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Abstract. There are two main drawbacks seen in the use of the multi-gas detection method based on the tuneable diode laser absorption spectroscopy (TDLAS). The first is that multiple lasers have traditionally been employed in the detection system, which means not only the system cost, but also the system response time is increased. The second major issue is the existence of a number of kinds of cross interference, and thus the sensitivity and accuracy of the existing multi-component gas detection approach has been greatly restricted, and this has become a technical bottleneck for practical multi component gas detection. To address this, a synchronous detection technology for a high precision multi-component gas detection scheme using a single light source is reported. By measuring the spectral absorption feature of each individual gas at different concentrations, the relationship of each gas sample present to the spectral absorption value can be established and the concentrations of each individual gas can be calculated. This novel method has been shown to improve the precision achieved in the detection of the multi-component gas samples by20%, compared with the previous precision measured, with the induction in the interference effects on the measurements due to the different gases present, while at the same time reducing the detection cost and response time.

1. Introduction

There are various types of coal geology in China [1] that continue to make a major contribution to China's economy and indeed will do so for many years to come. Arising from the complexity of the geological conditions and the particularity of the production conditions, major accident due to fire often occur [1] and lives are lost. According to published statistics, more than 130 large and medium-sized coal mines, across 25 provinces in China are seen as being threatened by spontaneous combustions [1]. Among these fire accidents, the spontaneous combustion goaf fire has become one of the major disasters that directly threaten the coal mine safety [2]. Before the spontaneous combustion of coal, many kinds of gases (such as CO, CO_2, CH_4, C_2H_4, C_2H_2, etc.) have been gradually released in the goaf area. By accurately detecting the concentration of each gas within the mixed gases, it is

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possible to provide early warning signal for preventing the spontaneous combustion in the goaf and significantly increase coal mine safety [3].

In order to detect different gases within the multi-gas mixture based on TDLAS, different types of schemes have been developed, such as time division multiplexing [4] and wavelength division multiplexing [5]. One of the drawbacks of the methods mentioned above is that multiple lasers and their driving modules and temperature control modules have to be used. This means that not only the system cost is increased, but also there is a negative effect on the system response time. In addition, there are an overlap in the near infrared spectral absorption band for the target gases, this results in a certain level of spectral absorption interferences between different gases. Because of the existence of all kinds of cross-talking interferences in the detected signal, the sensitivity and accuracy of the existing multi component gas detection have been greatly restricted. This becomes a technical bottleneck for multi component gas detection.

In this paper, a synchronous detection technology for high precision multi component gas detection scheme using a single light source is reported. In this scheme, the absorption spectra of the targeted gases have been selected within the modulation wavelength range; by measuring the spectral absorption of each individual gas at different concentration, the relationship between each gas concentration and the spectral absorption value can be established and recorded, with reduced interference effects and offering low cost, short response time and high detection accuracy.

2. Multi-gas Detection System based on TDLAS

The basic theory underpinning the TDLAS approach is based on the Lambert-Beer law. When a parallel light beam of intensity $I_0(\lambda)$ passes through a filled gas cell, if the light source spectral covers one or more gas absorption features, the relationship between the transmitted light $I(\lambda)$, the incident light $I_0(\lambda)$ and the gas concentration C is given by[6]:

$$I(\lambda) = I_0(\lambda)exp[-\alpha(\lambda)CL] = I_0(\lambda)exp[-PS(T)\phi(\lambda)CL] \quad (1)$$

where, $\alpha(\lambda)$ is the absorption coefficient of the medium; L is the length of gas cell; $S(T)$is the intensity of characteristic spectral lines (all related to temperature); P is the total pressure of gas medium; C is the volume concentration of measured gas; the $\phi(\lambda)$ is the line-shape function, related to temperature, total pressure and the individual components present in the gas. Thus taking the logarithm on the both side of Eq. (1) yields [6]:

$$PCS(T)L = \int_{-\infty}^{\infty} -\ln\left(\frac{I}{I_0}\right) d\lambda = A \quad (2)$$

where A is the absorption cross section.

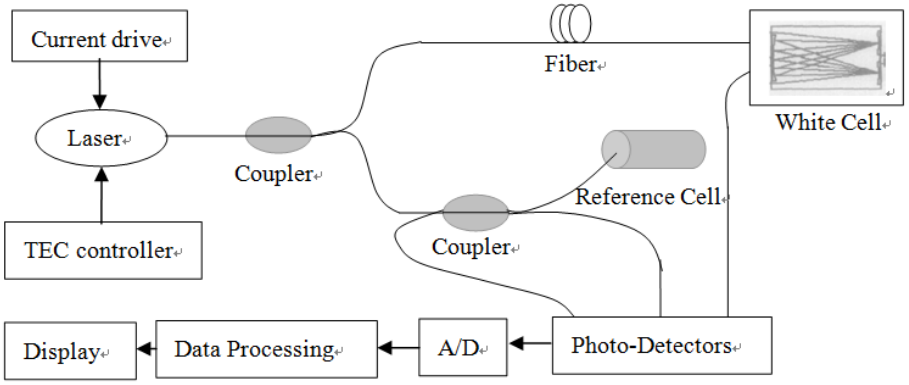

Figure1. The block diagram of multi-gas detection system

The block diagram of multi-gas detection system based on TDLAS is shown in Figure 1. The temperature control circuit and current driver circuit used ensure that the diode laser is working at a constant temperature, outputting a power laser power from the CW laser near-infrared used and adjusting the laser at its centre wavelength of 1566.7nm. The sawtooth wavefrom is produced by the

digital-to-analogue (D/A) circuit to achieve the required laser wavelength modulation and a InGaAs photo-detector has been selected, operating over the wavelength range from 600nm-1700nm [3,7].

3. Novel Multi-gas Detection Method

In this synchronous detection scheme, the composition of a multi-component gas sample can be evaluated with high precision, using a single light source. In order to increase the gas concentration measurement accuracy, the spectral absorption value is measured by calculating the cross section of the absorption spectra around the peak absorption wavelength of the targeted gas. The novel multi-gas detection method includes two main processes: the calibration process and the detecting process, as shown schematically in Figure 2. In the calibration process, the relationship between the concentration values of each target gas and the absorption cross section around the peak absorption wavelength of this gas can be determined and kept in a data base, which can be used to work out the concentration of the each gas when the measured data of mixed gas are obtained.

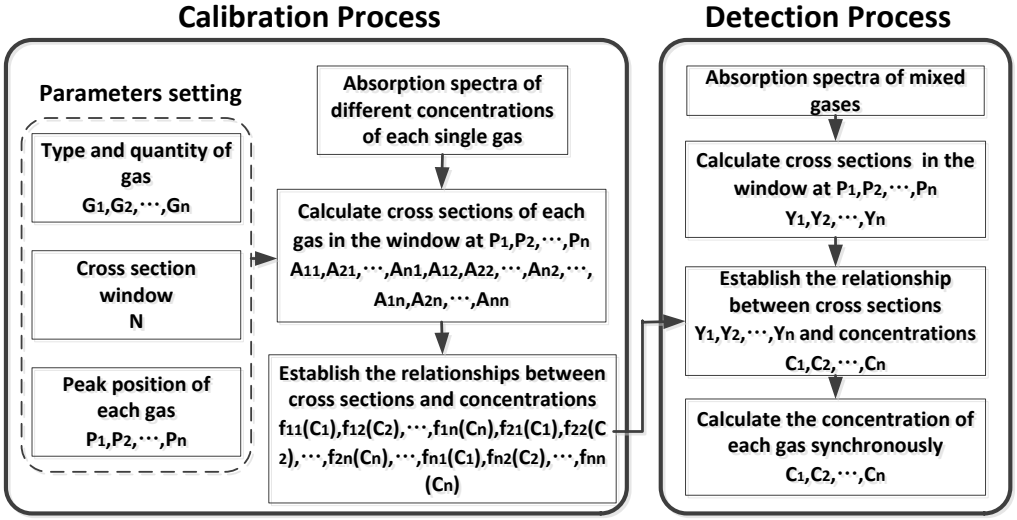

Figure2. Flow chart showing the processes involved in the novel multi-gas detection method

4. Experiments Approach and Results Obtained

In the experiment carried out, the detection system used was as shown in Figure 1. The laser temperature was controlled at 24.9 degrees while the current scanning range was 55-90mA, with an output modulation wavelength range from 1566.519nm to 1566.822nm, which covers the complete absorption peak of CO and CO_2. So in the experiment, we calculated the concentrations of CO and CO_2 in the mixed gas using the novel multi-gas method.

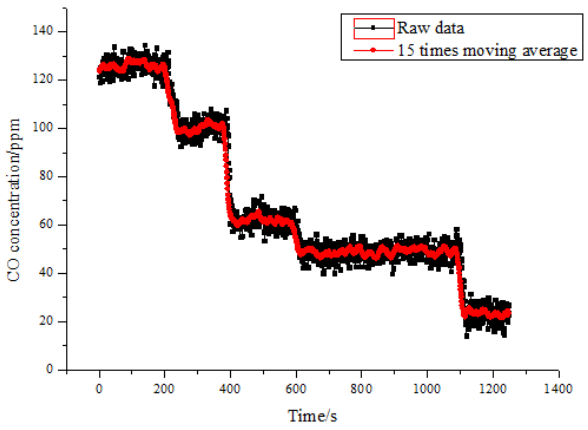

Figure3. Monitoring CO concentration

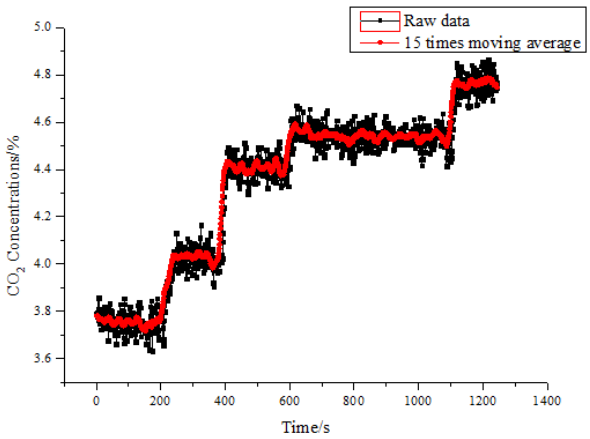

Figure4. Monitoring CO_2 concentration

Five different types of mixed gas samples were prepared and used: 3.75%CO_2 + 125ppm CO, 4%CO_2 + 100ppm CO, 4.375%CO_2 + 62.5ppm CO, 4.5%CO_2 + 50ppm CO, and 4.75%CO_2 + 25ppm CO. Figure 3 shows the measurement of the CO concentrations from these mixed samples and Figure 4 shows similar results from the CO_2 in these same samples. It can be seen that the fluctuation of the CO concentration monitored is ~15ppm, while for CO_2 it is ~0.2%. Using a moving average approach (for 15 samples), the fluctuation of CO decreased to 5ppm, and for CO_2 to 0.07%.

Table1. Data from a series of measurements of CO and CO_2 mixed samples

Ture gas value data		Measurement Data		Errors in the measurement	
CO/ppm	CO2/%	CO/ppm	CO2/%	Absolute error CO/ppm	Relative error CO2/%
125	3.75	130.99	3.75	5.99	0.16
100	4	105.38	4.03	5.38	0.75
62.5	4.375	66.96	4.41	4.46	0.74
50	4.5	54.04	4.54	4.04	0.94
25	4.75	28.52	4.77	3.52	0.32

Table 1 shows the value and error monitored for each CO and CO_2 sample. From this table, it can be seen that the CO test concentration is ~28.52ppm in the mixed gases sample of (4.75%CO_2 + 25ppm CO) yielding an absolute measurement error of ~3.52ppm. Previous experience has shown that the effect of 5% CO_2 on the measurement concentration of the CO in the sample is ~152ppm, allowing a reduction in the impact of CO_2 on the CO measurement of ~97%. The CO_2 concentration can be calculated at the same time, reflecting well the advantages of high measurement accuracy and because of the use of a single laser, the response time and the system cost is reduced.

5. Conclusion

A novel, sample multi-gas detection approach based on single laser has been developed, the underpinning theory analysed and an experimental verification undertaken. The outputs obtained show reduced interference effects when different gases were used, an acceptable measurement accuracy, and high precision synchronous detection with different mixed gas samples. However, the calibration process needed for this method is somewhat complex, so the calibration accuracy has a real influence on the detection accuracy. Improving the calibration process is the next step in this on-going work.

6. Acknowledgments

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References

[1] Liang Yuntao, Hou Xianjun, Luo Haizhu, et al. *Coal Science and Technology*, 2016, vol.44 (6):1-6
[2] Xian Xuefu, Wang Hongtu, Jiang Deyi, et al. *Engineering Science*, 2001, vol.3 (2):28-32
[3] Tingting Zhang, Ynbin Wei, Zhaowei Wang, et al. *International Conference Optical Communications and Networks*, 2017
[4] Fan Jie, Chen Xiao, Huang Qifeng, et al. *Spectroscopy and Spectral Analysis*, 2013, vol33 (12):3326-3329
[5] Liu Jin, Yang Haima. *Chinese Journal of Scientific Instrument*, 2005, vol26 (8):162-163
[6] Ning. Li, *Zhejiang University*, 2008
[7] Tingting Zhang, Yubin Wei, Yanfang Li, *Fourth Asia Pacific Optical Sensors Conference*, 2013