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Experimental study on two tunnel micro-leakage monitoring methods based on distributed fiber optic sensing technology

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ABSTRACT: Real-time monitoring and accurate localization of pipeline leaks are crucial for pipeline safety. Conventional methods often fail to detect micro-leaks and face issues such as low positioning accuracy, high false alarm rates, and inability to monitor long distances. This study proposes two innovative leakage monitoring methods based on distributed temperature sensing (DTS) and distributed strain sensing (DSS). The first method utilizes evaporation-induced relative humidity measurement. By measuring the temperature of DTS fiber optic cables wrapped in gauze, real-time detection and localization of leaks in pipelines carrying ambient-temperature liquids can be achieved. A significant temperature drop at the leakage location allows precise identification of micro-leaks. The second method employs fiber optic cables with water-swelling blocking yarns for localized strain sensing, combined with Optical Frequency Domain Reflectometry (OFDR). At the leakage location, the strain of the sensing fiber significantly decreases, providing a distinct signal for detection. Indoor experiments confirmed the feasibility of both methods, demonstrating their ability to achieve real-time monitoring and precise localization of micro-leaks. These methods offer novel solutions for addressing pipeline leakage challenges.

KEY WORDS: Micro-Leakage; Distributed Fiber Optic Sensing; Distributed Temperature Sensing; Distributed Strain Sensing.

1 INTRODUCTION

Pipeline transportation is a widely adopted technology for conveying fluids such as gases and liquids. In recent years, it has developed rapidly and has been extensively applied in sectors such as energy, municipal infrastructure, and water conservancy due to its advantages of high transport capacity, small land footprint, short construction cycles, and low operational costs. As one of the five major modes of modern transportation—alongside rail, road, waterway, and air—pipeline systems have become the predominant solution for transporting water, oil, and gas across land, playing a critical role in national economic development and public safety [1,2].

However, as pipelines age, they become increasingly vulnerable to damage caused by thermal expansion and contraction, fatigue, corrosion, foundation settlement, or accidental excavation. These factors frequently lead to failures such as rupture or leakage, resulting in significant resource loss and economic damage. Consequently, real-time monitoring and accurate localization of pipeline leakage are essential to ensuring safe operation, protecting public assets, and maintaining system reliability [2].

Conventional leakage detection methods—such as the negative pressure wave, mass balance, ground-penetrating radar (GPR), capacitive sensing, electromagnetic reflection, and acoustic emission (AE)—have been widely utilized, but each presents notable limitations. While some offer advantages like fast response or low cost, they often suffer from poor localization accuracy, high false alarm rates, limited sensitivity to small or slow leaks, and an inability to monitor over long distances. For example, the negative pressure wave method is effective only for large and sudden leaks; the mass balance method lacks precise localization capability; and GPR and AE techniques are heavily dependent on operator expertise and are sensitive to environmental noise. These drawbacks significantly restrict their applicability in large-scale or complex pipeline systems.

In this context, distributed fiber optic sensing (DFOS) has emerged as a promising alternative, offering numerous advantages such as corrosion resistance, compact structure, high sensitivity, immunity to electromagnetic interference, and long-term operational stability [3]. By monitoring physical parameters such as temperature, strain, or vibration, DFOS enables distributed and real-time leak detection with high spatial resolution.

Among DFOS techniques, temperature-based methods have been most extensively studied. For instance, Vogel et al. [4] employed Distributed Temperature Sensing (DTS) to detect pipeline leaks by identifying abnormal temperature variations, a method that has since gained widespread adoption. Wang et al. [5] applied Brillouin Optical Time-Domain Reflectometry (BOTDR) for temperature-based leak detection and investigated how different installation methods influence sensing performance. However, these approaches typically rely on a significant temperature difference between the leaking fluid and the surrounding environment. To address this issue, some researchers have introduced active heating of the fiber to enhance detection sensitivity [6], though this introduces safety concerns in environments containing flammable gases. Commercial systems such as Omnisens DiTeST, which utilize both Brillouin and Raman scattering to monitor temperature and strain, can detect large-scale leaks but usually require the leakage volume to exceed 0.01% of the total flow to be identified [7].

Additional innovations include MacLean's polymer-embedded fiber design, which swells upon contact with leak fluids and causes signal attenuation detectable via Optical

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Time-Domain Reflectometry (OTDR) [8]. While effective, this design is single-use and must be replaced after each leak event. Similarly, Jia et al. adopted Brillouin Optical Time-Domain Analysis (BOTDA)-based strain sensors, which exhibited significant accuracy degradation and poor reusability after leakage exposure. Interferometric methods such as Sagnac or Mach-Zehnder configurations offer high sensitivity but require complex signal processing. Moreover, Stajanca et al. [9] applied Distributed Acoustic Sensing (DAS) based on Rayleigh scattering to detect vibrations from gas leaks, but the method was highly susceptible to environmental noise, had low localization accuracy, and consumed large amounts of optical fiber.

Despite these advancements, current DFOS-based technologies still face three main challenges:

(1) limited ability to detect ambient-temperature liquid leaks without external heating;

(2) low sensitivity to small or slow leakage events, resulting in potential missed detections; and

(3) dependence on non-reusable sensing materials, such as polymer coatings that degrade upon fluid exposure.

To address these limitations, this study proposes two novel DFOS-based methods for micro-leakage monitoring in tunnel pipelines. The first method utilizes evaporation-induced humidity sensing, in which a gauze-wrapped DTS fiber detects localized temperature drops caused by water evaporation at leak points. The second method employs Optical Frequency Domain Reflectometry (OFDR)-based strain sensing, using fiber optic cables integrated with water-swelling blocking yarns that exhibit measurable strain changes upon contact with leaking fluid.

2 MATERIALS AND METHODS

2.1 Pipeline Leakage Sensing Principle Based on EETS-DTS

Distributed Temperature Sensing (DTS) technology measures temperature along an optical fiber by exploiting the temperature-dependent intensity ratio between Stokes and anti-Stokes components of Raman backscattered light. When a pump pulse is launched into the fiber by a DTS laser source, photon–molecule interactions generate backscattered Raman signals at two distinct frequencies—Stokes and anti-Stokes. The Stokes signal intensity is largely temperature-independent, while the anti-Stokes intensity is strongly temperature-sensitive, increasing with local fiber temperature.

The DTS interrogator calculates the temperature at each point by computing the intensity ratio of the anti-Stokes to Stokes signals and locates the scattering position using the round-trip travel time of the light pulse. The temperature T can be expressed as follows:

$$R(T) = \frac{I_F}{I_S} = \left(\frac{v_F}{v_S}\right)^4 e^{\frac{-hcv}{KT}} \quad (1)$$

where $R(T)$ is the temperature function, I_F is the anti-Stokes light intensity, I_S is the Stokes light intensity, ν_S is the central frequency of the Stokes component, ν_F is the central frequency of the anti-Stokes component, c is the speed of light in vacuum, ν is the Raman shift, K is the Boltzmann constant, h is the Planck constant, and T is the absolute temperature.

The distance from the laser input to the scattering point can be determined by:

$$X = \frac{cT}{(2n)} \quad (2)$$

where X is the distance, v is the speed of light in vacuum, t the travel time of the light and n is the refractive index of the fiber. By combining Equations (1) and (2), the temperature at any point along the fiber can be measured in a distributed manner.

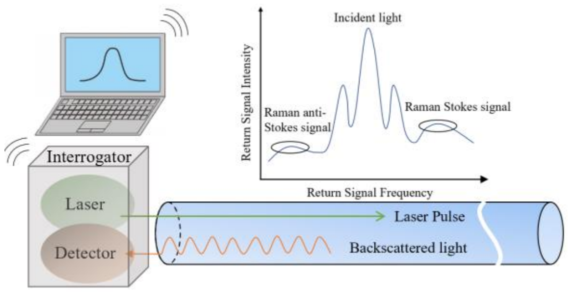

Figure 1. Principle of distributed temperature sensing (DTS) technology.

In unsaturated air, evaporation can occur at any temperature. When leakage occurs in a pipeline, the leaked liquid may come into contact with the sensing cable. However, conventional temperature-sensing cables have smooth outer surfaces, which inhibit significant evaporation, leading to minimal temperature drop. To enhance detection sensitivity, Sun et al. [10] proposed wrapping the fiber with porous gauze, which increases water absorption and promotes evaporation.

The proposed Evaporation-Enhanced Temperature Sensing DTS (EETS-DTS) method involves deploying a gauze-wrapped DTS cable beneath the pipeline. The gauze absorbs leaking water and facilitates capillary spreading due to its high porosity and large surface area. This promotes enhanced evaporation, resulting in a localized temperature decrease at the leak site, which is detected by the DTS system. Over time, a thermal equilibrium is reached between the heat loss due to evaporation and the heat supplied by ambient air, causing the gauze temperature to stabilize at a value lower than the surrounding dry areas.

For ambient-temperature water leakage, the temperature difference ΔT between dry and wet cables can be estimated using the World Meteorological Organization (WMO) psychrometric formula:

$$\Delta T = T_1 - T_2 = \frac{e_w(t_2) - U/100 \cdot e_w(t_1)}{AP} \quad (3)$$

where $e_w(T_1)$ and $e_w(T_2)$ are the saturated vapor pressures corresponding to the dry and wet cable temperatures, U is the relative humidity (%RH), A is the psychrometric coefficient (related to air velocity and sensor design), and P is the atmospheric pressure (MPa). Hence, the temperature difference is mainly influenced by humidity and ventilation conditions.

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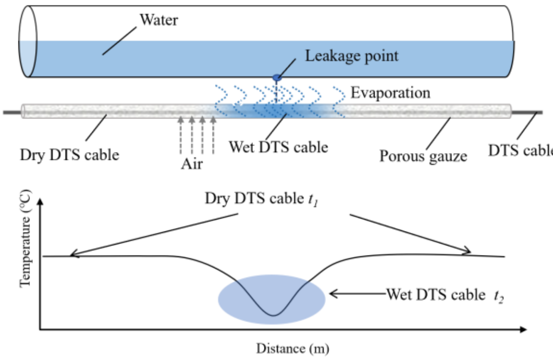

Figure 2. Schematic of the EETS-DTS leakage detection principle.

The DTS cable used in this study (model NZS-DTS-C09) has an outer diameter of 5 mm and consists of five structural layers: a tight-buffered optical fiber, spiral steel armor, Kevlar yarn, braided metal mesh, and a protective outer sheath (Figure 3). The spiral armor and braided mesh provide mechanical protection, the Kevlar layer enhances tensile strength, and the outer sheath offers good thermal conductivity and flame resistance. The cable operates reliably within a temperature range of –20 °C to 85 °C.

Temperature data are collected using a DTS interrogator (model NZS-DTS-A03), manufactured by Suzhou Nanzee Sensing Technology Co., which provides high-resolution distributed temperature profiling along the fiber. The key specifications of the device are listed in Table 1.

(a)

(b)

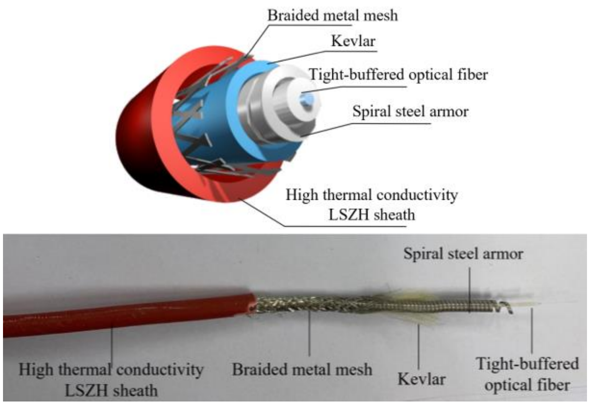

Figure 3. Structure of the DTS temperature-sensing cable: (a) Schematic diagram; (b) Physical photograph.

Table 1. Specifications of the DTS interrogator.

Parameter type	Value
Measurement range (km)	1~16
Temperature range (°C)	-40~120
Fiber type	Multimode 62.5/125 or 50/125
Temperature accuracy (°C)	±0.3
Temperature resolution (°C)	0.1
Response time (s)	2 s/channel
Spatial resolution (m)	0.5~3
Number of channels	4
Fiber connector type	FC/APC
Communication interface	USB / RS232 / Ethernet
Power supply	DC19V

2.2 *Pipeline Leakage Sensing Principle Based on OFDR*

Optical Frequency Domain Reflectometry (OFDR) is a high-resolution sensing technique based on frequency-swept continuous wave interferometry (FMCW). It employs a laser source with linear wavelength sweep combined with heterodyne detection. The optical signal is split into two arms: a reference arm and a signal arm. Due to differences in optical path lengths, the Rayleigh backscattered signal from the sensing fiber interferes with the reference signal, producing a beat frequency that is directly proportional to the scattering position. By applying a Fast Fourier Transform (FFT) to the interference signal, a spatially resolved Rayleigh scattering profile can be obtained.

Rayleigh scattering originates from random microscopic fluctuations in the refractive index of the fiber. Froggatt and Moore modeled these variations as a weak random Bragg grating. When external strain is applied to the fiber, the local spectrum of the Rayleigh scattering shifts. The magnitude of this spectral shift is linearly proportional to the applied strain. By comparing the shifted spectrum with a reference state, the strain distribution along the fiber can be quantified with high spatial resolution.

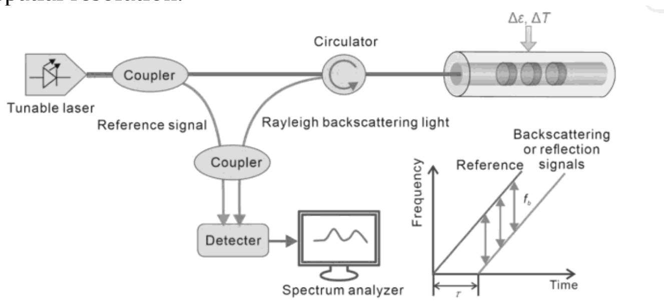

Figure 4. Measurement principle of OFDR.

Building upon the high-resolution strain measurement capability of OFDR, this study proposes a novel strain-sensing cable that incorporates water-swelling yarns into a fixed-point sensing structure. These yarns are made of polyester filaments coated with super-absorbent polymers (SAPs) and are commonly used as water-blocking fillers in optical cables. The SAPs contain abundant hydrophilic functional groups and a moderately cross-linked polymer network, enabling them to absorb water up to hundreds or even thousands of times their own weight. Once hydrated, the yarns expand into a hydrogel, maintaining structure under pressure and remaining functional under thermal cycling.

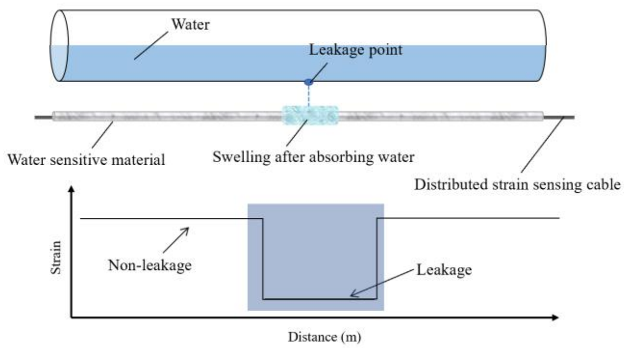

Figure 5. Schematic of pipeline leakage detection using OFDR and water-swelling yarns.

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In the proposed sensing cable, the fiber is pre-tensioned between discrete fixed points. Upon contact with leaked liquid, the SAP yarns rapidly swell, reducing the tensile force acting between anchor points. This localized strain reduction is accurately captured by the OFDR system, allowing for precise leakage detection. The cable features a four-layer construction, consisting of: a 0.9 mm tight-buffered strain-sensing fiber, a spiral armored tube, water-swelling yarn, and an outer braided mesh (Figure 6).

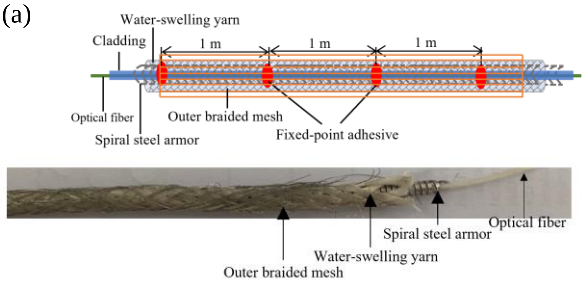

Figure 7. Structure of the strain-sensing cable with water-swelling yarns: (a) Schematic diagram; (b) Physical photograph.

The cable is fixed at 1-meter intervals, creating a structure with discrete sensing segments. The outer mesh ensures that the yarn remains in place during operation. The yarn itself consists of two components: a super-absorbent polymer (e.g., polyacrylate), which swells when exposed to water, and reinforcement fibers (e.g., nylon or polyester), which improve tensile strength and elongation properties. The key specifications of the water-swelling yarn and the OFDR interrogator (model OSI-S) are presented in Tables 3 and 4, respectively.

Table 3. Performance parameters of water-swelling yarn.

Property	Value
Yarn linear density (dtex)	3330
Basis weight (m/kg)	3000
Breaking strength (N)	≥100
Elongation (%)	15
Swelling rate (ml/g in 1st minute)	≥60
Long-term thermal swelling (150 °C, 24 h, ml/g)	≥65
Instant thermal swelling (230 °C, 10 min, ml/g)	≥65
Moisture content (150 °C, 1 min)	9

Table 4. Specifications of OSI-S OFDR interrogator.

Type	Specification
Portable enclosure dimensions (mm)	280×250×164
Portable enclosure weight (kg)	4.5
Spatial resolution (mm)	1-100
Maximum sampling resolution (mm)	1
Temperature accuracy (°C)	±0.1
Temperature repeatability (°C)	≤0.1
Measurement range (m)	100

3 RESULT

3.1 EETS-DTS Monitoring

Based on the spatial resolution of the DTS system, the length of gauze wrapping on the EETS cable was set to 1.8 meters. To simulate leakage, a 2-meter-long PVC pipe with an inner diameter of 75 mm and a leakage hole at the bottom was used. The fiber optic cable was secured directly beneath the pipe using plastic zip ties. Before the experiment, the water inside the pipe was left to stand for 24 hours to allow its temperature to reach equilibrium with ambient conditions.

During the test, the PVC pipe was maintained in a fully filled state. A dual-probe PT100 thermometer was employed to continuously monitor and record both the water temperature inside the pipe and the ambient air temperature. As humidity can significantly influence evaporative cooling, a digital hygrometer was placed near the pipe to record ambient relative humidity throughout the experiment.

The DTS temperature-sensing cable was connected to a temperature calibration box, which in turn was linked to the DTS interrogator, enabling real-time acquisition of the distributed temperature profile along the fiber. The complete experimental setup is shown in Figure 8.

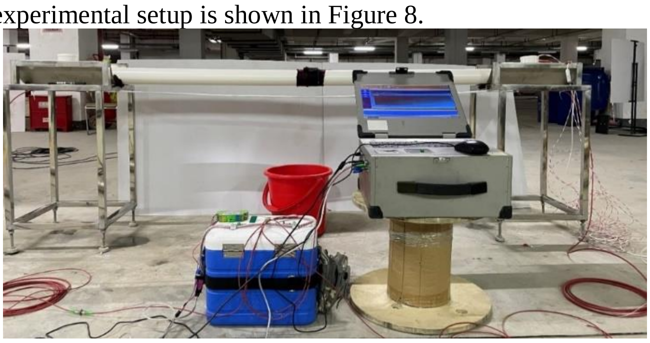

Figure 8. Photograph of the experimental setup.

Figure 9 presents the temperature variation trends at different positions along the bare DTS cable wrapped with gauze. The observed behavior is consistent with that of the sheathed cable: the temperature at each point decreases over time, and the closer a point is to the leakage location (located at 6.02 m), the greater the temperature drop. Furthermore, the temperature distribution is approximately symmetrical about the leakage point.

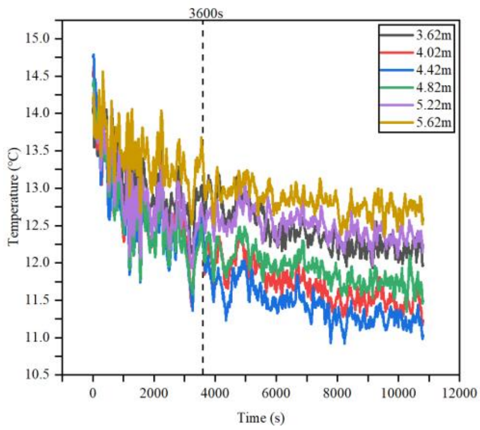

Figure 9. Temperature variation trends at different positions along the bare DTS temperature-sensing cable.

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However, in contrast to the sheathed condition, where temperatures eventually stabilized, the bare cable setup exhibited a continuous temperature decrease over time, without reaching equilibrium. This indicates that the evaporative heat loss exceeded the heat replenishment from the surrounding environment, suggesting that a dynamic thermal balance was not achieved during the experiment. One possible explanation is that, in this configuration, the gauze was directly wrapped onto a copper mesh, enhancing the fluid contact efficiency and promoting stronger evaporation, which resulted in sustained cooling.

Figure 10 illustrates the temperature distribution profiles along the bare cable at different time intervals. Similar to the sheathed condition, the temperature profile forms a characteristic "arch-shaped" curve, indicating that the temperature is lowest near the leakage point at any given time. However, compared with the sheathed cable, the bare cable exhibits a sharper temperature gradient, with a maximum temperature difference of 2.8 °C observed at 3600 seconds.

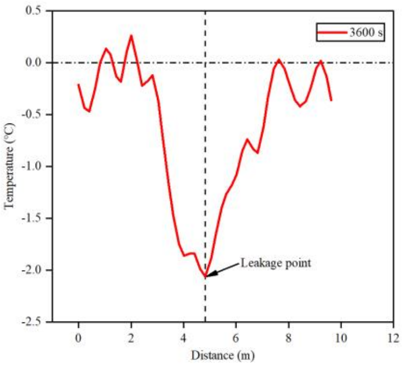

Figure 10. Temperature distribution along the bare DTS sensing cable at 3600 s.

These results indicate that the protective sheath has a noticeable effect on the EETS-DTS leakage detection performance. The bare cable yields clearer monitoring results, suggesting improved sensitivity. Therefore, the following sections focus on analyzing influencing factors for the bare EETS-DTS configuration.

3.2 OFDR-Based Monitoring

In this experiment, a peristaltic pump was employed to control the leakage rate, and both ends of the strain-sensing optical fiber cable—embedded with water-swelling yarns—were fixed in place. The leak outlet of the pump was precisely aligned with the sensing section of the cable. The selected leakage rate was 70 mL/min. The OFDR interrogator was connected to capture wavelength shift data corresponding to strain variations. The experimental setup is shown in Figure 11.

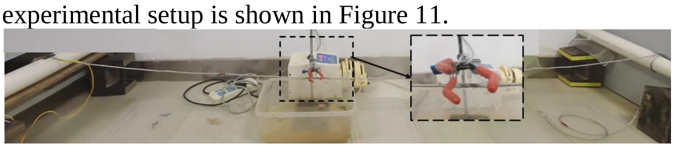

Figure 11. Experimental setup for OFDR-based leakage monitoring.

The measured strain distribution along the fiber is shown in Figure 12. Upon leakage, the strain recorded by the OFDR system dropped sharply and then stabilized. Throughout the leakage process, the strain-affected segment—defined by a significant drop in measured strain—spanned from 3.36 m to 4.36 m. In contrast, the rest of the cable exhibited minimal strain change, resulting in a distinct step-like pattern in the strain profile.

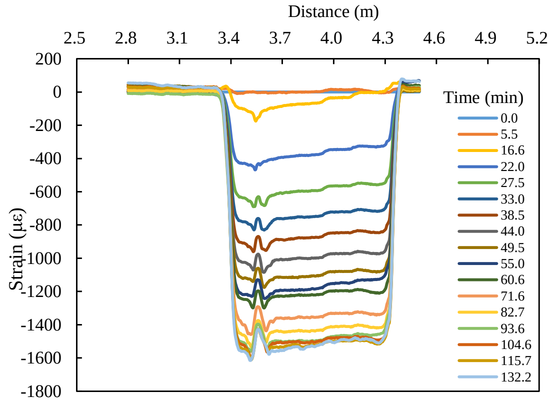

Figure 12. Strain magnitude measured by the fixed-point strain-sensing cable with water-swelling yarns.

To further analyze strain behavior, two points were selected: one located within the strain-drop region and the other outside it. Their strain variation over time is compared in Figure 13. It is evident that the strain at the leakage point decreased rapidly at first, followed by a gradual stabilization, while the unaffected region maintained a stable strain level throughout. The time required for the strain to stabilize was approximately 100 minutes.

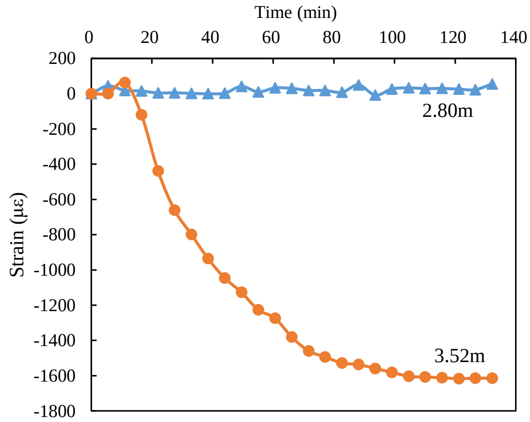

Figure 13. Strain variation over time at the leakage point of the strain-sensing cable with water-swelling yarns.

4 DISCUSSION

4.1 Applicability Analysis

This study presents two pipeline leakage monitoring methods: one based on evaporation-induced humidity sensing using DTS, and the other based on strain sensing using Optical Frequency Domain Reflectometry (OFDR) combined with water-swelling yarns. Both methods are suitable for detecting ambient-temperature liquid leaks in environments where the pipeline is exposed to air, such as underground utility corridors and aboveground pipelines. However, they are not applicable to

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buried pipelines, where direct air contact is absent, and evaporation or swelling may be inhibited.

The current work focuses on leakage scenarios involving water as the leaking medium. The effectiveness of these methods for other fluid types (e.g., oils, chemicals) requires further study, as variations in fluid properties may affect evaporation behavior or interaction with swelling materials.

The first method, based on evaporation sensing (EETS-DTS), is generally applicable in a wide range of environments and performs especially well in conditions with low humidity and high airflow, which enhance evaporation and generate more distinct temperature differences. In high-humidity environments, however, evaporation may be limited or suppressed, leading to reduced sensitivity or loss of functionality.

The second method, based on OFDR strain sensing with water-swelling yarns, demonstrates broader applicability. It is insensitive to environmental variables such as humidity and wind speed and exhibits high sensitivity, enabling the detection of small-scale or micro-leaks with better reliability.

4.2 Practical Application Analysis

Both methods offer distributed monitoring capabilities for pipeline leakage and are particularly advantageous for detecting small-volume, ambient-temperature liquid leaks. They are well-suited for underground utility corridors and open-air pipelines, where sensing cables can be conveniently installed beneath the pipelines.

The EETS-DTS method supports long-distance distributed measurement, but it offers relatively low measurement accuracy. In practical scenarios, elevated ambient humidity may cause natural temperature fluctuations, leading to false positives. Additionally, in harsh environments—such as acidic, dusty, or corrosive conditions—the gauze layer may degrade or fail over time, compromising the monitoring performance. For long-term or demanding applications, regular gauze replacement is recommended to ensure reliability.

The fixed-point strain-sensing cable embedded with water-swelling yarns also enables distributed leakage detection. However, given that standard OFDR systems are limited to approximately 100 meters, it is advisable to adopt alternative demodulation technologies such as Brillouin Optical Domain Frequency Analysis (BODFA) or Brillouin Optical Time-Domain Reflectometry (BOTDR) for longer-distance applications.

In practical deployment, a hybrid monitoring strategy is recommended: (1) Use the EETS-DTS method in well-ventilated, low-humidity environments to take advantage of its evaporation-based sensitivity. (2) In environments where the EETS-DTS method is inapplicable or limited, deploy the strain-sensing cable with water-swelling yarns to ensure continued leakage detection.

5 CONCLUSION

This study proposed and experimentally validated two novel pipeline leakage monitoring methods based on distributed fiber optic sensing (DFOS): an evaporation-enhanced temperature sensing method using DTS (EETS-DTS), and a fixed-point strain sensing method using OFDR combined with water-swelling yarns. Both approaches demonstrated effective capabilities for detecting small-scale leaks of ambient-temperature liquids in tunnel or aboveground pipeline environments.

The EETS-DTS method leverages gauze-wrapped optical fibers to amplify evaporation-induced temperature differences, enabling distributed leak localization with a relatively simple setup. It is particularly effective in low-humidity, well-ventilated environments. The OFDR-based strain sensing method utilizes the swelling behavior of specially embedded yarns to detect leakage-induced strain changes with high resolution and sensitivity, and is less affected by environmental variables.

Laboratory experiments confirmed the feasibility and reliability of both methods. The EETS-DTS technique offers advantages in long-range monitoring, while the OFDR-based method provides high accuracy in micro-leak detection. A hybrid deployment strategy is recommended to combine the strengths of both approaches for broader practical applicability.

Overall, the proposed methods provide promising and complementary solutions for pipeline leakage monitoring, offering new perspectives for enhancing infrastructure safety and maintenance in complex pipeline networks.

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