absorption theory, a methane detection system based on differential radio algorithm is designed successfully in this paper. By using a wideband infrared LED, accompanied with a PIN photoelectric diode, the cost of the system decreases. A differential light path with differential ratio algorithm is designed seriously, which can guarantee the stability and accuracy of the system. The experiment results indicate that the measurement range is between 5×10^{-4} and 5×10^{-3}, and the relative error is less than 2.0%.

References

[1] LIU Zhu-qin, BAI Ze-sheng. Achievement of methane detection method. Instrument Technique and Sensor, 2009, 11: 89-91.

[2] ZHU Hong-xiu, SUN Lian-kun, WANG Zhong-hua, et al. Design of infrared methane gas concentration detection system. Journal of Applied Optics, 2014, 35(5): 890-894.

[3] QIAN Xu, CHENG Ming-xiao, WANG Xue-hua, et al. Design of gas detecting system based on infrared photo acoustic spectrum. Transducer and Micro System Technologies, 2014, 33(12): 98-103.

[4] GAO Hao. Application of wavelength control technology in mine-used laser methane sensor. Safety in Coal Mines, 2014, 45(12): 102-105.

[5] DU Wei-ran, HUANG Zhi-wei, RONG Feng, et al. Design of infrared methane concentration measurement instrument. Industry and Mine Automation, 2015, 41(3): 87-92.

[6] GUO Wei-qing, WANG Zhi, LI Xin-bei. Optical fiber methane gas sensor. Infrared, 2007, 28(5): 21-28.

[7] LIANG Yong-zhi, LI Mao-dong, XIA Lu-yi, et al. Algorithmic research of detecting gas with infrared methane sensor. Instrument Technique and Sensor, 2012, (11): 149-150.

[8] HUANG Jian-qiang, ZHAI Bing, YE Wei-lin, et al. Near-infrared CH4 detection device using wavelength-modulation technique. Journal of Optoelectronics · Laser, 2014. 25 (5): 947-953.

[9] WANG Yu-tian, GUO Zeng-jun, WANG Li-tian, et al. Study on transmission-type optical fiber CH4 sensor. Journal of Transcluction Technology, 2001, (6): 147-151.

[10] YANG Ren-di, ZHANG Yan-li. Design of intelligent methane concentration detector. Industry and Mine Automation, 2009, (11): 69-72.

[11] LU Xu-tao, LI Jing, LU Hai-feng. Portable high-precision system for CH4 concentration detection in mines based on the laser mode-hopping. Spectroscopy and Spectral Analysis, 2015, 35(3): 846-849.

[12] LI Yuan, CHEN Zhi-gang, LI Kai. Ammonia concentration detection system for mainstream smoke of tobacco based on characteristic infrared absorption method. Spectroscopy and Spectral Analysis, 2013, 33(6): 1521-1524.

[13] QIAO Ji-ping, QIN Jian-min, YAN Xiao-yan, et al. Design of methane concentration monitoring system based on LabVIEW and characteristic absorption spectrum. Instrument Technique and Sensor, 2013, (10): 70-72.

基于差分红外吸收的甲烷浓度检测系统

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摘　要： 红外吸收法是目前甲烷浓度检测的理想手段，但其成本较高，难以推广应用。本文采用宽带红外LED光源并配合PIN光电二极管，设计了一种低成本的甲烷检测系统。为了克服因采用宽带光源带来的不足，设计了一种差分光路，并采用差分比例算法来保证系统的稳定性和精度。最后，通过实验验证了本系统及提出算法的有效性。

关键词： 甲烷检测；红外吸收；差分光路；差分比例算法

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