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A long-term stable monitoring system for atmospheric carbon monoxide based on 2.3 μm laser absorption

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Abstract. Recent progress in the development of an atmospheric carbon monoxide (CO) monitoring system using a $\sim 2.33 \mu\text{m}$ laser absorption sensor is reported. The principles of detection technology and the algorithms used for removing noise are discussed. In order to eliminate the cross interferences from the effects of CO_2 and H_2O in the atmosphere, a Distributed Feedback (DFB) laser at a specific wavelength of 2330.18 nm was employed in the system. The CO monitoring system demonstrated excellent accuracy and stability in long-term continuous monitoring. The results obtained have validated the use of such a CO monitoring approach in practical gas monitoring applications.

1. Introduction

As a colourless and odourless gas, carbon monoxide (CO) has been viewed as a silent killer due to its strong affinity for haemoglobin and it is known that exposure to the gas can seriously affect human health. In addition, CO gas present in ambient air at higher concentrations is very dangerous as it can burn or even explode, when the concentration ranges from 12.5% to 74.5%. Moreover, monitoring of CO present is an effective tool to forecast spontaneous combustion in the goaf areas of a coal mine (defined as those parts of the mine from which the coal has been wholly or partially removed) and to monitor combustion efficiency of boilers in coal-fired power plant, as it is one of the most prominent indicators of incomplete combustion of hydrocarbon fuels. Therefore, an effective CO monitoring system is important for a range of practical safety-focused monitoring applications. Monitors of this type can be developed by using Tunable Diode Laser Absorption Spectroscopy (TDLAS) technology, which has been widely used for CO gas sensing, taking advantage of the potential for real time monitoring, offering high sensitivity, long-term stability and excellent reliability.

In previous work, a fiber-based CO sensing system has been developed using a distributed feedback (DFB) diode laser in the wavelength region near $1.56 \mu\text{m}$ ^[1]. It has been successfully applied in the field of coal mine safety, but compared to near-infrared diode lasers, a CO sensor using a diode laser around $2.3 \mu\text{m}$ can provide more sensitive detection because of the stronger first overtone band of CO near $2.33 \mu\text{m}$. Thus such a sensor has attracted significant attention in recent years^[2-4]. A number of $\sim 2.3 \mu\text{m}$ laser-based CO monitoring systems have been demonstrated by different groups for diverse applications such as fire detection, atmospheric environmental condition monitoring or



combustion optimization. Examples include a VCSEL-based calibration-free CO sensor, with an in-line reference cell^[5] and a real-time *in-situ* CO sensor in a pulverized-coal-fired power plant^[6]. More recently, CO measurement has been reported using an extended-wavelength multi-mode diode laser at 2.33 μm ^[7]. Nevertheless, a reliable and long-term stable CO monitoring system, with high sensitivity (in the ppm range) is of real practical value, taking advantage of the excellent accuracy and lower cross interference available from such an approach. In this work, a TDLAS-based CO monitoring system using a 2.33 μm DFB laser is reported, based on the key principles of the detection technology discussed, together with algorithms used for removing noise, with the method employed for eliminating the cross interference from CO₂ and H₂O in the atmosphere.

2. Principles of the detection system

As a spectroscopic method for gas detection, TDLAS technology can be distinguished between conventional direct absorption spectroscopy and wavelength modulation spectroscopy. The former method allows a reliable sensor with the simple and compact structure to be developed, and this approach is adopted in this research. By ramping up the laser current, the emitting laser wavelength can be tuned in an approximately linear way. The intensity of the laser decreases when the laser light is passed through a CO gas sample and as a result, the measured small dip in the background line creates the gas absorption signal. According to the Lambert-Beer law, the CO gas concentration can be obtained using following formula:

$$C = \frac{A}{PS(T)L} \quad (1)$$

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

where C is the volume concentration of the measured CO gas sample, I_0 is the initial light intensity, I is the light intensity due to the absorption, λ is the laser wavelength, L is the length of the optical path, P is the total pressure of the gas medium and $S(T)$ is the intensity of the characteristic spectral lines (which show a temperature dependence).

3. Experimental Investigation

Figure 1 shows a schematic of the CO gas monitoring system developed. In order to avoid cross interference with other gases in the atmosphere, the diode laser operates at a wavelength ~ 2330 nm, which is the absorption line of the CO gas, a wavelength where the corresponding absorption intensity is $3.39 \times 10^{-21} \text{ cm}^{-1}/(\text{mol} \times \text{cm}^{-2})$. Meanwhile, applying good temperature control and a stable current driver, the DFB diode laser steadily operated at a temperature of 29.5°C and over the current range from 60 – 85 mA, with an output power > 2 mW. The laser wavelength modulation was obtained using a 50 Hz sawtooth wave produced by the current driver circuit. The effective length of the gas cell used was ~ 3.3 m. Both sides were coated with gold film inside the gas cell, providing a broadband transmission over the range from 0.2 to 12 μm . Following data acquisition and analogue-to-digital conversion, three different algorithms using Fourier-transform, least-squares fitting and Kalman filtering are used to improve the system performance.

4. Results and discussion

4.1. Cross interference issues

During practical measurements with the system described, cross interference is mainly seen from different hydrocarbon gases present, arising from the overlapping absorption bands in the infrared spectral region. For the CO monitoring system, the interference from both CO₂ and H₂O are the major challenge in the atmospheres investigated. Therefore, based on the molecular absorption Hitran database, the absorption peaks of CO, CO₂, and H₂O are highly relevant and illustrated in Figure 1. As shown, the CO absorption line at 2330.18 nm is the preferred choice to use as its absorption

intensity is greater in that region than that of CO₂ and H₂O by several orders of magnitude (showing almost no interference from CO₂ and H₂O in the atmosphere).

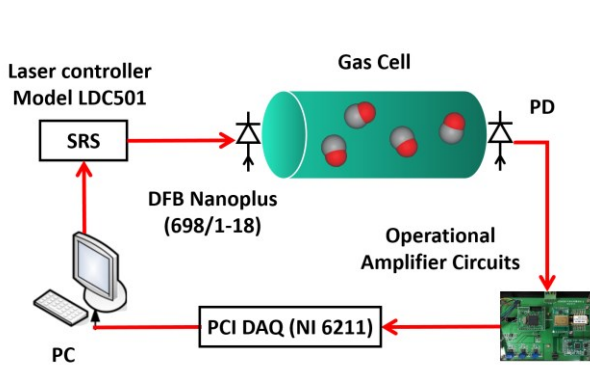


Figure 1. Schematic of the CO gas monitoring system developed.

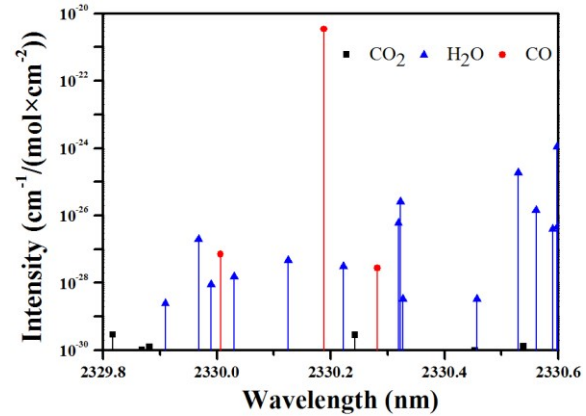


Figure 2. Illustration of key absorption lines in the spectral region around 2330 nm.

4.2. Monitoring system

In the experiment carried out, the Fourier-transform method was used to eliminate the interference effects generated and which resulted from the gas cell. Least-squares fitting was employed to remove the random noise, which improved considerably the signal-to-noise ratio (SNR) and the detection accuracy. Furthermore, the Kalman filtering algorithm was applied to enhance sharply the stability and reliability of the monitoring system developed.

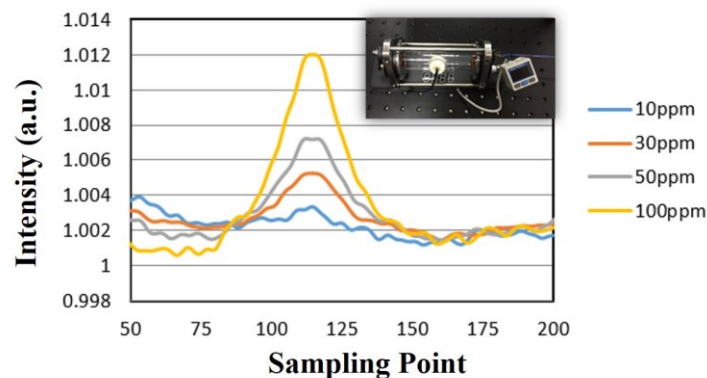


Figure 3. Normalized signals showing the absorption intensity for four different gas concentrations and the actual gas cell used (inset).

The CO gas, at a concentration of 100 ppm, was mixed with nitrogen (N₂) to create various known, standard CO gas samples – at 10 ppm, 30 ppm, and 50 ppm. These gases were successively filled into the gas cell. The inset in Figure 3 shows the actual gas cell used in the CO monitoring system. The signals detected were transmitted to a PC and processed using a normalization approach. Figure 3 shows the normalized absorption intensity corresponding to the four different concentrations shown. The results show that the CO monitoring system could readily sense the CO gas, at a concentration as low as 10 ppm. Figure 4 shows the software interface of the CO monitoring system, developed using LabView. The interface was designed to show the key control parameters and run data from the CO sensor developed, together with graphs showing the changes in the detection signal, the average

detection signal, the normalized signal, the least-squares fitted curve, and a real-time display value of CO concentration. Data recorded (and illustrated in Figure 4(a)) can be used to determine that the detection accuracy of system was about ± 2.5 ppm when as low as 10 ppm CO gas was detected during the experiment. As illustrated in Figure 4(b), the CO monitoring system can operate with high precision for quite a long period in practice.

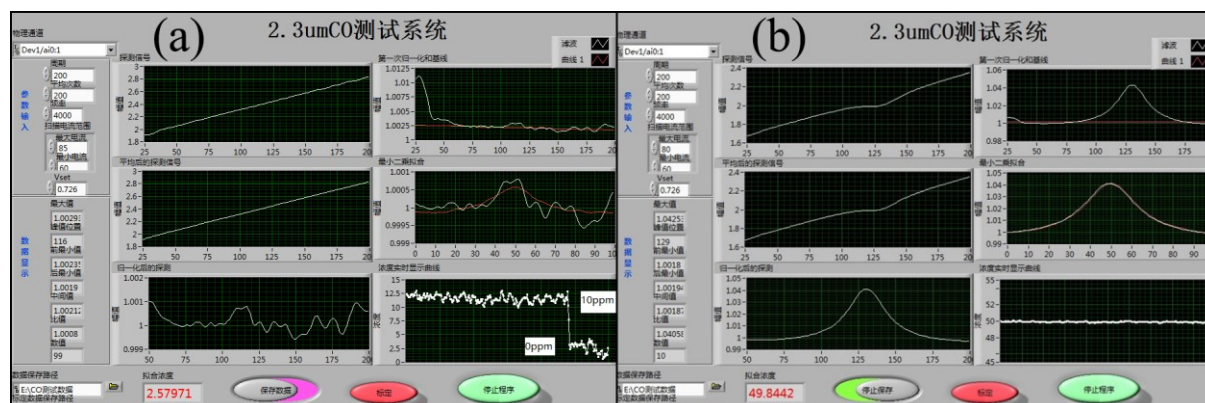


Figure 4. The LabView user interface for the CO monitoring system when detecting the CO gas at a concentration of 10 ppm (a) and 50 ppm (b). (The features of the display are discussed in the text)

5. Conclusion

In summary, the underpinning principles of the detection technology used and the algorithms employed for removing noise in a laser-based CO gas detection system were introduced. The system has used a DFB laser at a wavelength of 2330.18 nm, where this wavelength was chosen to eliminate the cross interference from both CO₂ and H₂O in the atmosphere. The CO monitoring system developed has demonstrated high precision and stability for long-term, continuous monitoring of this important pollutant and flammable gas. The results obtained have shown that such a CO monitoring system is well suited to practical applications in gas monitoring, for example use in mine goafs. Further work is under way and is focused on eliminating the smaller cross interference from the CH₄ gas that is regularly seen in mines, with an improvement of detection accuracy being targeted through a longer optical path in the gas cell being used.

6. Acknowledgement

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