Energy Proceedings
Vol 56, 2025
ISSN 2004-2965

Experimental Study on Carbon Dioxide Pipeline Leak Detection Based on Distributed Acoustic Sensing

Dianqiang Xu[1,2], Shuai Wang[1,2], Jiateng Duan[1,2], Kaixuan Feng[1,2] , Yu Liu[1,2*]

1 Dalian University of Technology, Dalian, Liaoning, China

2 Ningbo Institute of Dalian University of Technology, Ningbo, Zhejiang, China
(*Corresponding Author: liuyu@dlut.edu.cn)

ABSTRACT

Carbon dioxide (CO2) is typically transported in liquid or supercritical states, which are highly corrosive, posing a risk of corrosion leakage in transport pipelines. The function of detection technologies lies in the ability to promptly identify pipeline leaks, thus reducing potential risks.

This study includes an experimental investigation into the acoustical technology for pipeline leak detection based on Distributed Acoustic Sensing (DAS). The experiments were carried out within a 210-meter-long pipeline with an inner diameter of 44 millimeters, equipped with electromagnetic valves and circulation pumps. In this experiment, designed to validate the feasibility of the detection technique, pipeline leakage detection with supercritical carbon dioxide was performed.

It was validated through detection experiments involving different phases and leak severities that the feasibility of pipeline leak detection technology based on DAS is established. The distinguishing properties of acoustic signals between leak and normal states were explored using the spectrum subtraction algorithm (SSA) and correlation analysis approaches to compare the DAS signals. The results indicate that significant signal intensity differences exist in specific frequency domains for pipeline leak signals. Signals remain reasonably constant during steady operation because flow rates are consistent. When a leak occurs, large changes in signals near the leak location are noted, allowing leak identification based on differences in signal response times. During continuous leakage, the energy of signals at specific frequencies around the leak site is significantly higher than in areas without leaks.

This study may provide novel methodologies for low signal-to-noise ratio processing and bad point signal identification in the DAS signals, and establish a theoretical foundation for the engineering application of DAS in CO2 pipeline leak detection.

Keywords: Leak detection, Distributed Acoustic Sensing, Spectral Subtraction Algorithm, Correlation Analysis

NONMENCLATURE

Abbreviations	
APEN	Applied Energy
Symbols	
n	Year

1. INTRODUCTION

With the increasing pressure on environmental protection, and under the current conditions where it is impossible to completely abandon fossil fuels, Carbon Capture, Utilization, and Storage (CCUS) technology has become an indispensable component of carbon neutrality strategies[1]. It serves as a crucial technical means and a foundational safeguard for achieving the temperature control targets set forth in the Paris Agreement. There are often significant spatial distances between carbon capture systems and utilization or storage systems. Therefore, carbon dioxide transportation technology is a necessary means for the effective development of CCUS[2]. Pipeline transportation, as one of the five major transportation methods, has advantages such as low maintenance costs after initial investment, high transportation efficiency, high safety, minimal resource waste, and minimal environmental impact. Carbon dioxide transportation technology is also evolving from tanker and ship transportation to pipeline transportation[3].

This is a paper for International CCUS Conference 2024 (ICCUS 2024), June 20-22, 2024, Beijing, China.

Currently, carbon dioxide transportation pipelines have been thoroughly validated through numerous engineering case studies. Several countries, including China, have established and implemented CCUS projects that primarily utilize pipeline transportation. However, carbon dioxide transportation pipelines face significant challenges related to aging, corrosion, leakage, and third-party interference. These issues pose substantial risks to the safety of the pipelines[4].

Therefore, achieving real-time online monitoring of pipeline operational status to promptly detect and warn of potential leakage risks has become a major challenge in the field of pipeline monitoring. Presently, traditional methods for monitoring carbon dioxide pipelines primarily include acoustic detection, pressure wave methods, and neural network-based pipeline leak detection methods. The acoustic detection method primarily relies on the negative pressure wave generated by leakage. Sensors positioned above and below the leak detect the signals, which are then analyzed through correlation processing to determine the location of the leakage[5]. However, its detection range is limited, making it difficult to achieve full coverage for long transportation pipelines. The pressure wave method primarily utilizes a rapid electromagnetic valve to generate pressure waves[6]. The propagation of these pressure waves within the pipeline is then analyzed to detect blockages and leaks. However, there are currently no practical field applications for leak detection using this method. The neural network-based pipeline leak detection method utilizes parameters such as pressure and flow within the transportation pipeline. Machine learning algorithms based on neural networks analyze these parameters to provide early warnings for blockages or leakage[7]. However, this method requires extensive data training for different pipelines and lacks intuitive data support.

In recent years, distributed fiber optic sensing technology has been applied to pipeline leak monitoring due to its extremely low light transmission loss and low cost. Among them, Distributed Acoustic Sensing (DAS) technology utilizes the impact of external acoustic signals on the optical signals within the fiber to detect external acoustic signals[8]. It has high sensitivity, enabling long-distance, distributed measurements with excellent real-time capabilities during the measurement process. However, distributed fiber optics in pipeline leak monitoring currently face issues such as high noise levels and poor signal readability, which affect detection effectiveness and lead to false alarms for leakage signals [9]. In summary, further research is needed in the field of pipeline leak detection to improve the identification of leak signals and the handling of noise signals in DAS. This study conducted a series of fiber optic leak detection experiments using a multi-phase carbon dioxide recirculation pipeline that was independently designed and constructed. The results show that the pipeline leak detection method based on DAS has a high capability for leakage identification. However, there are indeed issues with noise signals and faulty data that require post-processing. Additionally, quantitative detection of leak sizes still requires further research.

2. EXPERIMENTAL SYSTEM AND METHODOLOGY

2.1 Experimental System

To conduct experimental research on the carbon dioxide pipeline leak detection method based on the DAS system, this study has established a carbon dioxide pipeline experimental platform, as illustrated in Figure 1. The platform primarily consists of the main pipeline, temperature control system, pressure stabilization system, gas injection and recirculation system, and DAS data acquisition system. The main pipeline consists of a 210-meter-long stainless steel pipe with a 44 mm inner diameter and a 3 mm wall thickness, along with electromagnetic valves to simulate leakage. The temperature control system is composed of alternating layers of heating elements and insulation. The pressure stabilization system consists of a pressure-regulating bladder and a safety valve. The gas injection and recirculation system is composed of a gas pressurization device and a supercritical carbon dioxide recirculation pump. The DAS system consists of a DAS fiber optic main unit and optical fibers arranged in a coiled and tiled configuration along the outer wall of the pipeline.

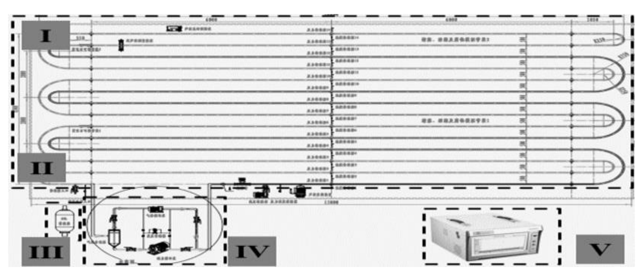
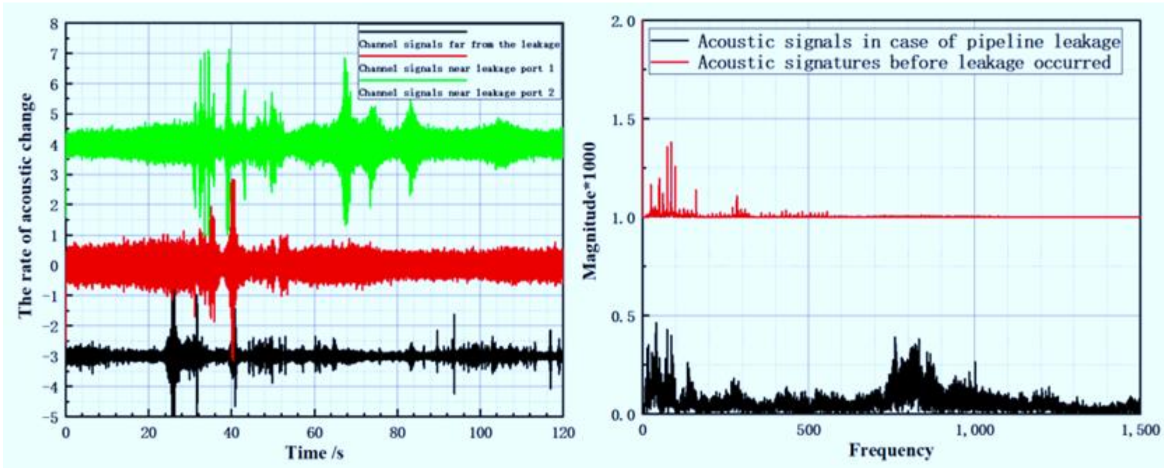


Fig. 1. The schematic diagram of the pipeline system of leakage detection experiment based on DAS

2.2 Experimental Methodology

Before conducting the leak detection experiments, it is necessary to first install and arrange the optical fibers. The optical fibers are installed alternately in coiled and tiled configurations along the outer wall of the pipeline,



(a) The DAS signal data graph (b) Acoustic wave frequency domain graph

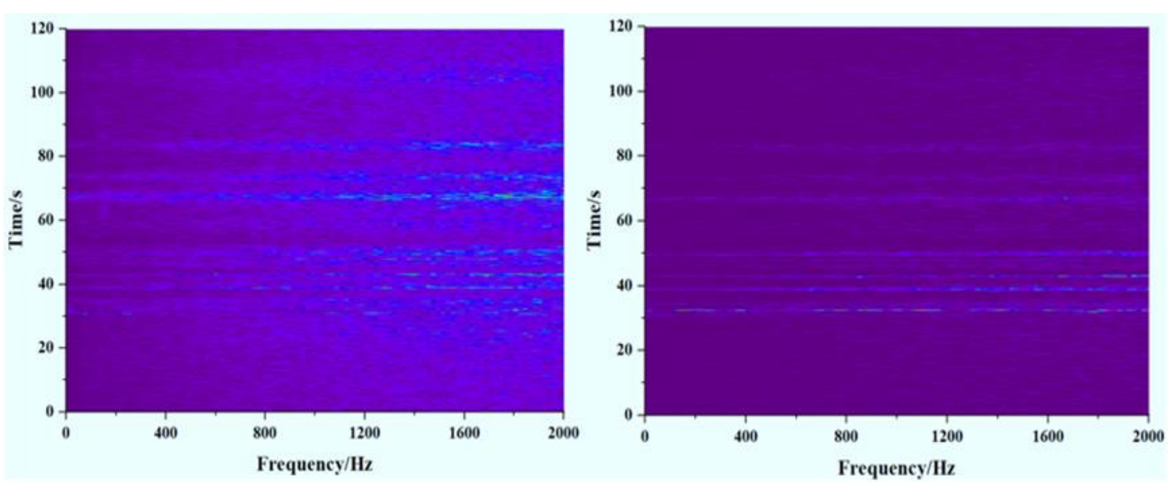
Fig. 2. The experimental data recording chart for a pipeline leak detection system

with the coiled configuration primarily used for signal collection. Subsequently, carbon dioxide is injected into the experimental pipeline using a pressurizer. After a certain amount has been injected, the circulation system and heating system are activated. Heating continues until the experimental temperature and pressure reach 35°C and 8.5 MPa, respectively. At this point, heating is stopped, and the carbon dioxide reaches a supercritical state and begins to circulate. According to the experimental requirements, the necessary outlet diameter is set on the electromagnetic valve to simulate the leakage. The DAS data acquisition system is activated to collect background noise signals. Then, the electromagnetic valve is activated to simulate leakage. After the leak has stabilized, it continues for a certain period before being closed. Finally, the DAS data acquisition system is shut down, completing the experiment.

3. EXPERIMENTAL RESULTS

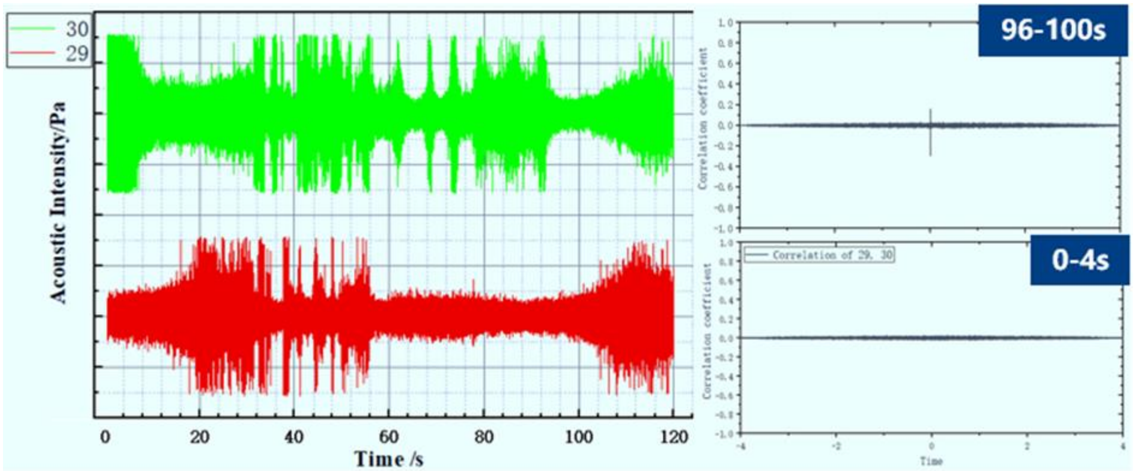
3.1 Signal Noise Reduction

Provide sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described. To evaluate the feasibility and effectiveness of pipeline leak detection technology based on the DAS system, experiments were conducted using the carbon dioxide pipeline experimental setup shown in Figure 1. First, the required leak outlets are installed at the exit of the electromagnetic valve to simulate pipeline leaks. The leak outlet size is 1.0 mm, and the pressure is maintained at 8.5 MPa in a supercritical state. The leak outlet is positioned at the



(a) The signal graph before noise reduction (b) The signal graph before noise reduction

Fig. 3. Time-frequency graphs of experimental signals for leakage detection before and after noise reduction



(a) The experimental data graph of faulty signals (b) The Correlation analysis graph

Fig. 4. The data processing graph for faulty signal recognition.

central part of the pipeline to minimize the impact of the circulation pumps at both ends on the leak signal monitoring. The experimental results are shown in Figure 2, where the horizontal axis represents time and the vertical axis represents the rate of acoustic signal change in the pipeline. In the DAS signal, the first wave around 30 seconds represents the rate of acoustic signal change caused by the initiation of the leak when the electromagnetic valve is activated. The second wave around 50 seconds indicates the rate of acoustic signal change when the leak ceases as the electromagnetic valve is closed. The intermediate signals represent the rate of acoustic signal change during the leak process. As shown in Figure 2(a), the optical signal intensity of the fibers located far from the leak outlet is significantly lower than that of the fibers near the leak outlet. Therefore, we can locate the leak signals by analyzing the overall optical signal intensity of the fibers. The closer the optical fiber channel is to the leak location, the higher the signal intensity it collects. Figure 2(b) shows the frequency-domain signal measured by the acoustic sensors placed near the leak outlet. By comparing the signals in the leak and non-leak states, it can be observed that the acoustic signals generated by the leak in the experimental pipeline are primarily distributed in the 600-1000 Hz range.

We performed Short-Time Fourier Transform (STFT) on the optical fiber signals to analyze their time-frequency information[10]. The results are shown in Figure 3(a). The results demonstrate that the time-frequency signal is highly irregular and chaotic, making it difficult to identify distinct time-frequency features that characterize the leakage condition. Even within the primary frequency domain range of the leak signal (600-1000 Hz), it is challenging to find meaningful information. Therefore, we attempted to introduce a spectral subtraction noise reduction algorithm (SSA)[11]. The background noise in the non-leak state was analyzed in the frequency domain. Subsequently, based on the obtained data, the overall data was subjected to frequency domain noise reduction to obtain the noise-reduced effective signal. The processed signal was then subjected to STFT, and the experimental results are shown in Figure 3(b). As shown in the figure, the time-frequency map of the signal after spectral subtraction noise reduction clearly exhibits distinct striped patterns between 30 and 50 seconds, which differ noticeably from other times. Therefore, we can use this time-frequency feature to identify and assess the optical fiber signals for pipeline leak detection, enabling accurate detection of leak conditions.

3.2 Faulty Signals

During subsequent experiments, we observed significant anomalous signals, as shown in Figure 4(a). We observed significant anomalous signals in the 0-4 seconds range, where the signal intensity reaches extreme values for an extended period. If this signal were caused by normal pipeline noise, such intense signals would be expected to be detected by adjacent channels as well. However, the DAS signals from adjacent channels lack this corresponding signal, indicating that the signal is unrelated to the pipeline's inherent signals. The primary cause of this signal is the uneven distribution of scattering points and varying scattering intensities in the sensor fiber, due to limitations in the manufacturing process. This can lead to some channels exhibiting abnormally high signal intensities. Such signals are typically difficult to remove using filtering or spectral subtraction methods. We refer to them as faulty signals.

Since faulty signals are usually caused by issues in the fiber manufacturing process, they tend to be random signals from the problematic channel and have minimal interference with adjacent channel signals. Therefore, to address the interference of faulty signals with normal signals, we use the Pearson correlation coefficient[12] to analyze the correlation between faulty signals and valid signals in the experiment. This allows us to distinguish between effective signals and faulty signals. The results are shown in Figure 4(b). We found that the signal correlation for faulty signals is less than 0.01, whereas the correlation for normal signals is above 0.4. Therefore, we can use the strength of correlation to filter out faulty signals in the optical fiber data.

4. CONCLUSIONS

In this study, we conducted supercritical carbon dioxide leak detection experiments in a custom-built pipeline with a diameter of 44 mm and a length of 220 meters. The experimental results indicate that the DAS-based leak detection technology has high feasibility. During the leak detection experiments, the signal remained relatively constant during stable operation. In the leak experiments, the DAS signal energy during leakage is significantly higher than the intensity in non-leak areas. Thus, performing time-frequency analysis on the optical fiber signals reveals distinguishing features between leak and non-leak states. Additionally, the signal near the leak location changes significantly compared to signals farther from the leak. By analyzing the optical fiber signal intensity, we can identify the fiber channel closest to the leak location and thus determine the leak position. Because optical fiber signals are highly susceptible to noise interference and have a low signal-to-noise ratio, it is difficult to precisely distinguish the boundaries between leak and non-leak intervals in the signal. Therefore, this study employs spectral subtraction noise reduction algorithms to effectively improve the signal-to-noise ratio of the optical fiber signals. The processed time-frequency map reveals distinctive features of the leak signals, characterized by high-intensity, striped time-frequency patterns. Due to faulty signals caused by fiber manufacturing processes, spectral subtraction algorithms are ineffective at reducing these signals, which can significantly impact the identification of valid and effective signals. By analyzing the correlation with the optical fiber signals from adjacent channels, it can be observed that valid signals have a correlation coefficient above 0.4, while faulty signals have a correlation coefficient below 0.01. Faulty signals can be identified based on the signal correlation with adjacent channels. Therefore, before performing time-frequency analysis and identification on DAS-based pipeline leak detection signals, correlation analysis should be conducted to ensure that faulty signals do not interfere with valid signals. This helps prevent false leak detections. Further research and exploration are needed to develop methods for additional noise reduction and identification in data with faulty signals. Additionally, autonomous identification and alarm systems for leak signals remain a key development goal for this detection method.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Mi, J., Ma, X. Development Trend Analysis of Carbon Capture,Utilization and Storage Technology in China. Proceedings of the Chinese Society of Electrical Engineering 2019, 39 (9), 2537-2543.

[2]de Visser, E., Hendriks, C., Barrio, M., Molnvik, M. J., de Koeijer, G., Liljemark, S., Le Gallo, Y. Dynamis CO2 quality recommendations. International Journal of Greenhouse Gas Control 2008, 2 (4), 478-484.

[3]Dou, L. R., Sun, L. D., Lyu, W., Wang, M. Y., Gao, F., Gao, M., Jiang, H. Trend of global carbon dioxide capture, utilization and storage industry and challenges and countermeasures in China. Petroleum Exploration and Development 2023, 50 (5), 1246-1260.

[4]Qin, J., Li, Y., Wu, D., Weng, H., Wang, G. CCUS global progress and Chinas policy suggestions. Petroleum Geology and Recovery Efficiency 2020, 27 (1), 20-28.

[5]Zhang, J., Lian, Z., Zhou, Z., Xiong, M., Lian, M., Zheng, J. Acoustic method of high-pressure natural gas pipelines leakage detection: Numerical and applications. International Journal of Pressure Vessels and Piping 2021, 194.

[6]Li, J., Zheng, Q., Qian, Z, Yang, X. A novel location algorithm for pipeline leakage based on the attenuation of negative pressure wave. Process Safety and Environmental Protection 2019, 123, 309-316.

[7]Willis, A. J., Design of a modified sequential probability ratio test (SPRT) for pipeline leak detection. Computers & Chemical Engineering 2011, 35 (1), 127-131.

[8]Hussels, M.-T., Chruscicki, S., Arndt, D., Scheider, S., Prager, J., Homann, T., Habib, A. K. Localization of Transient Events Threatening Pipeline Integrity by Fiber-

Optic Distributed Acoustic Sensing. Sensors 2019, 19 (15).
[9]Huang, C., Peng, F., Liu, K. Pipeline Inspection Gauge Positioning System Based on Optical Fiber Distributed Acoustic Sensing. Ieee Sensors Journal 2021, 21 (22), 25716-25722.
[10]Gulamhusein, M. N., Fallside, F. SHORT-TIME SPECTRAL AND AUTOCORRELATION ANALYSIS IN WALSH DOMAIN. Ieee Transactions on Information Theory 1973, 19 (5), 615-623.
[11]Xiaolin, C. A. O., Suli, Z., Ping, W. U., Tiefu, D. MATLAB based Spectral Subtraction Algorithm for Speech Enhancement. Computer Simulation 2006, 23 (3), 278-280,283.
[12]Edelmann, D., Mori, T. F., Szekely, G. J. On relationships between the Pearson and the distance correlation coefficients. Statistics & Probability Letters 2021, 169.