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Quasi-distributed multipoint laser methane detection system and its application in cable trench safety monitoring

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Abstract. A low power consumption, quasi-distributed, multi-point laser methane detection system incorporating a Vertical Cavity Surface Emitting Laser (VCSEL) has been designed and its performance discussed. Being based on the features of the methane absorption spectrum and adaptive tracking technology, the system can realize on-line methane monitoring across 14 channels of sensors, with the maximum transmission distance for each sensor being 10km. Working across a temperature range of 0℃-40℃, the measurement error was determined to be less than ±0.03% (of the gas concentration) when the methane volume concentration lies in the range up to 10% methane. The system has been tested in-the-field in a cable tunnel belonging to a power supply company in Jinan in China and the test results achieved show that the system has the high accuracy and good stability needed for use in industrial safety monitoring.

1. Introduction

With the rapid development of China's industry and the large-scale urban network transformation [1], there is increasing activity in the construction of distributed networks to meet the range of communications and service needs. The use of more data transmission services and the need for better communications infrastructure has meant that there is increasing use of overhead lines as a seemingly inevitable trend in the rapid urban development being seen. This expansion of the number of service-carrying tunnels, often containing gas pipelines as well, means there is a need gas pipeline monitoring and an effective methane detection device, for use in such tunnels to prevent the build-up of the gas and the prevention of fire and explosions.

Tuneable Diode Laser Absorption Spectroscopy (TDLAS) has become an important approach methane detection. This was first put forward in the 1970s by Hinkley and Reid [2] and with the continuous development of the technology, more and more different kinds of gases can be detected effectively, such as O_2, H_2O, CO and in particular NOx, which is hazardous in the atmosphere [3-6]. In the recent years, the rapid development of tuneable semiconductor lasers which have the characteristics needed for in-the-field sensors of small size, long life and high power, thus further promoting the range of applications of TDLAS. With this approach, multiple gases in gas mixtures can be detected at the same time using remote detection methods with an open light path [7-9].

To decrease the complexity and the power consumption of the sort of detection system that can be used effectively in these tunnels, a wavelength adaptive tracking system is reported [10]. In order to reduce the cost of systems that could be applied in-the-field, a distributed wavelength adaptive tracking laser methane detection system is presented in this paper. It can realize on-line methane monitoring across 14 channels, where the maximum transmission distance for each sensor is 10km. This is particularly well suited to the range of applications considered, be the power cable trenches or other tunnels, and test result obtained have shown that the detection system has high measurement precision, a large range and good stability.

2. Measurement principle and system design

2.1. Measurement principle

Based on the Beer-Lambert law, when monochromatic light of wavelength, λ, is transmitted through the sample gas, the relationship between the intensity of the received light signal, $I(\lambda)$, and the light transmitted by the laser, $I_0(\lambda)$, can be given by the following relationship:

$$\mathrm{I}(\lambda) = I_0(\lambda) exp[-\alpha(\lambda)CL] = I_0(\lambda) exp[-PS(T)CL] \qquad (1)$$

where $\alpha(\lambda)$ is the gas absorption coefficient; C is the gas (volume) concentration; L (cm) is the length of the absorption path; $\mathrm{S}(T)$ is the intensity of characteristic spectral line of the studied gas; P is the pressure of the sample gas and $\phi(\lambda)$ is the lineshape function.

Equation (1) can further be rewritten in the following way

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

Allowing the gas concentration to be given by:

$$\mathrm{C} = \frac{A}{PS(T)L} \qquad (3)$$

Then according the equation (3), if P, $S(T)$ and L are all known, the gas concentration can be obtained if the integral values are used in the frequency domain in equation (3).

2.2. System design

The methane sensor system was designed using the wavelength adaptive tracking technique, where the absorption peak lines at wavelengths of 1645.5nm, 1650.9nm and 1653.7nm were chosen as the best absorption lines. A schematic of the system is shown in Figure 1, in which the laser is modulated by a sawtooth current signal. The light from the VCSEL source is divided into 16 beams. One beam is used as a reference signal for the initial light power, a further beam is input to the photodetector after passing through a transmission chamber, filled with a high concentration of methane gas. The other 14 beams of light create the 14 sensor channels where the light passes through to the gas sample to the photoelectric detector. A voltage corresponding to that signal is generated and send to CPU, where after analysis, the methane concentration at 14 distinct monitoring points is obtained.

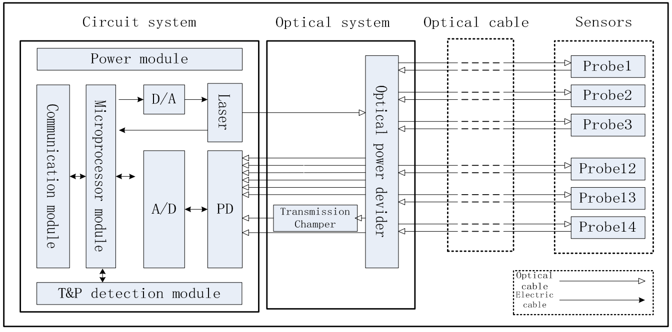

Figure 1 System structure, showing the 14 distinct sensing channels

3. System test

3.1. Calibration data in LAB

Each of the 14 channels that comprises the detector system is relatively independent of each other. However, due to the differences between the couplers used, the effective length of each probe and the photodetector and the conversion acquisition circuit used, there is a need to calibrate and thus verify the performance of each sensing probe, for each channel, before the device is used in a field test. After the calibration of each channel, and at temperatures that correspond to cable trenches across the world at different seasons (0℃, 9.5℃, 29.5℃, 31℃ and 41℃), gas mixtures created with high purity nitrogen and various levels of methane gas, at volume concentrations of 0.5%, 1.5%, 3.5%, 6.0%, 8.3% and 10.1% were used to evaluate the performance of the sensor system. Typical, sample results from the large datasets that were obtained are shown in Figure 2 (where the temperature was 0℃ and 40℃). The measurement precision that was derived from the results of those tests can be seen from the graphs in Figure 2.

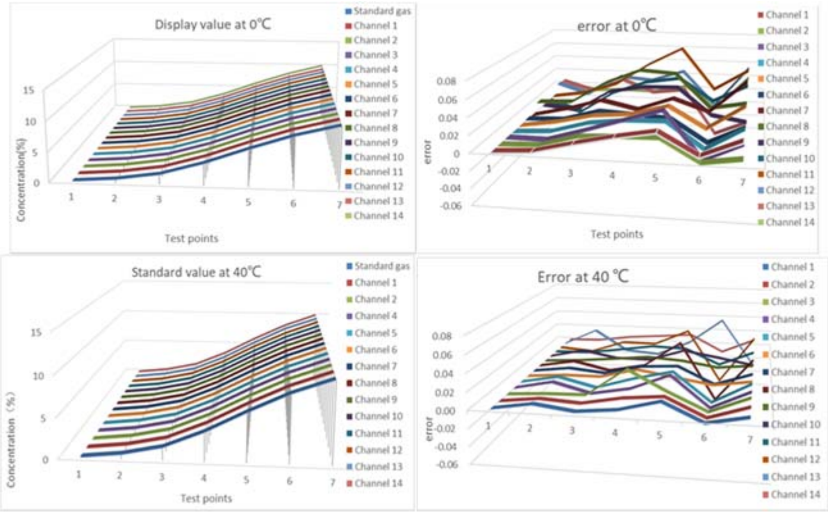

Figure 2 Sample results showing the measurement of gas concentration (left hand upper and lower graphs) and the measurement error (right hand upper and lower graphs) from the different sensor channels, 1 – 14 used (and shown in different colours) at temperatures of 0℃and 40℃, as shown.

3.2. Field test data

Field tests next were carried out to verify that the systems operated well in the environment for which it was designed. The site chosen was a cable tunnel owned and operated by a Power Supply Company in China. Here the system was installed between two fire doors, and a photograph of the installation on site is shown in Figure 3. The cable trench in this test was 80 m in length, with width and height of ~2 m. After closing two fire doors, a closed space of volume about$\sim 3.2 \times 10^5$ L was formed. A standard gas sample, at a pressure of 10Mpa, a volume of 8L and a concentration of 3% (vol/vol) is slowly released into the closed space. After time is allowed for gas diffusion to occur, the maximum theory concentration of CH_4 reached in the roadway is about 0.075%. To give comparative data, the electrochemical methane sensors used gave a 'zero reading' during the test. The results of the tests with the optical sensors used are shown in Figure 4. Here the maximum measured values for the CH_4 concentration, in the two channels used, are 0.09% and 0.07% respectively (which are in agreement with theoretical predictions). Figure 3 shows the gas concentration recorded at two different sensor locations (shown as Channel 1 and 2). The two graphs are similar in shape (with different maxima – before the error is included – but also in part due to the different locations used and the gas diffusion) and they show a small time difference, also due to the diffusion time of the gas in the chamber.

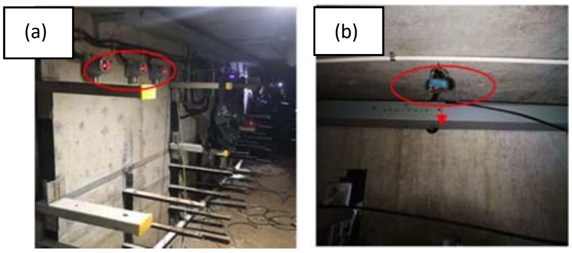

Figure 3 Photographs of sensors deployed in the field – (a) electrochemical methane sensors and (b) a single laser-based methane sensor

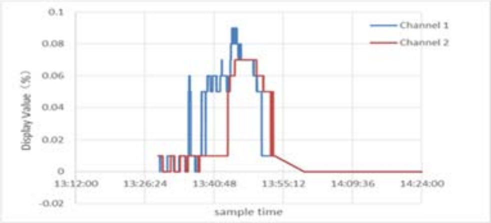

Figure 4 Field test data showing the gas concentrations displayed measured from Channel 1 and 2.

4. Conclusion

A multi-point distributed methane system with wavelength adaptive tracking has been presented. The test results from both laboratory and field tests show that the system has the desired characteristics of high measurement precision and good stability. On-going work is designed to enhance the measurement accuracy of the system by extending probe's effective absorption length and optimization algorithm.

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