

Research Progress on Leak Detection, Localization, and Intelligent Identification Technologies for Hydrogen Storage Pipelines

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Abstract

With the rapid development of the hydrogen energy industry, hydrogen storage pipelines—as critical infrastructure for large-scale hydrogen transportation—have drawn widespread attention regarding their safe operation. This paper focuses on the current state of development in hydrogen storage pipeline leak monitoring technology. It provides a systematic review of the mechanisms of leak formation, diffusion patterns, and leak signal characteristics. The paper summarizes leak detection and localization technologies based on fluid parameters, acoustics, optics, and sensors, with a particular emphasis on analyzing research progress in the application of machine learning, deep learning, and multi-source information fusion for intelligent leak identification. It also discusses the challenges facing current technologies and outlines future development trends, with the aim of providing guidance for the advancement and engineering application of hydrogen storage pipeline leak monitoring technology.

Keywords

Hydrogen Storage Pipelines; Leak Detection; Leak Localization; Intelligent Identification.

1. Introduction

Driven by the global transition to low-carbon energy and the “dual carbon” strategic goals, hydrogen energy is regarded as a vital component of the future energy system due to its advantages, including widespread availability, clean and efficient use, and zero carbon emissions at the point of consumption. In recent years, China, the European Union, Japan, and the United States have successively released hydrogen energy development plans, positioning hydrogen as a key technological pathway for promoting energy structure adjustment and achieving deep decarbonization. As the scale of renewable energy-based hydrogen production continues to expand, establishing a safe and efficient storage and transportation system has become a critical link in the development of the hydrogen industry [1]. Currently, hydrogen transportation methods primarily include high-pressure long-tube trailer transport, liquid hydrogen transport, solid-state hydrogen storage, and pipeline transport. Among these, pipeline transport offers advantages such as high transmission capacity, low operating costs, and strong continuous hydrogen supply capabilities, making it a key method for achieving large-scale, long-distance hydrogen transmission in the future [2]. However, due to hydrogen's hydrogen embrittlement effects and strong permeation capabilities, hydrogen transmission pipelines still face numerous challenges regarding material suitability, safe operation, and integrity management. Therefore, conducting research on safety monitoring and leak early warning for hydrogen transmission pipelines is of great significance [1].

Compared to natural gas, hydrogen has characteristics such as small molecular size, fast diffusion rate, low viscosity, and high permeability, making it extremely prone to leakage through welds, flanges, and microcracks in materials. At the same time, hydrogen has a minimum ignition energy of only about 0.02 mJ, a wide explosive limit range (4%–75% by

volume), a rapid combustion rate, and weak flame radiation. Once a leak occurs, it can easily trigger fires or even explosions, posing a serious threat to the safety of personnel and equipment [3]. As hydrogen transmission pressures and scales continue to increase, traditional natural gas pipeline leak detection technologies are no longer sufficient to fully meet the requirements for pure hydrogen transmission. Consequently, extensive research has been conducted both domestically and internationally on technologies such as fiber-optic sensing, acoustic detection, laser spectroscopy, gas sensors, and infrared imaging to enhance the sensitivity of hydrogen leak detection and real-time monitoring capabilities [4]. Establishing a highly sensitive and reliable online monitoring system to enable rapid leak detection and early warning is a critical technical foundation for ensuring the safe operation of hydrogen storage pipelines.

In recent years, hydrogen storage pipeline leak monitoring technology has gradually evolved toward intelligent systems and the integration of multi-source information, with research primarily focused on three areas: leak detection, leak localization, and intelligent identification. In terms of leak detection, methods such as the mass balance method, the negative pressure wave method, the real-time transient model (RTTM), distributed fiber optic sensing, and hydrogen sensors have been extensively studied; among these, distributed fiber optic monitoring and laser spectroscopic detection have become hot research topics in recent years due to their high sensitivity and continuous online monitoring capabilities [5]. In terms of leak localization, methods based on negative pressure wave propagation, time difference analysis, and model inversion enable rapid identification of leak locations, while localization algorithms that combine experimental data with numerical models can further improve localization accuracy [6]. With the advancement of artificial intelligence, deep learning algorithms such as convolutional neural networks (CNNs), long short-term memory networks (LSTMs), and Transformers have been introduced into the field of leak identification, demonstrating good recognition capabilities under complex operating conditions [7]. However, most current research is still conducted on laboratory platforms, suffering from issues such as insufficient real-time performance, limited adaptability to complex operating conditions, and weak model generalization capabilities. Therefore, building a high-precision, real-time hydrogen storage pipeline leak monitoring system that integrates physical models, multi-source monitoring data, and intelligent algorithms will become an important future research direction.

2. Mechanisms of Hydrogen Storage Pipeline Leaks and Monitoring Requirements

2.1. Mechanisms of Leak Formation

Leaks in hydrogen storage pipelines are typically the result of the combined effects of material degradation, structural defects, and the external environment. Among these, hydrogen embrittlement is a typical failure mechanism that distinguishes pure hydrogen transmission pipelines from natural gas pipelines. Under high pressure, hydrogen atoms readily diffuse into the metal lattice, leading to a decrease in the material's ductility and toughness and promoting crack initiation and propagation; in severe cases, this can cause brittle fracture of the pipeline. In addition, during long-term service, pipelines are also affected by factors such as soil corrosion, stress corrosion, and electrochemical corrosion, which can cause the pipe wall to thin or form localized corrosion pits, thereby creating pathways for leaks. Under periodic pressure fluctuations, fatigue crack propagation is likely to occur in weld zones and heat-affected zones, while welding defects (such as porosity, lack of fusion, and slag inclusions) can also reduce the pipeline's overall load-bearing capacity. In addition to material and manufacturing factors, external factors such as damage caused by third-party construction, mechanical impact, and geological disasters are also major causes of leaks in hydrogen

transmission pipelines. Therefore, material properties, operating conditions, and environmental factors should be comprehensively considered to establish a full-lifecycle integrity management system, thereby reducing the risk of leaks and ensuring the safe operation of the pipeline.

2.2. Patterns of Leakage Propagation

Following a leak in a hydrogen storage pipeline, hydrogen—under high pressure—first forms a high-velocity jet, which then mixes with the surrounding air through entrainment and continues to disperse, ultimately forming a flammable cloud with a specific concentration distribution. In the initial stage of the leak, the jet's characteristics are primarily determined by the ratio of the internal pipe pressure to the ambient pressure. When the pressure ratio exceeds a critical value, the leaking fluid exhibits critical flow or even supersonic jet flow, with a flow velocity approaching or exceeding the local speed of sound; the mass flow rate of the leak is primarily controlled by the internal pipe pressure. As the pressure gradually decreases, the jet flow transitions to subsonic flow, at which point the leakage flow rate is jointly influenced by the pressure difference between the inside and outside of the pipe. Hydrogen has low density and high buoyancy, and its diffusion rate is significantly faster than that of natural gas; therefore, its diffusion range is significantly affected by factors such as the leak aperture, internal pipe pressure, wind speed, wind direction, and surrounding obstacles. In enclosed or semi-enclosed spaces, hydrogen tends to accumulate at the top, forming hazardous clouds that increase the risk of fire and explosion; in open environments, natural ventilation accelerates the dilution of hydrogen, reducing the size of the hazardous area. Therefore, a precise understanding of the patterns of leak dispersion is a crucial foundation for conducting leak monitoring, risk assessment, and safety protection design.

2.3. Characteristics of Leakage Signals

When a leak occurs in a hydrogen storage pipeline, it is accompanied by a series of physical field changes, which serve as a crucial source of information for leak detection and localization. First, a leak causes sudden changes in pressure and flow rate within the pipeline, generating a negative pressure wave that propagates along the pipeline; this wave can be used for long-distance leak detection and localization. Second, the friction between high-speed hydrogen jets and air generates broadband acoustic signals and pipeline vibration signals, whose frequency and amplitude are closely related to the leak aperture, pressure, and flow rate; therefore, acoustic emission and vibration monitoring technologies have been widely applied in leak identification research. Furthermore, due to the Joule-Thomson effect during gas expansion and heat exchange in high-speed jets, localized temperature changes occur near the leak area, which can be monitored using infrared thermal imaging and distributed fiber-optic temperature measurement technologies. For methods that directly detect hydrogen concentration, gas-sensitive sensors and laser spectroscopy technologies can capture real-time changes in hydrogen concentration at the leak site, enabling highly sensitive leak detection. In recent years, multi-source signal fusion technology has gradually become a research hotspot. By integrating various types of information—including pressure, acoustic, vibration, temperature, and concentration data—it is possible to effectively improve the accuracy and reliability of hydrogen storage pipeline leak detection under complex operating conditions.

3. Hydrogen Storage Pipeline Leak Detection and Location Technology

3.1. Methods Based on Fluid Parameters

Leak detection methods based on fluid parameters are currently the most mature technology used in hydrogen transmission pipelines; they primarily rely on the conservation of pressure, flow rate, and mass during pipeline operation to determine the presence of leaks. The mass

balance method detects leaks by comparing the difference in flow rates between the pipeline inlet and outlet. It features a simple principle and is easy to implement; however, it is susceptible to measurement errors and fluctuations in operating conditions, making it difficult to detect small leaks. The pressure gradient method establishes a pressure model based on changes in pressure distribution caused by leaks; when an abnormal pressure gradient occurs, it indicates a leak in the pipeline. This method is suitable for steady-state operating conditions but has limited adaptability to complex operating conditions. The Negative Pressure Wave (NPW) method is currently one of the most widely used methods. When a leak occurs in a pipeline, a negative pressure wave is generated at the leak point and propagates along both ends of the pipeline; by detecting the time difference in the arrival of the waves, the leak can be located. It offers advantages such as fast response speed and high localization accuracy, but is susceptible to interference from environmental noise and pressure fluctuations. The Real-Time Transient Model (RTTM), on the other hand, establishes a mathematical model of pipeline flow to predict parameters such as pressure and flow rate in real time, and combines this with monitoring data to determine the leakage status. It offers advantages such as high detection accuracy and strong adaptability to complex operating conditions; however, model development is complex, computational demands are high, and it requires high precision in pipeline parameter data.

3.2. Acoustic-Based Methods

Acoustic detection methods utilize sound waves or vibration signals generated during a leak to identify and locate leaks, and are characterized by their non-contact nature and fast response times. Acoustic Emission (AE) technology collects elastic wave signals generated by leaks through the deployment of piezoelectric sensors; it can detect crack propagation in materials and minute leaks, and is therefore widely used in the integrity monitoring of pressure vessels and pipelines. Ultrasonic testing, on the other hand, utilizes high-frequency ultrasonic signals generated by high-speed hydrogen jets. It offers strong resistance to environmental noise and is suitable for the early detection of microleaks; however, it has a short propagation distance and places high demands on sensor placement. In recent years, microphone array technology combined with beamforming algorithms has enabled the spatial localization of leak sources, effectively improving localization accuracy in complex environments. With advancements in digital signal processing and artificial intelligence, the extraction of acoustic features—combined with algorithms such as convolutional neural networks (CNNs) and long short-term memory networks (LSTMs)—can further improve leak detection accuracy and resistance to interference. However, acoustic methods are susceptible to environmental noise, equipment vibration, and changes in wind speed; therefore, they typically require integration with other monitoring methods for comprehensive assessment.

3.3. Optical-Based Methods

Optical detection technology offers advantages such as non-contact operation, high sensitivity, and strong resistance to electromagnetic interference, making it a key area of development in hydrogen storage pipeline leak monitoring in recent years. Among these, tunable diode laser absorption spectroscopy (TDLAS) utilizes hydrogen's absorption characteristics at specific laser wavelengths to detect concentration, offering advantages such as fast response times and high detection accuracy. Infrared thermal imaging technology, on the other hand, enables visual monitoring by detecting changes in the temperature field around leak areas. It is suitable for large-scale inspections in complex environments but is susceptible to ambient temperature fluctuations. Distributed fiber-optic sensing technology can continuously monitor temperature and vibration changes along the pipeline. Among these, fiber Bragg gratings (FBGs) are primarily used for local strain and temperature monitoring, while Distributed Acoustic Sensing (DAS) enables continuous vibration monitoring over ranges of tens of kilometers and has

become a key technology for online monitoring of long-distance hydrogen transmission pipelines. Compared to traditional detection methods, optical technologies offer advantages such as wide coverage, real-time online monitoring, and long service life; however, they involve higher equipment costs and place greater demands on installation conditions and data processing capabilities, so their engineering applications still require further optimization.

3.4. Sensor-Based Methods

With the advancement of microelectronics technology, various types of hydrogen sensors have become an integral part of leak detection systems in hydrogen storage facilities. Electrochemical sensors utilize the redox reaction of hydrogen to generate an electrical signal for concentration detection; they are characterized by high sensitivity and fast response times, but are susceptible to temperature and humidity fluctuations. Metal-oxide-semiconductor (MOS) sensors detect hydrogen by measuring changes in the resistance of the sensitive material caused by hydrogen; they offer advantages such as low cost, simple structure, and ease of integration, but they operate at relatively high temperatures and have relatively poor selectivity. Micro-Electro-Mechanical Systems (MEMS) sensors, manufactured using micro- and nanofabrication processes, are characterized by their small size, low power consumption, and fast response times, making them suitable for distributed monitoring networks. In recent years, novel nano-sensitive materials such as graphene, carbon nanotubes, and two-dimensional materials have been increasingly applied in the field of hydrogen detection, significantly improving sensor sensitivity and detection limits while providing new technical pathways for the development of smart sensors. In the future, multi-sensor fusion monitoring will become the primary direction for enhancing the reliability of safety monitoring in hydrogen storage pipelines.

3.5. Comparison of Methods

Table 1. Comparison of Leak Detection Methods for Different Hydrogen Storage Pipelines

Method	Positioning Capability	Sensitivity	Real-Time Performance	Cost	Typical Applications
Mass Balance Method	★★★	★★★	★★★	Low	Long-distance pipelines
Pressure Gradient Method	★★★	★★	★★★	Low	Pipelines in Steady-State Operation
Negative Pressure Wave Method	★★★★	★★★	★★★★★	Middle	Long-Distance Hydrogen Pipelines
RTTM	★★★★★	★★★★★	★★★★★	High	SCADA Online Monitoring
Acoustic Emission	★★★★	★★★★★	★★★★★	Middle	Localized Leak Detection
Ultrasound	★★★	★★★★★	★★★★★	Middle	Micro-leak Detection
Microphone Array	★★★★	★★★★★	★★★★★	Middle	Leak Source Localization
TDLAS	★★★	★★★★★	★★★★★	High	Hydrogen Storage Stations, Inspection Rounds
Infrared Thermal Imaging	★★	★★★	★★★★★	High	Drone Inspections
FBG	★★★	★★★★★	★★★★★	High	Strain/Temperature Monitoring
DAS	★★★★★	★★★★★	★★★★★	High	Long-Distance Hydrogen Pipelines
Electrochemical Sensors	★	★★★★★	★★★★★	Low	Hydrogen Storage Facilities
MOS Sensors	★	★★★★★	★★★★★	Low	Fixed Monitoring Stations
MEMS/Nano Sensors	★★	★★★★★	★★★★★	Middle	Smart Monitoring Network

Different leak detection technologies have their own scope of application and technical characteristics. Methods based on fluid parameters are suitable for online monitoring of long-distance hydrogen transmission pipelines; they offer advantages such as mature engineering applications and strong localization capabilities, but are relatively sensitive to changes in operating conditions. Acoustic methods can quickly identify minute leaks, but their noise immunity is significantly affected by the environment. Optical detection technologies feature high sensitivity and wide coverage, making them particularly suitable for online monitoring of newly constructed hydrogen transmission pipelines, but they come with higher system costs. Sensor-based methods feature simple structures and high detection accuracy, making them suitable for monitoring hydrogen storage stations and localized areas, though they struggle to achieve continuous localization over large areas. Therefore, in practical engineering applications, a multi-source information fusion approach is commonly adopted, combining various technologies—such as fluid parameters, acoustic signals, fiber-optic monitoring, and gas sensors—to enhance leak detection accuracy and system reliability, thereby providing technical support for the intelligent monitoring of hydrogen storage pipelines.

4. Intelligent Leak Detection Technology for Hydrogen Storage Pipelines

4.1. Leak Signal Processing

Signals such as pressure, vibration, acoustic emission, and flow rate generated during hydrogen storage pipeline leaks exhibit distinct nonlinear and nonstationary characteristics. Directly using raw signals for leak detection is prone to interference from environmental noise and fluctuations in operating conditions; therefore, signal preprocessing and feature extraction form a crucial foundation for intelligent detection. The Fast Fourier Transform (FFT) can convert time-domain signals into frequency-domain signals and is suitable for analyzing the frequency composition of leak signals under steady-state conditions; however, its ability to analyze non-stationary signals is limited. The Wavelet Transform (WT) offers excellent local time-frequency analysis capabilities and can effectively extract transient leakage features; it is widely used in the processing of pressure wave and acoustic emission signals. Empirical Mode Decomposition (EMD) and its improved algorithm, Collective Empirical Mode Decomposition (CEEMDAN), can adaptively decompose complex signals, reduce modal aliasing, and enhance the ability to extract weak leakage features. In recent years, Variational Mode Decomposition (VMD) has garnered significant attention in the processing of hydrogen storage pipeline leak signals due to its high decomposition accuracy and strong noise resistance. In practical applications, methods such as VMD, CEEMDAN, and wavelet denoising are often combined to provide high-quality feature inputs for subsequent machine learning and deep learning models.

4.2. Machine Learning Recognition

As the volume of monitoring data continues to grow, machine learning methods have gradually become a key technical tool for identifying leaks in hydrogen storage pipelines. By establishing a mapping relationship between sample features and leak status, machine learning enables leak classification and localization, offering higher detection accuracy and robustness compared to traditional threshold-based methods. Support Vector Machines (SVM) are well-suited for classifying small-sample, high-dimensional data and can effectively improve detection accuracy under complex operating conditions in leak detection. Random Forests (RF) perform classification by ensemble learning using multiple decision trees; they possess strong resistance to overfitting and can assess the importance of individual monitoring features, making them widely used in the analysis of pressure, flow, and vibration signals. In recent years, XGBoost—a highly efficient gradient boosting algorithm—has achieved favorable results in leak condition identification and leak severity classification due to its fast training speed and excellent generalization performance. Overall, machine learning algorithms offer advantages

such as simple models and high training efficiency; however, their performance relies heavily on manual feature extraction, and there is still room for improvement in their adaptability to complex operating conditions and unknown scenarios.

4.3. Deep Learning Recognition

In recent years, deep learning has gradually become a hot research topic in the field of intelligent hydrogen storage pipeline leak detection due to its powerful automatic feature learning capabilities. Convolutional neural networks (CNNs) can automatically extract local features from pressure waves, acoustic emissions, and vibration signals, demonstrating high accuracy in leak classification and fault detection. Long Short-Term Memory (LSTM) networks are well-suited for processing monitoring data with temporal correlations and can effectively capture the dynamic characteristics of leak signals as they change over time. To further improve recognition performance, researchers have proposed a hybrid CNN-LSTM model, which uses CNNs to extract spatial features and LSTMs to learn time-series features, thereby achieving high-precision recognition under complex operating conditions. In recent years, Transformer models have demonstrated significant advantages in modeling long time series thanks to their self-attention mechanism and have gradually been applied to pipeline leak prediction and condition assessment. Additionally, Graph Neural Networks (GNNs) can propagate features by utilizing the topological structure of pipeline networks and multi-node monitoring information, providing new research approaches for leak localization in complex hydrogen transmission networks. In the future, building intelligent monitoring models by integrating Transformer, GNN, and digital twin technologies will become a key development direction for intelligent detection in hydrogen storage pipelines.

4.4. Multi-Source Information Fusion

A single monitoring method is susceptible to factors such as environmental noise, operating conditions, and sensor performance, making it difficult to meet the high-reliability leak detection requirements for hydrogen storage pipelines. Therefore, multi-source information fusion has gradually become a hot topic in current research. This approach comprehensively utilizes various monitoring data—including pressure, flow rate, vibration, acoustic emission, fiber-optic monitoring, and imagery—to achieve complementary leak detection through data fusion algorithms, thereby improving detection accuracy and system reliability. For example, combining negative pressure waves with flow monitoring can improve the accuracy of leak localization in long-distance pipelines; integrating distributed fiber-optic monitoring with acoustic emission technology enables rapid identification and spatial localization of leak events; and combining infrared and visible-light imagery with deep learning algorithms allows for the visual monitoring of leaks at hydrogen storage stations and in pipeline corridor areas. In recent years, with the development of the Internet of Things (IoT), edge computing, and digital twin technologies, multi-source data fusion has gradually evolved from traditional feature-level fusion toward decision-level and intelligent fusion. By establishing a digital twin of the hydrogen transmission pipeline network to enable real-time updates of monitoring data, dynamic model corrections, and risk prediction, the intelligence level of hydrogen storage pipeline leak monitoring systems can be further enhanced, providing technical support for the future construction of smart pipeline networks.

5. Summary

In recent years, with the rapid development of the hydrogen energy industry, hydrogen storage pipeline leak detection technology has gradually evolved from traditional single-parameter detection toward intelligent, multi-source fusion approaches. Methods based on fluid parameters—such as mass balance, negative pressure waves, and real-time transient models—

have established a solid foundation for engineering applications, while technologies such as acoustic emission, ultrasonics, distributed fiber optics, laser spectroscopy, and infrared imaging have further enhanced the sensitivity and real-time performance of leak detection. At the same time, intelligent algorithms such as support vector machines, random forests, convolutional neural networks, long-short-term memory (LSTM) networks, and Transformers have gradually been applied to leak identification and localization, enhancing data analysis capabilities under complex operating conditions. However, existing research still faces certain limitations. On the one hand, most findings are primarily based on laboratory or small-scale test platforms, with insufficient validation under the complex operating conditions of actual hydrogen transmission networks; on the other hand, there are significant variations across different studies regarding leak aperture, operating pressure, environmental conditions, and evaluation metrics, and there is still a lack of unified datasets and standardized evaluation systems. Furthermore, factors such as environmental noise, temperature fluctuations, and mechanical vibrations can interfere with monitoring signals, while AI models also suffer from issues such as heavy reliance on training data and insufficient cross-scenario generalization capabilities. In the future, leak monitoring for hydrogen storage pipelines will further evolve toward digitalization, intelligence, and collaboration. By integrating multi-source information—including pressure, flow rate, vibration, fiber optics, imagery, and gas concentration—the accuracy and reliability of leak detection and localization will be enhanced; At the same time, the introduction of technologies such as digital twins, edge computing, the Internet of Things (IoT), and drone inspections will drive monitoring systems toward an integrated approach that moves beyond simple detection to include real-time sensing, intelligent diagnosis, risk early warning, and autonomous decision-making, thereby providing more reliable technical support for the safe operation and smart management of hydrogen storage pipelines.

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