Pipeline Laser Methane Detector Based on TDLAS Technology for In-situ Direct Measurement

Yao WANG 1, 2

1 China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing 400039, China;

2 State Key Laboratory of the Gas Disaster Detecting, Preventing and Emergency Controlling. Chongqing 400037, China)

*Corresponding author’s e-mail: wangyao309@163.com

Abstract: In order to quickly detect methane gas in real time, solve the defects of the traditional "extraction method" methane concentration measurement of gas pipeline based on pump suction or differential pressure sampling, and ensure the sensor's performance requirements for resolution, a pipeline laser methane detector for in-situ direct measurement, based on TDLAS technology, has been developed. By studying effect of different chamber length on the resolution of different concentrations of methane gas, the gas chamber with length in the range of 4~6cm can meet the performance requirements as much as possible, and the detector combine with the processing circuit designed with low power consumption for concentration demodulation. Test has shown that the measurement error in the range of 0%~10% is less than ±0.05%CH4, and the measurement error is less than ±5% of the true value in the range of 10%~100%.

1. Introduction

According to the national coal mine accident analysis, among the coal mining safety accidents, gas accident has always been one of the most important accident types in China's coal mining safety accidents[1]. In order to prevent and control the occurrence of gas accidents, it is particularly important to carry out gas drainage, monitoring and control in high gas mines according to the gas control policy of "pumping before mining, monitoring and control, and determining production by wind" and the requirements of "reliable ventilation, pumping and mining marking, effective monitoring and management in place"[2]. In addition, gas extraction and utilization is also an important part of China's energy structure. However, there are major potential safety hazards in the process of gas emission, transportation and extraction. Therefore, studying the safety guarantee technology of gas extraction, transportation, utilization and emission can effectively improve the safety of coal mining, promote the development of gas extraction and utilization and energy conservation and emission reduction industry, and provide safety technical guarantee for promoting the realization of the double carbon goal of "carbon neutrality and emission peak"[3].

According to the detection principle, the traditional on-line monitoring or portable instrument can be divided into thermal catalytic type, thermal conductivity type, gas sensitive type, optical interference type and infrared type[4]. In recent years, with the development of harmonic detection technology based on tunable diode laser absorption spectroscopy, laser methane detection has gradually become an important detection method of trace gases. By using the narrow line width and
tunable characteristics of semiconductor laser, the measurement of gas concentration is realized by measuring the intensity of characteristic absorption line of detection gas. Compared with traditional detection methods, laser methane detection has the advantages of good real-time performance, long service life, high accuracy and no frequent calibration[5]. According to Article 2 of the notice on strengthening gas control and effectively curbing major accidents in coal mines (2017) No. 18 document of the State Administration of Work Safety: The upgrading and transformation of safety monitoring system is actively promoted and the use of advanced and practical infrared, laser and other methane sensors is promote. However, whether the traditional detection principles such as optical interference (light tile), thermal catalysis, thermal conductivity and infrared are used, or the laser spectral absorption detection principle is used to detect the methane concentration in the gas pipeline, the sample gas is generally led from the gas pipeline to the detection element probe for concentration measurement through the "extraction method", and the commonly used methods of sample gas extraction are pump suction method or differential pressure gas extraction method. But the characteristic of this method is that the measured gas is first led out of the gas pipeline through the gas taking device, then introduced into the gas filtering device through the gas guide pipe, and finally enters the detection element probe for concentration measurement under the action of gas diffusion. Its disadvantages are: (1) The measured gas needs to pass through the gas taking device, filtering device and intermediate link diversion gas path, and finally diffuse to the detector probe, resulting in long measurement response time and poor real-time performance. (2) Temperature and pressure compensation is required for pipeline concentration measurement and calculation. After the measured gas is led out from the pipeline through the gas taking device, the measured temperature and pressure cannot reflect the real working conditions in the transmission pipeline. (3) Due to the temperature difference caused by the measured gas led out from the pipeline, the water vapor in the measured gas is easy to form condensate at the probe end of the detection element, which affects the detection performance of the probe. (4) Due to the need of gas taking auxiliary device for measurement, there are many intermediate links of gas path and long gas path, which is prone to air leakage, resulting in measurement data distortion. (5) Generally, the structure design of gas intake auxiliary device is complex and not compact enough.

In this paper, combined with the inevitable trend of TDLAS technology applied to methane concentration monitoring in gas drainage pipeline and natural gas transmission pipeline, in order to solve the defects of methane concentration measurement in traditional "extraction method" gas pipeline based on pump suction or differential pressure collection of sample gas, and the influence of optical path length of absorption chamber on the contradictory relationship between measurement range and measurement precision, a pipeline laser methane detector based on TDLAS technology for in-situ direct measurement is designed.

2. Measurement principle of TDLAS

The application of TDLAS harmonic detection technology for gas concentration detection is based on the principle of gas infrared spectrum absorption[6-7]. When the infrared light emitted by the laser irradiates the methane gas, due to the characteristic absorption of the light power of the methane gas in the infrared band, the light intensity will decay accordingly, and then the gas concentration is determined by measuring the change of light intensity[8-9].

According to Beer-Lambert law, each gas with polar molecular structure has a corresponding characteristic absorption wavelength. When the optical path and reflection coefficient are unchanged, the light intensity of a single color light passing through the gas to be measured can be expressed as[10-11]:

$$I_r = I_o \exp[-PS(T)\varphi(\nu)L]$$

In the formula, $I_o$ is the initial laser intensity, $I_r$ is the laser intensity after gas absorption, $S(T)/(\text{cm}^2\cdot\text{atm}^{-1})$ is the intensity of the characteristic spectral line of the gas, which is only related to the gas temperature, $P$ is the gas pressure, $L$ is the propagation distance of the laser in the gas, that is,
the optical path length, $X$ is the gas concentration, $\varphi(\nu)$ is a linear function, which describes the shape of the gas absorption spectral line.

From formula (1):

$$-\ln \frac{I}{I_0} = P(S(T)\varphi(\nu)XL$$

It is generally considered that the linear function of gas absorption is standard and can be normalized, that is:

$$\int \varphi(\nu)d\nu \equiv 1$$ (3)

Combined with formulas (2) and (3), the following formula can be derived:

$$X = \frac{\int \ln \frac{I}{I_0}d\nu}{PS(T)L}$$ (4)

It can be seen from formula (4) that the gas concentration can be calculated as long as the laser intensity after the laser beam passes through the gas to be measured is measured. Therefore, the light absorptivity of the gas chamber directly affects the accuracy of measurement.

For laser gas detection technology, in the range of 100% requirements, the length of the gas cell optical path affects the measurement resolution of the low-end (0%~10%) and the high-end (10%~100%). The reasonable design of air chamber structure enables the product to meet the performance requirements: the resolution is required to be 0.01% at the low-end (0%~10%) and the resolution is required to be 0.1% at the high-end (10%~100%).

The absorption rate of specific absorption peak of methane gas in unit optical path is $\mu$. The light absorptivity of the gas chamber is $K$.

$$K = \frac{I_l}{I_0} = 1 - e^{\mu L}$$ (5)

According to the HITRAN spectral library, $\mu=4.204E^{-3}$ cm$^{-1}$ (1% methane gas), -4.122E$^{-2}$ cm$^{-1}$ (10% methane gas), -3.448E$^{-3}$ cm$^{-1}$ (100% methane gas) at 300K and a standard atmospheric pressure.

According to formula (5), the light absorptivity corresponding to 100% methane gas is 96.72%, 81.90% and 49.52% respectively for three optical path gas chambers of 10 cm, 5 cm and 2 cm. The light absorptivity of the gas chamber is directly proportional to the measurement resolution. The absorptivity is higher, and the measurement resolution is higher. Assuming 10% methane gas, the measurement resolution of optical path of 10 cm gas chamber is 0.01%, which is nominal value of laser methane sensor. The relationship between the length of the air outlet chamber and the measurement resolution of the sensor obtained from formula (5) is shown in Figure 1.

![Figure 1 Relationship between optical path length of gas chamber and measurement resolution](image)

1. 1% CH$_4$  2. 10% CH$_4$  3. 100% CH$_4$

4. The product of the resolution corresponding to 10% CH$_4$ and 100% CH$_4$
By analyzing the data above, it can be seen that in order to ensure that the low-end measurement resolution is 0.01% and the high-end measurement resolution is 0.1% within the methane concentration range of 0% - 100%, the resolution change curve corresponding to 10% methane gas and the resolution change curve corresponding to 100% methane gas are multiplied according to the resolution value corresponding to the same optical path length. Obtain the resolution product effect value. Obviously, the optimal resolution optical path value is near the minimum value of curve 4, that is, the optical path length of the air chamber should be set at 4 ~ 6 cm, which is the area near the minimum of curve 4.

3. Design of pipeline laser methane detector for in-situ direct measurement

The pipeline laser methane detector based on TDLAS technology for in-situ direct measurement is designed in this paper, which is composed of main meter and detection rod. In order to improve the real-time and accuracy of measurement, the probe rod is directly inserted into the pipe to realize in-situ direct measurement of gas concentration, as shown in Figure 2. Under the combined action of gas flow and diffusion, the gas in the gas pipeline directly enters the gas absorption pool of the detection probe rod through the filter diaphragm, and the spectral absorption measurement is carried out. In addition, the probe rod integrates a temperature probe and a pressure probe. The temperature probe is directly inserted into the pipe to measure the real temperature in the pipe. The pressure detection needle is directly connected with the pipeline gas without passing through intermediate links and affected by external conditions, so as to ensure the real-time and accuracy of measurement. The incident laser beam comes from the laser emission source, enters the laser collimator through optical fiber transmission, and then passes through the gas absorption cell in the detection rod. Finally, the light wave enters the laser detector and is converted into an electrical signal, which is demodulated by the supporting processing circuit. In this way, the detector is applied to methane concentration monitoring of gas drainage pipeline and natural gas transmission pipeline combined with TDLAS technology, which solves the defects of traditional "extraction method" methane concentration measurement of gas pipeline based on pump suction or differential pressure sampling.

![Diagram of installation and use of laser methane detector](image)

**Fig. 2 Diagrammatic sketch of installation and use of laser methane detector for in-situ direct measurement pipeline**

1. Main header  2. Laser  3. Sealing ring  4. Detecting rod  5. Pressure detection element  6. Conduit

3.1 Structural design of detecting rod

The probe at the front end of the detecting rod is equivalent to the laser measurement air chamber, and its structure has a decisive impact on the measurement response speed and measurement accuracy. The detecting rod is composed of installing flange, support rod, sealing ring, absorption cell, laser collimator, detector, filter, temperature probe, pressure detection needle tube, etc., as shown in Figure 3. The detecting rod integrates a temperature probe and a pressure probe. The temperature probe is directly inserted into the pipe to measure the real temperature in the pipe. The pressure detection
needle is directly connected with the pipeline gas without passing through intermediate links and affected by external conditions, so as to ensure the real-time and accuracy of measurement.

Figure 3 Structure of the detecting rod
1. Mounting flange  2. Support rod  3. Sealing ring  4. Pressure detection needle tube  5. Laser collimator  6. Temperature probe  7. Absorption cell  8. Protective sleeve for electric wire  9. Filter  10. Protective cover of filter  11.Laser detector

According to Beer-Lambert law, the detection sensitivity is related to the optical path length of gas absorption. Considering the easy processing and installation convenience of the air chamber, the measuring rod is designed as a hollow cylinder. The effective optical path is 50 mm and the material is stainless steel. Cylindrical filter membrane and diaphragm protective cover are set outside the absorption tank at the front end of the detecting rod, which can reduce the pollution of the air chamber to a certain extent and effectively prolong the adjustment free period of the detector. Temperature and pressure sampling points are set in the absorption tank to compensate and calculate the analytical concentration. One end of the gas chamber is a laser collimator and the other end is a laser detector. The collimator and the detector are connected and coupled efficiently to realize the propagation of light in the absorption cell for spectral characteristic absorption and light intensity measurement.

3.2 Design of processing circuit
The circuit design of the detector mainly includes power module, low-power MCU, low-power laser, temperature control and driving circuit, photoelectric conversion circuit, display module and audible and visual alarm module.

The detector adopts low-power design strategy, selects low-power TEC small package laser and low-power photoelectric conversion chip, so as to achieve very low power consumption in essence, and designs the low-power temperature control driving circuit for the selected laser. The optimized algorithm is adopted to reduce data overhead and equipment power consumption overhead, so as to achieve the low-power design of the detector. The detector is equipped with laser temperature control current interface and driving current interface to realize the control and adjustment of laser output wavelength center. The data storage chip mainly accesses the temperature setting value corresponding to the laser and the original data storage. Then the converted and adjusted photoelectric signal, temperature signal and pressure signal are directly sampled by ad, and the low-power MCU realizes signal acquisition and simplified algorithm demodulation. The microprocessor on the main board reads the demodulation physical quantity detection values in real time and displays them. At the same time, it controls the buzzer and alarm lamp to give periodic audible and visual alarm according to the preset alarm point information.
4. Test verification

The detector is fed with methane standard sample gas, and then the output signal is detected after absorption in the gas chamber. The first harmonic amplitude signal is extracted by band-pass filter, phase-locked amplification and low-pass filter. After A/D sampling and data processing, the peak, peak and average values of the first harmonic are obtained. Finally, the concentration value of the gas to be measured is obtained by data fitting.

4.1 Calibration

- **Zero point regulation:** After the zero point of the sensor is stabilized in clean air for 20 min, adjust the concentration display value to 0.
- **General linear adjustment:** Inject 2.00% CH₄ standard gas according to the specified flow rate. After the display is stable for 1 min, adjust the concentration value displayed by the detector to be consistent with the concentration of standard gas, and do not calibrate again in subsequent measurement.
- **Internal linear adjustment:** Inject 0.50% CH₄, 2.00% CH₄, 8.50% CH₄, 20.0% CH₄, 60.0% CH₄ and 85.0% CH₄ respectively according to the specified flow. After the display is stable for 1 min, adjust the concentration value displayed by the detector to be consistent with the concentration of standard gas.

4.2 Error measurement

According to the specified flow, inject 1.00% CH₄, 8.01% CH₄, 35.0% CH₄, 75.0% CH₄ and 100.0% CH₄ into the tester in turn. After the display is stable for 1 min, record the concentration value. The basic measurement error is the difference between the arithmetic mean value of three measurements and the standard value.

| Standard value (%CH₄) | Original signal value | Average measured value (%CH₄) | Basic error (%CH₄) | Relative error (%) |
|-----------------------|-----------------------|------------------------------|-------------------|-------------------|
| 1.00                  | 17 662                | 0.98                         | -0.02             | -1.00             |
| 8.01                  | 7 643                 | 7.97                         | -0.03             | -0.37             |
| 35.0                  | 23 034                | 35.1                         | 0.1               | 0.30              |
| 75.0                  | 34 073                | 75.1                         | 0.1               | 0.10              |
| 100.0                 | 41 064                | 99.8                         | -0.2              | -0.20             |

It can be seen from the measurement data in Table 1 that the measurement error of the tester is less than ± 0.05% CH₄ in the range of 0% - 10%, and the measurement error is less than ± 5% of the true...
value in the range of 10% - 100%. The detector is used for coal mine safety monitoring, and its performance meets the requirements of relevant national standards.

5. Conclusion
In order to ensure the performance requirements of the detector for resolution, by analyzing the resolution influence curves of different gas chamber lengths on different concentrations of methane gas, the resolution product effect value is obtained by multiplying the resolution value corresponding to the same optical path length. It is obtained that the optical path length of the gas chamber is set in the range of 4 ~ 6 cm, which can meet the performance requirements for resolution to the greatest extent. This paper only studies the influence of the structural design of the detecting rod on the resolution, and the measurement resolution of the sensor can be improved from other aspects.

In this paper, a pipeline laser methane detector based on TDLAS technology for in-situ direct measurement is designed, and the effective optical path is 50 mm. When in use, the probe rod is directly inserted into the pipeline and equipped with a low-power processing circuit for concentration demodulation to realize the direct measurement of in-situ gas concentration, which solves the defects of the traditional "extraction method" methane concentration measurement of gas pipeline based on pump suction or differential pressure sampling.

The test shows that the measurement error of the detector is less than ± 0.05% CH4 in the range of 0% ~ 10%, and the measurement error is less than ± 5% of the true value in the range of 10% ~ 100%. The laser methane detector is used for coal mine gas concentration monitoring, and its performance meets the requirements of relevant national standards.

Foundation item
Special project of science and technology innovation and entrepreneurship fund of Tiandi Science & Technology Co., Ltd (No.2021-TD-MS008), Independent key R & D scientific research projects of CCTEG Chongqing Research Institute (2021ZDXM03).

References
[1] Meng, Y., Xie, D.H., Su, B. (2020) Statistics and analysis of coal mine production safety accidents in China from 2010 to 2019. Mineral Engineering Research, 35: 27-33.
[2] Li, X.Q. (2021) Coal mine gas control and prevention strategy analysis. Modern Chemical Research, 11: 47-48.
[3] Hu, X.L., Song, W., Peng, C.S. (2021) Control and utilization of coal mine gas to achieve carbon peaking and carbon neutrality. Huadian Technoligy, 43:52-56.
[4] Liu, Y.P., Wang, X., Li, S.S. (2015) Gas concentration detection method based on infrared absorption spectroscopy technology. Acta Photonica Sinica. 44: 1-7.
[5] Chang, L. (2016) Laser methane sensor for coal mine based on pressure compensation. Safety in Coal Mines. 47: 126-128.
[6] Dong, L., Ma, J.G., Yin, W.B. (2005) An analysis of frequency stability of LD stabilized to CH4 absorption lines at 1.6um. Acta Photonica Sinica. 34:489-492.
[7] Wang, Z., Cao, J.N., Zhang, K.K. (2010) Research on practicality of methane gas sensor based on harmonic peak to average power ratio. Chinese Journal of Lasers. 37: 1505-1509.
[8] Ma, X.K., Rui, Q.H., Zhou, Y. (2015) Design of mine laser methane sensor based on TDLAS technology. Colliery Mechanical & Electrical Technology. 4:28-30.
[9] Zhang, K.K. (2012) Research on the spectrum absorptive optical gas detection theory and technology. Harbin Engineering University. Harbin.
[10] Pang, T., Wang, Y., Xia, H. (2016) Full scale methane sensor based on TDLAS technology. Acta Photonica Sinica. 45:1-7.
[11] Pang, T. (2016) Research and system design of gas on line monitoring in industrial process. University of Science and Technology of China. Hefei.