Journal of Computers Vol. 33 No. 3, June 2022, pp. 195-206
doi: 10.53106/199115992022063303016

Research and Simulation of Oil and Gas Pipeline Leak Detection Based on Optical Fiber Sensors

YingGang Xie[1*], Yuanxiong Chang[1], YunBin Ma[2], HongDa Tang[1]

[1] Key Laboratory of Information and Communication Systems, Ministry of Information Industry, Beijing Information Science and Technology University, China
{xieyinggang, chyx, tanghongda}@bistu.edu.cn
[2] Intelligent Research Center, National Pipeline Network Group Research Institute, China
mayb01@pipechina.com.cn

Received 16 April 2022; Revised 16 May 2022; Accepted 16 June 2022

Abstract. This subject mainly researches and simulates the detection method of gas environment by TDLAS gas detection technology. At present, the design of the underground pipe network is relatively complex, which often requires a lot of manpower and financial resources to maintain, and occasionally the corresponding leaked data cannot be detected or transmitted in time. However, if the gas concentration can be detected by TDLAS technology, the corresponding leak points can be found in time. It is directly transmitted to the corresponding host computer through the optical fiber perception, so that the inspectors can find the leakage in time. This subject mainly studies and simulates the application of TDLAS direct absorption method for gas detection, which can accurately measure the methane concentration in the gas environment. Corresponding coordination is mainly carried out through the semiconductor laser, the adjusted signal is injected into the gas chamber environment, and the concentration of the gas in the corresponding environment is calculated by comparing the changes of the light intensity before and after, so that the concentration change of a corresponding gas environment can be fed back.

Keywords: TDLAS, spectral absorption, direct absorption, gas concentration detection, pipe network

1 Introduction

Natural gas is one of the main energy sources currently used by people. At the same time, natural gas transportation is an important part of fossil energy transportation, mainly through pipelines. The construction and leak detection of natural gas pipelines are the key points related to the safety of natural gas development and application. TDLAS detection technology can pre-detect the pipeline, so as to detect the problem of natural gas leakage in time, and analyze the hidden dangers of the corresponding pipeline [1]. The main problem in the operation and maintenance of underground natural gas pipelines is the leakage of gas. If leakage occurs, it will affect the safety of the surrounding environment [2]. At present, there are also a large number of underground natural gas pipeline networks in the city. It is an extremely large and complex system. In our lives, every household has a corresponding gas supply. If a problem occurs, it will cause a lot of economic losses and casualties, which will affect the normal life of every resident living in the city. Therefore, timely and accurate detection of natural gas pipelines is required.

2 Principle of TDLAS Detection Technology

Tunable Laser Diode Absorption Spectroscopy (TDLAS) technology is based on the consistent and stable absorption of the absorption spectrum of the semiconductor laser light source and the gas molecules corresponding to the absorption intensity of the gas [3]. By measuring the degree to which the gas absorbs light of a specific wavelength, the concentration of the gas can be obtained. At present, there are two main methods of TDLAS technology, direct absorption method and harmonic modulation method [4]. The front-end circuits of the two are basically the same, as shown in Fig. 1. The corresponding modulated signal is loaded on the light source to modulate its wavelength. The modulated light enters the gas chamber and is accepted by the fiber probe. After pre-amplification and preliminary filtering, the subsequent steps of the two methods are different [5]. The wave-

* Corresponding Author

length modulation method will carry out secondary coordination and transmit it to the corresponding detection instrument [6], while the direct absorption method is directly detected through a low-pass filter [7].

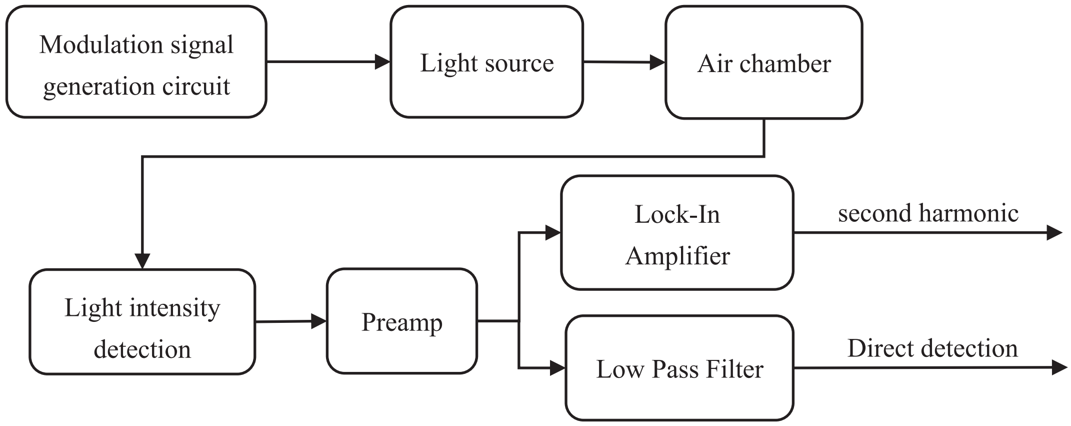


Fig. 1. Detection systems

This time, the direct absorption method was adopted. The TDLAS direct absorption method mainly modulates the output frequency and output wavelength of the emitted laser by superimposing a low-frequency sawtooth wave on the semiconductor laser [8], and then analyzes the absorbance by comparing the output light intensity with the light intensity before output [9]. Thereby, parameters such as gas concentration, temperature and pressure of the gas to be measured are calculated according to the formula [10]. The overall environment process is shown in Fig. 2.

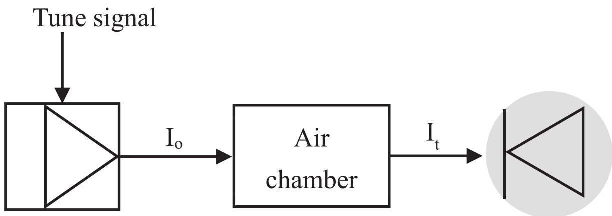


Fig. 2. Gas absorption process

In the direct absorption method, the basic formula of the absorption process mainly adopts the Lambert-Beer law [11], and its formula is

$$I_t = I_0 \cdot exp(-P \cdot C \cdot S(T) \cdot \Phi(v) \cdot L) \quad \textbf{(1)}$$

In the formula, I_t is the light intensity passing through the air chamber；I_0 is the light intensity before incident; P is the pressure; C is the gas concentration; $S(T)$ is the spectral line intensity; $\Phi(v)$ is a linear function of absorption, indicating the state of the absorption line of the gas to be measured, v is the laser frequency; L is the optical path [12].

Ideally, the spectrum would have a discrete distribution, but in fact would have a continuous function centered on the gas absorption site [13]. And there is the highest absorption peak at the absorption point [14], and the shape of the absorption line is described by a Lorentzian linear function [15]. Its linear function can be expressed as:

$$\Phi L(v) = 1/2\pi \ (\Delta V_L)/((v\text{-}v_0)^2+((\Delta v_L)/2)^2) \quad \textbf{(2)}$$

v is the laser scanning wavelength range; v_0 is the transition frequency of the corresponding spectral line; ΔV_L is the half-width of the absorption spectrum [16]. Under normal circumstances, the temperature and pressure are in a normal outdoor environment, and the detection technology can effectively measure the gas concentration in the corresponding environment [17], and can be used in a test environment with low relative accuracy [18].

The direct absorption method of TDLAS gas detection technology mainly directly detects the change of light intensity before and after laser absorption [19], to calculate the corresponding gas concentration, and then achieve the function of detecting gas concentration [20]. Because the gas absorption wavelength and frequency of each gas are different, the laser of the corresponding special band can be modulated for the gas to be measured, and the purpose of measuring a single gas can be achieved by aligning with the required wavelength of the gas to be measured [21]. Align the absorption peak of the gas to be measured and select a coordinated plan that can make the output wavelength of the laser absorbed [22]. After passing through the gas to be measured, the corresponding absorption line is obtained and then the concentration is analyzed [23]. Its absorption detection process is shown in Fig. 3.

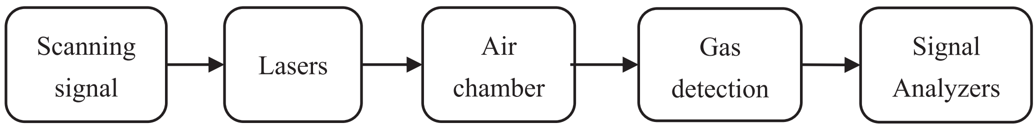


Fig. 3. Work flow chart

The direct absorption method mainly detects the gas concentration according to the change of light intensity before and after [24]. Let the light intensity before the incident be I_0, the light intensity absorbed after passing through the gas chamber is I_t, $k(v)$ is the absorption coefficient, L is the optical path, and P is gas pressure [25]. From this, the absorption coefficient $k(v)$ can be expanded into $k(v) = S(T)g(v)$, where $S(T)$ is the absorption line intensity of the gas, and $g(v)$ is the linear function of the absorption line spectrum. According to the Lambert-Others law [26], using the direct absorption method, the formula for calculating the corresponding gas concentration is:

$$C = (ln\ (I_0/I_t))/(S(T)g(v)PL) \quad \textbf{(3)}$$

3 System Simulation

The optical fiber system designed this time mainly uses the direct absorption method to complete the determination of gas concentration, and mainly uses three parts to complete the construction of this experiment and simulation. The light source module modulates the preliminary injected current to complete the preliminary modulation. The gas chamber module, which simulates the gas environment in an enclosed space. The detection module completes the detection of the gas concentration in the corresponding environment and outputs the corresponding waveform.

3.1 Light Source Module

TDLAS gas detection uses tunable lasers for the corresponding wavelength modulation characteristics and narrow linewidth characteristics to realize the gas concentration detection of the gas to be measured [27]. In the system, in order to realize the detection of methane gas concentration, it is necessary to select the gas absorption peak at 1652.72 nm. Therefore, the superimposed scanning signal needs to be satisfied and can be output stably at the center wavelength of 1652.72 nm. In order to achieve accurate absorption of the corresponding methane gas concentration, when simulating the corresponding laser, it is necessary to pay attention to the greater the output power of the laser, the better the linearity, and simulate the semiconductor laser to accurately and fully cover the absorption peak of the methane gas required for scanning. The specific simulation model is shown in Fig. 4.

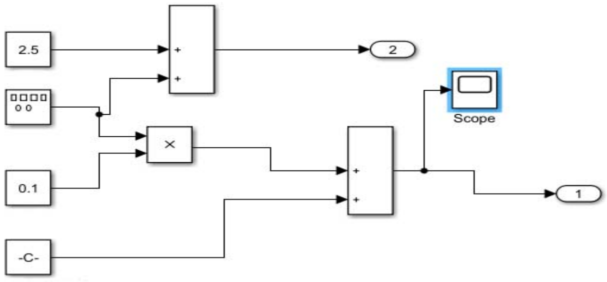


Fig. 4. Light source simulation module

The light source module mainly uses the 10Hz low-frequency sawtooth wave as the tuning signal. The tuned laser intensity and laser frequency are shown in Fig. 5.

$$v_t = v_o + A_m \cdot a_v \tag{4}$$

$$I_t = I_o + A_m \cdot b_I \tag{5}$$

Among them: v_t is the output frequency of the semiconductor laser; v_o is the gas absorption center frequency; I_t is the output light intensity; I_o is the initial light intensity; A_m is the amplitude of the sawtooth wave; a_v and b_I are the modulation frequency and the change of light intensity after modulation, respectively. Set the initial light intensity to 2.5V and the sawtooth amplitude to 1V.

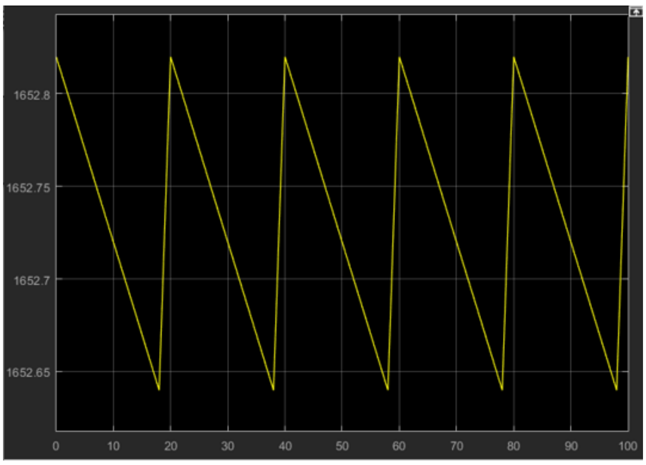


Fig. 5. Sweep frequency after sawtooth tuning

It can be seen that the scanning frequency completely scans the required gas absorption frequency of 1652.72 nm, thus ensuring that the corresponding gas absorption amplitude can be accurately captured after passing through the actual environment.

3.2 Air Chamber Module

The gas chamber module is mainly constructed according to the linear function of the absorption line of the gas to be tested at the specified absorption peak wavelength, which is mainly composed of the Lorentz linear function [28]. It should be noted that the corresponding $\Phi L(v)$ should be selected for the absorption of the linear function. The main function of the gas cell module is to simulate the absorption of light by the laser injected into the gas cell.

The air chamber module mainly includes Lorentz linear function simulation, linear strength simulation and basic environmental parameter settings. The design is mainly based on the Lorentzian linear absorption spectrum function of methane gas at 1652.72nm, to simulate the absorption process of the gas to be measured in a closed environment, and the simulation model design is mainly based on formula 1 and formula 2. The specific simulation process is shown in Fig. 6.

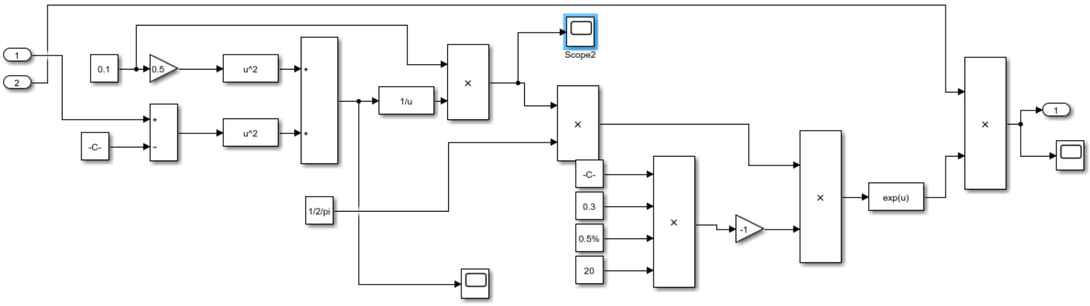


Fig. 6. Air chamber simulation module

Among them: N is the concentration of 5%; $S(T)$ is the gas absorption spectrum, 0.036; L is the optical path, 20; P is the pressure, 0.3; the modulation frequency is 0.5; v_o, v_t are the modulated scanning frequency and laser frequency.

After the modulated scanning signal in the light source simulation module is injected into the gas simulation module and the corresponding gas is absorbed, it can be seen that the corresponding absorbed light intensity variable is obtained through the Lorentz linear function and the gas environment to be measured. The corresponding light intensity changes are shown in Fig. 7.

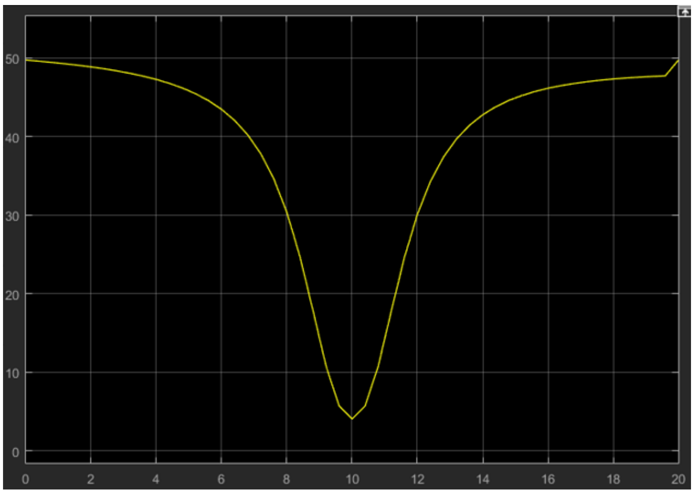


Fig. 7. Changes in light intensity after passing through the air chamber

It can be seen that the corresponding light intensity will have a minimum point with the change of time. According to the Lambert-Beer law, it can be known that this position expresses the position with the highest absorption efficiency of the corresponding gas. That is, the time corresponding to $v_o = v_t$ is the gas absorption situation in the current environment, and the scanning signal overlaps with the gas absorption frequency, which is recorded as the current gas concentration to be measured.

3.3 Data Detection Module

The data detection simulation module is the focus of this research and simulation. According to the current mine environment, the corresponding parameters are designed and the methane gas detection in the corresponding environment is carried out. By inputting the light intensity I_t of the gas to be measured in the gas chamber simulation module into the corresponding gas detection module, and calculating the corresponding gas absorbance, the absorption curve of the absorbance A with the simulation step size can be obtained.

The main application of the data monitoring simulation module is to express its absorbance as formula 6.

$$A = -\ln(I_t / I_o) \quad \textbf{(6)}$$

The specific process is shown in Fig. 8.

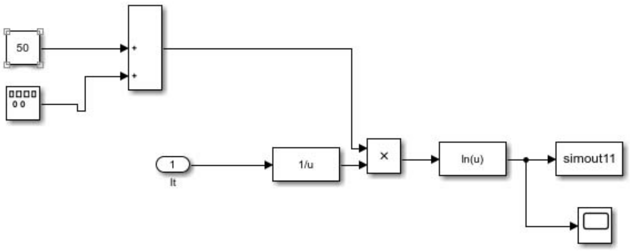


Fig. 8. Data monitoring simulation module

The direct measurement uses the adjusted initial light intensity I_o and the I_t of the absorption measurement through the gas cell module, recording the point at each simulated wavelength, after fitting the points, the fitted data can obtain the corresponding absorbance curve of the gas to be measured, as shown in Fig. 9.

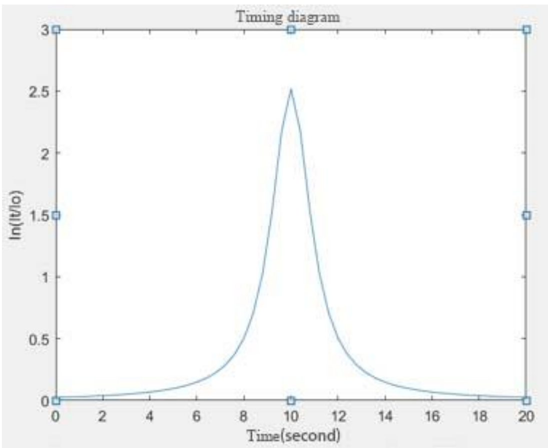


Fig. 9. Absorbance change

According to the change of absorbance, it can be determined that there is a scanning signal overlapping position in the central absorption peak, and the corresponding absorbance A is brought into the gas concentration detection formula by taking the central position.

$$N = \frac{1}{\sum_{i=1}^{n} S(T)PL} \int_0^{\infty} \ln(\frac{I_0}{I_t}) dv \quad \textbf{(7)}$$

The gas concentration of the gas to be measured can be calculated to determine whether the gas meets the leakage standard in the underground pipe network environment. The direct absorption method can quickly reflect the gas concentration value in the current simulation environment, and can provide good real-time performance. At the same time, the cost is low and corresponding equipment can be laid on a large scale.

4 Analysis of Influencing Factors

4.1 Influence of Temperature on TDLAS Detection

In industry, the influence of temperature on environmental detection is an important index. For example, in industrial combustion efficiency, the accuracy of temperature is a very critical factor for the entire combustion system. It can be used as a feedback signal to control the input and output of the system. The main research in this topic is the research on the methane gas environment in the normal temperature and normal pressure environment in daily life. Therefore, the detection of the temperature effect of TDLAS is mainly based on the gas temperature in the normal environment. In the gas environment, under the condition of keeping the pressure constant, set the temperature change to decrease successively, and compare the results of the absorbance amplitude at different temperatures. As shown in Fig. 10.

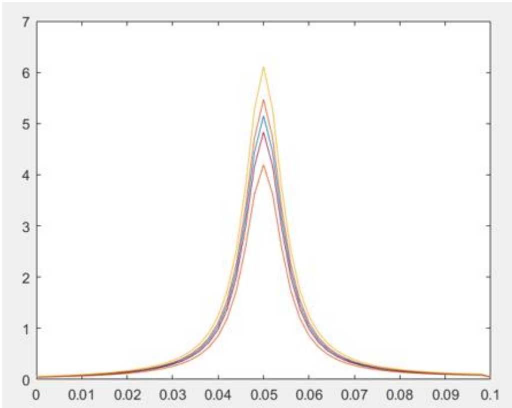
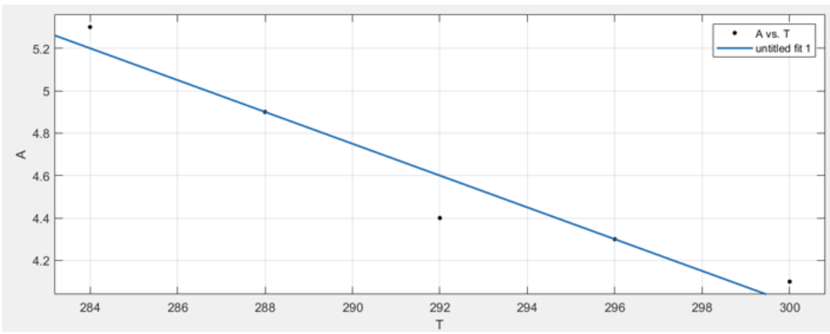


Fig. 10. Absorbance changes at different temperatures



Take temperature change	Absorbance amplitude change
284K	5.4
288K	4.9
292K	4.4
296K	4.3
300K	4.1

Fig. 11. Temperature and absorption photometric coupling

It can be found from Fig. 10 that when the temperature changes, the absorbance decreases with the decrease of the temperature, and the corresponding data are organized, as shown in Fig. 11, it can be found that the absorbance amplitude will increase with the gradual decrease of the temperature, and the overall relationship is linear. It can be inferred that when the temperature is lower, the absorbance in TDLAS gas detection can achieve higher accuracy.

4.2 The Effect of Pressure

In TDLAS direct absorption method gas detection technology, pressure is an important influencing variable. To analyze the harmonic signals output by the direct absorption method of methane gas under different pressures, five different pressures (1Pa is normal and 1 standard atmosphere) were extracted from low to high and compared with the absorbance amplitude under normal atmospheric pressure. Observe the corresponding more obvious changes in absorbance amplitude. As shown in Fig. 12.

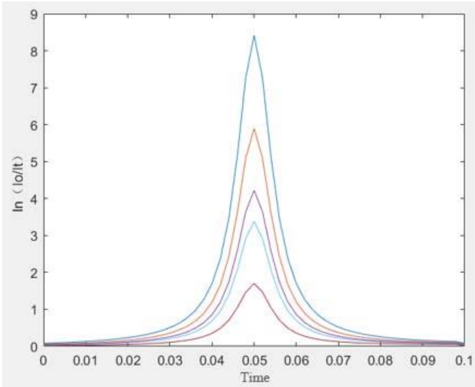
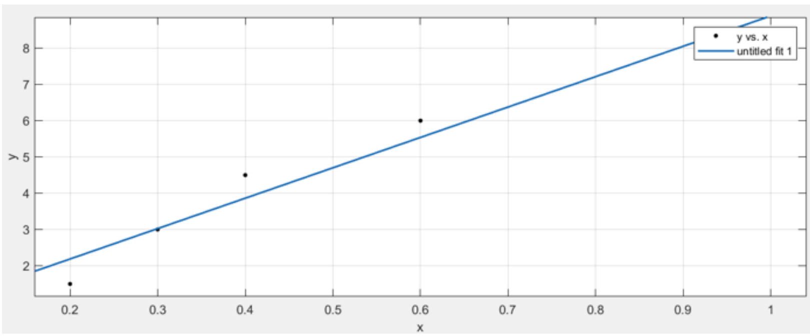


Fig. 12. Absorbance changes under different pressures



Take pressure change	Absorbance amplitude change
0.2P	1.0
0.3P	3.0
0.4P	4.4
0.6P	6.1
1.0P	8.9

Fig. 13. Pressure and absorbance coupling results

It can be analyzed that as the gas pressure gradually increases, the absorbance amplitude of the signal will gradually increase. As shown in Fig. 13, it can be found that the pressure has a linear relationship with the signal amplitude, and the coupling coefficient is 0.95, so it can be said that the amplitude of the absorbance increases as the pressure increases. Therefore, a lower gas pressure value can be set when designing the direct absorption method simulation, which can have a better detection lower limit, thereby ensuring the detection of low-concentration gases.

4.3 Effect of Gas Concentration

For the detection of methane gas in the mining industry, the focus is to detect the concentration below 5% and above 15%, because the methane gas in the concentration range of 5%-15% will explode. In the mining detection application, the data is updated in real time, so there will not be a correspondingly high concentration of methane gas, so the main thing to verify is the methane gas concentration below 5%. Now take the methane gas concentration of 1% to 5% in turn and observe whether the corresponding gas is distorted, and compare the absorbance amplitude results under different gas concentrations. The experimental results are shown in Fig. 14 below.

Take gas concentration changes	Absorbance amplitude change
1%	0.8
2%	1.7
3%	2.6
4%	3.2
5%	4.3

Fig. 14. Absorbance changes at different concentrations

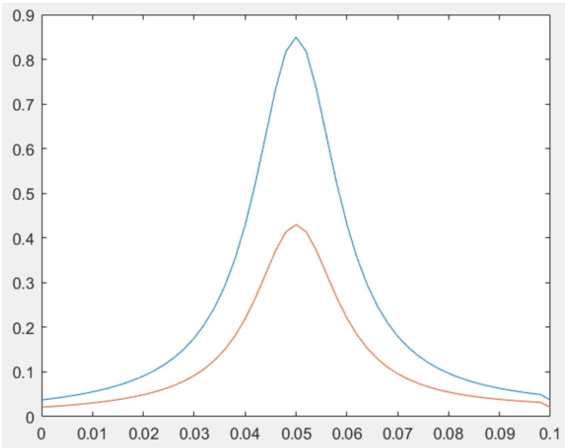


Fig. 15. Absorbance amplitude at 1% and 0.5% concentration

Through experiments, it can be found that the data in the methane gas detection area, that is, between 1% and 5%, can clearly transmit the change of the gas absorption luminosity amplitude. With the increase of the concentration, the absorbance amplitude increases, and there is no obvious distortion. However, when the 1% concentration test results are observed alone, the gas to be tested has begun to be distorted. In Fig. 15, it can be seen that the gas concentration at 0.5% concentration can be found to be further aggravated, so it can be detected normally when the gas concentration is between 1% and 5%, which can be used as a mining detection method.

4.4 Influence of the Actual Gas Environment

The environment used in this simulation is mainly the change of a single environmental factor. For the influence of TDLAS detection technology, it can be seen that the corresponding environment will change and the corresponding light absorption amplitude will change. But in real life, the environment of gas detection is complex and multi-faceted. Now take the corresponding parameters of the gas environment in five places in China to detect whether the change of the absorbance amplitude will be distorted due to the influence of multiple factors. In order to prevent the interference of other preset factors, the frequency of the scanning signal is set to 10Hz, the amplitude of the scanning signal is set to 1mA, and the gas concentration is set to 10%, the specific temperature and pressure of the corresponding location for subsequent collection are shown in Fig. 16.

Area	Take temperature change	Take pressure change	Absorbance Amplitude Change
Beijing	301K	1.001	3.327
Shanghai	298K	1.006	3.365
Wuhan	304K	1.007	3.239
Jilin	295K	0.971	3.224
Guangzhou	296K	1.010	3.368

Fig. 16. Local data taken

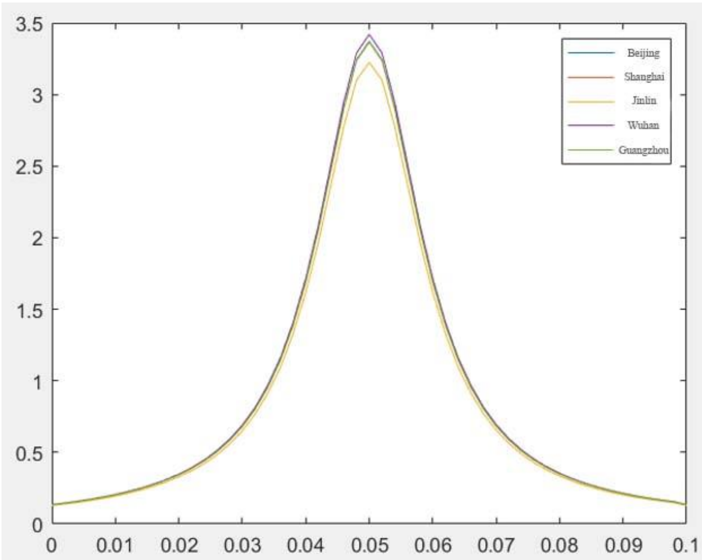


Fig. 17. Absorbance amplitude changes in different regions

The amplitudes of the received harmonic signals in Fig. 17 are very different, and there is no distortion. Therefore, it can be considered that in most normal underground pipe network environments, the changes of some parameters will not have a great impact on the gas detection technology, and can be applied to the gas detection of underground pipe networks.

5 Conclusion

Based on TDLAS technology, this subject researches on the measurement theory of methane gas absorption, and builds a complete simulation system to study the absorption comparison of main leaking gases in mine leakage. The effect of multiple factors affecting the absorption of the corresponding gas is studied, and the optimal measurement environment is designed according to the corresponding influencing factors.

The system has different pressure and temperature changes in different regions. In real life, it should be noted that different measurement parameters and modulation frequency should be set in different regions according to the local environment. How to eliminate unexpected errors is the next step. Therefore, in the simulation process, it is necessary to further eliminate the influence of errors caused by environmental factors, and the corresponding frequency modulation method can be considered to further improve the environmental variables that may be generated in the pipe network environment.

This subject also needs to be improved in accuracy, to minimize the interference of related pressure, temperature, modulation frequency, and the noise interference of the experiment itself. For the establishment of the simulation model, the corresponding noise interference can be solved by adding multiple harmonics, and at the same time, the optimal scanning frequency can be found through many experiments, so as to improve the accuracy of concentration detection. For the complex environment of the pipeline network and the problem of reminding that the threshold exceeds the threshold, it is necessary to further understand the existing gas detection technology, design a better gas chamber simulation model, and at the same time allow the detected data to be transmitted to the software for threshold alarm.

The TDLAS gas measurement method can effectively solve the detection problems of the current pipeline network, and can also save a lot of manpower, and truly achieve real-time transmission and timely detection of hidden problems. Using this gas detection technology can accurately capture the gas concentration near the pipe network, so the TDLAS technology is of great significance in real life.

6 Acknowledgement

This work is supported by Beijing Natural Science Foundation (Grant No. 4192023 and 4202024); Research on the Theory and Technical System of Smart Pipe Network Project (Grant No. JCGL202109); the Gold-Bridge Funds for Beijing (Grant No. 2021bjjq0017).

References

[1] Y. Li, Z.-C. Guo, X.-C Meng, K.-F. Chen, L.-M. Ren, R. Mao, K.-F. Cen, Design of On-line Monitoring System for Combustion Field Parameters in Furnace Based on Tunable Diode Laser Absorption Spectroscopy Technology, Power Generation Technology 43(2)(2022) 353-361.

[2] J. Zhao, D. Zhang, Research on on-line detection of CH_4 gas based on TDLAS technology, Coal mine machinery 43(5) (2022) 41-43.

[3] G.-S. Wang, A. Guo, X.-N. Liu, L. Feng, P.-H. Chang, L.-M. Zhang, L. Liu, X.-T. Yang, Simulation of TDLAS gas detection system and analysis of influencing factors, Spectroscopy and Spectral Analysis 41(10)(2021) 3262-3268.

[4] L. MA, L.-X. Fan, S. Zhang, W.-F. Wang, G.-M. Wei, CH_4 gas detection and temperature compensation method based on TDLAS technology, Spectroscopy and Spectral Analysis 41(11)(2021) 3632-3638.

[5] W.-J. LV, H.-L. Li, W.-Z. Li, H.-S. LV, S.-Z. Zhang, L.-D. Fang, Optimization and experimental research on modulation parameters of TDLAS technology, Laser Technology 45(3)(2021) 336-343.

[6] P.-F. Liu, F.-H. Hao, S.-L. He, R. Liu, H.-L. Ge, Wavelength demodulation of distributed feedback active fiber grating sensor based on wavelength scanning, China Laser 43(10)(2016) 216-221.

[7] Y.-Q. Li, G.-Z. Yao, Z. Yang, A high-accuracy fiber grating wavelength demodulation system, Acta Photonica Sinica 41(12)(2012) 1405-1411.

[8] L.-L. Cui, Y.-M. Tian, Research on Optical Fiber Interference Microphone Based on Two-wavelength Demodulation, Semiconductor Optoelectronics 42(6)(2021) 828-833.

[9] X.-K. Song, L.-L. Ran, J.-R. Yang, X.-Y. Wei, C. Li, High-sensitivity microcavity fiber-optic strain temperature sensor, Journal of Natural Science of Heilongjiang University 38(5)(2021) 617-623.

[10]X.-R Dong, Highly Sensitive Strain Sensor Based on a Novel Mach-Zehnder Interferometer with TCF-PCF Structure, Sensors 18(1)(2018) 278-278.

[11]P.-S. Zhang, S.-A. Xu, Research on the development and application of mine optical fiber testing technology, Advances in Geophysics 31(3)(2016) 1381-1389.

[12]Y.-L. Zhao, X. Liu, Z.-Y. Lu, Overview of pipeline leak detection and location technology research, Electromechanical Information (1)(2022) 86-88.

[13]Y. Huang, D. Xie, L.-S. Yang, L.-N. Wang, Measurement and location analysis of underground metal pipelines based on distributed optical fiber sensing, World Nonferrous Metals (3)(2021) 225-226.

[14]B.-L. Zhang, Research on optical fiber sensing online measurement system for gas composition of petrochemical hydrogen-carrying pipelines, [dissertation] Wuhan University of Technology, 2018.

[15]S.-H. Zhang, Design of Optical Fiber Gas Concentration Sensor System Based on Differential Technology, Electronic Test (11)(2020) 15-16+19.

[16]C. Sun, J.-J. Ding, S. Zhang, Methane gas concentration signal acquisition method based on optical fiber sensor, Journal of Jianghan University (Natural Science Edition) 45(5)(2017) 439-443.

[17]B.-H. Zhang, J. Yang, W. Wei, X.-J. Xie, D.-Z. Zhang, Y.-H. Jiang, Research on gas pressure measurement technology based on TDLAS direct absorption method, Measurement technology 41(5)(2021) 100-107.

[18]W.-Y. Lu, X.-R. Zhu, Y.-S. Li, S.-C. Yao, Z.-M. Lu, Y. Qu, Y.-Z. Rao, Z.-H. Li, Comparison of on-line measurement of CO_2 by TDLAS direct absorption method and wavelength modulation method, Infrared and Laser Engineering, 47(7) (2018) 155-160.

[19]R. Cao, X.-W. Kang, M. Fu, N. Zhao, T. Zhang, Fast fitting method for gas concentration measurement based on TDLAS technology, Journal of Sensing Technology 33(2)(2020) 232-237.

[20]J. Xia, Design and implementation of coal mine laser methane detection module based on TDLAS technology, [disserta-

tion] Chongqing University of Posts and Telecommunications, 2020.
[21]X.-P. Zhong, L. Wang, W. Lan, F. Xing, Research on TDLAS temperature measurement based on filtered back-projection algorithm, Advance Technology 43(3)(2022) 50-58.
[22]R.-J. Li, F. Li, X. Lin, X.-L. Yu, Q.-L. Yang, X. Li, Research on Uncertainty Analysis Method of Temperature Measurement by TDLAS Technology, Measurement and Control Technology 39(9)(2020) 10-14+19.
[23]D. Peng, Application of absorption spectroscopy in diagnosis of complex flow fields, [dissertation] University of Science and Technology of China, 2019.
[24]L. Deng, Research on real-time monitoring system of methane based on TDLAS, [dissertation] Xiamen University, 2019.
[25]X.-L. He, Y.-G. Pan, Development status and application of TDLAS technology, Journal of Ezhou University 24(1)(2017) 102-104+109.
[26]Z.-H. Tu, Research on multiple interference factors and their suppression in methane infrared high-precision detection system, [dissertation] Shantou University, 2021.
[27]Y. Hou, R. Fan, X. Chen, The compensation algorithm based on Bayes theory of multi point measurement fusion for methane concentration, in: Proc. IEEE International Symposium on Computer, Consumer and Control, 2016.
[28]C. Floridia, F.-C. Salgado, J.-B. Rosolem, Methane leak detection and spectral analysis by using only optical time do main reflectrometry in semidistributed remote optical sensors, in: Proc. Sensors, 2017.