A Review of Oil and Gas Pipeline Leakage Detection Technology

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Abstract

In recent years, with the continuous growth of global energy demand and the acceleration of industrialisation, the construction scale and operational complexity of oil and gas pipelines, as the core infrastructure of energy transportation, have increased significantly. However, pipeline leaks not only cause wasted energy and economic losses but can also lead to serious environmental and safety concerns. Therefore, pipeline leakage detection technology, as a key means to ensure the safe and efficient operation of oil and gas pipelines, has received extensive attention. In this paper, the development process of pipeline leak detection and location technology is systematically reviewed, and the existing research results are comprehensively summarised and classified. According to the different detection methods, the detection methods are roughly divided into biological detection methods, hardware-based detection methods and software-based detection methods, with the basic principles and application scenarios of each method elaborated in detail. Secondly, the research status of Ground Penetrating Radar (GPR), a new detection technology, and its application potential in leak detection are also discussed. Finally, in light of the challenges faced by the current technology, the key directions for future research are proposed, including the improvement of detection accuracy, the development of new detection technologies, and the in-depth application of artificial intelligence in leakage diagnosis. The aim of this paper is to provide theoretical reference and practical guidance for the further development of pipeline leak detection technology.

Keywords

Oil and gas pipelines, Pipeline leak detection technology, Ground Penetrating Radar.

1. Introduction

Pipeline transportation has become the world's main mode of oil and gas transportation due to its advantages of large transportation volume, strong safety and low cost. Pipeline leak detection has been used since the beginning of the twentieth century, and the earliest detection methods were relatively simple, mainly relying on manual detection methods. In the seventies of the last century, there have been different methods of research and analysis on the problem of pipeline leakage at home and abroad, with the advancement of industrialisation, the corresponding acoustic and pressure equipment has been gradually developed, the pipeline leakage detection technology has gradually developed, and some signal processing and artificial intelligence methods have also begun to be applied. In 1977, Siebert et al.[1] proposed a cross-correlation analysis method based on pressure and flow rate to detect pipeline leaks by analysing sensor signals. On the basis of the cross-correlation analysis method, in 1984, Billmann et al.[2] proposed a nonlinear adaptive state sensor based on the monitoring of pipeline inflow and pressure to solve the problem that small leaks in oil and gas pipelines are difficult to locate. In 2001, Vogel et al.[3]first proposed a distributed optical fibre temperature sensing technology that can be applied to oil and gas pipeline leakage detection. In 2017, Kumar et al. [4] developed an acoustic sensor for online monitoring of buried pipelines to record small leakage signals, and combined with the capabilities of wavelet transform analysis and neural network classification, they proposed an algorithm with wavelet analysis and neural network modularisation, which effectively improved the accuracy of leakage signal identification and classification. In 2024, Abbas Rushdi et al.[5] proposed a LoRa-based wireless sensor network for real-time detection of long-distance pipeline leaks, combining multiple machine learning methods with a prediction accuracy of 89%.

As the scope and complexity of oil and gas pipeline laying continues to increase, the need for oil and gas pipeline inspection technology has become more urgent. In recent years, the relevant detection technologies and methods have been constantly developing and improving. In addition to the research on the existing commonly used typical hardware detection methods, there is also research on how to improve the accuracy, reliability and adaptability of the detection technology. Some new pipeline leakage fault detection technologies and methods are also increasingly being researched, such as ground penetrating radar exploration methods and thermal imaging methods. Timely summarising and analysing these research results can help guide the future efficiency, scientific application and development of oil and gas buried pipeline detection methods. This paper will expound on the principles and research status of the main methods of pipeline leakage detection both at home and abroad, and will prospect the future direction of pipeline leak detection technology.

2. Pipeline leak detection methods and progress

Pipeline leakage detection methods have different classification methods according to various bases, and can be divided into direct detection and indirect detection depending on the correlation of detection data parameters. According to the detection object and its location, it can be divided into internal pipeline inspection and external pipeline inspection. According to the degree of detection intelligence, it can be divided into automatic detection, semi-automatic detection and manual detection; According to the frequency period of the test, it can be divided into continuous detection and discontinuous detection. According to the different detection methods, this paper can be roughly divided into biological detection method, hardware-based detection method and software-based detection method, and its classification diagram is shown in Figure 1.

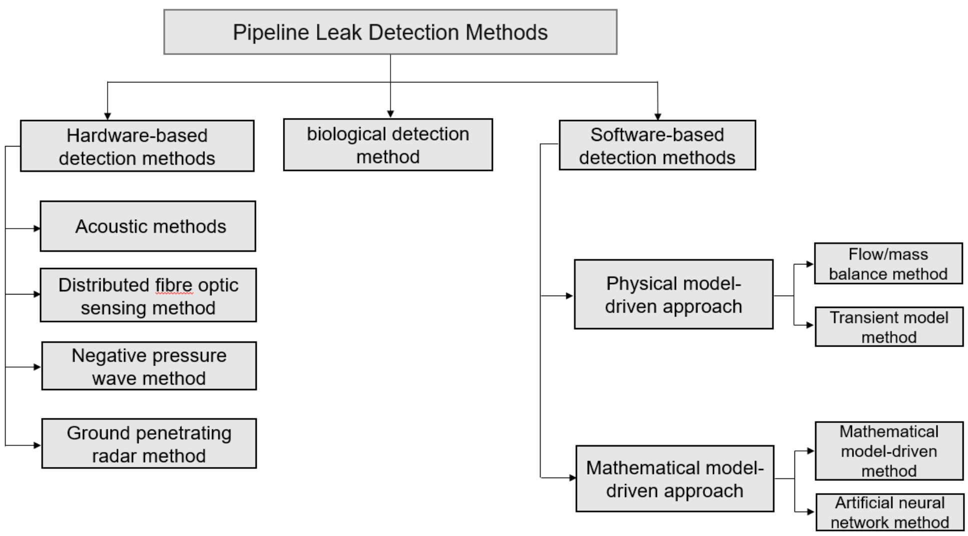

Fig. 1 Classification of pipeline leak detection methods

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2.1. Biological detection method

Biological detection method is a traditional, non-technical detection method, referring to the use of experienced personnel or other organisms to judge whether there is oil and gas leakage around the pipeline, including manual inspection method by inspectors holding testing equipment, driving inspection vehicles or with specially trained police dogs along the pipeline for manual inspection, abnormal detection of the pipe wall and the environment around the pipeline, observers and police dogs can determine the accident area by visual observation or the smell emitted by the leakage, identification and location of leakage cracks by handheld equipment or vehicle inspection machines; the biosensor method is to use suitable organisms such as mussels as sensors, and place them in the structure inside the pipeline or around the pipe wall to monitor environmental pollution, record their heart beat frequency signals, and identify whether leaks occur in the environment around the pipeline. The cost of such methods is low and the technical methods are simple and direct, but they are very limited in the applicable conditions and use environment, and it is difficult to realise the specific positioning of the leakage point in the face of the complex pipeline structure of the city and the buried pipeline manually or the dogs used, and the biosensor method is only suitable for the detection of shallow water areas. In terms of accuracy and real-time, it is largely limited by subjective ability, and can only be detected periodically for long-distance pipelines, and it is difficult for manual inspection methods to realise real-time detection of pipelines.

2.2. Hardware-based detection methods

2.2.1. Acoustic methods

Acoustic sensor detection method is one of the most widely used detection technologies for pipeline leakage, and acoustic detection methods include infrasonic method and ultrasonic method in addition to acoustic detection method. It uses an acoustic wave sensor device installed on the upstream and downstream outer wall of the pipeline to detect the change law and characteristics of the sound wave signal when there is a leakage in the oil and gas pipeline. When the pipe wall cracks and leaks, due to the pressure difference between the inside and outside of the pipeline, the oil and gas fluid is sprayed out from the leakage point, and the leakage hole of the pipe wall rubs against each other, producing oscillating sound waves. The sound wave signal, with a certain frequency and waveform characteristics, is received by the acoustic wave sensor, and the structure of the sensor device of the acoustic wave detection method is shown in Figure 2.

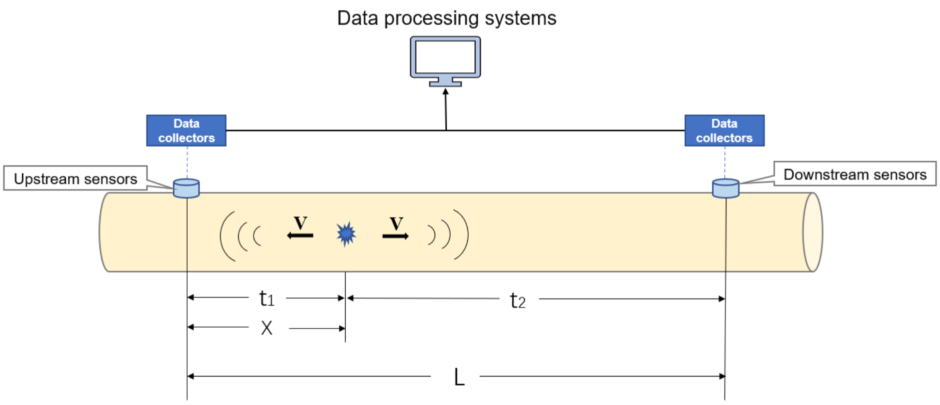

Fig. 2 Structure of the acoustic sensor device

In the figure, L is the distance between the upstream and downstream sensors; X is the distance from the leakage point to the upstream sensor; t_1 is the time it takes for the leakage point to generate the sound wave to the upstream sensor; t_2 is the time it takes for the leak to generate sound waves to the downstream sensor; v is the speed at which the sound wave travels through the pipe. The location of the leakage point can be determined according to the time difference between the sound waves generated by the leakage point and the upstream and downstream sensors, and the leakage point location formula is as follows:

$$X = \frac{L - v \times (t_1 - t_2)}{2} \tag{1}$$

The key and difficult point in the process of pipeline leak detection and positioning is the calculation of the time difference Δt and propagation velocity v, and in order to obtain a complete and effective leakage signal, the collected signal needs to be processed and analysed. According to the guided wave theory, the propagation velocity v of the elastic wave in the pipeline is not constant, but changes with the change of wave frequency, so it is very important to accurately determine the frequency of the pipeline leakage sound wave.Davoodi et al. [6]proposed a method combining wavelet transform, filtering, and cross-correlation analysis to deal with leakage continuous acoustic signals for leakage location, and the error percentage of the test results was less than 3%.In order to obtain more accurate time difference and velocity, signal denoising and leakage feature recognition are particularly important, and different time-frequency analysis methods have different signal processing effects on various pipelines and various leakage conditions, and further research is needed for the combined application of different positioning methods.

In view of the long distance and complex characteristics of pipelines, the acoustic detection method only needs to arrange enough acoustic wave sensors in the pipeline, and does not need to carry out mathematical modelling of the pipeline in advance, which has become one of the most widely used detection methods due to its simple application, strong practicability and high positioning accuracy. However, due to the short range of sound wave propagation, multiple sensors need to be arranged when inspecting long-distance pipes, and the cost of the device still needs to be considered.

2.2.2. Distributed fibre optic sensing method

In recent years, distributed optical fibre sensors (DOFS) have been widely used to locate pipeline damage or leakage due to the maturity and development of optical fibre devices because they can measure temperature and strain. Distributed fibre optic pipe leak detection refers to laying optical fibre cables along the pipe wall along the pipeline, arranging multiple sensors along the optical fibre and transmitting the sensor signal through the optical fibre, and passing the optical fibre back to the central control room for pipeline leak detection. The principle is shown in Figure 3.

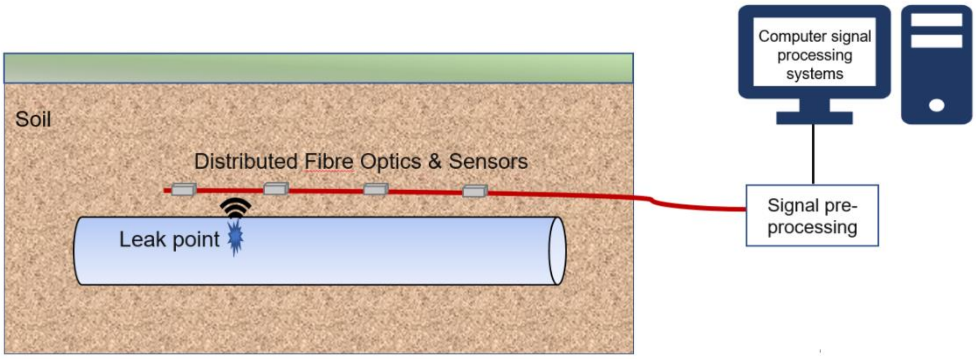

Fig. 3 Schematic diagram of a distributed fibre optic sensor

At present, the common distributed optical fibre sensing technology is divided into distributed temperature sensing, distributed strain sensing and distributed acoustic wave sensing according to its detection variables. The distributed sensing system uses optical time-domain reflectometry to detect and locate leaks, in which the distributed temperature sensing and distributed strain sensing adopt the Raman and Brillouin scattering principles, and the distributed acoustic sensing adopts the Rayleigh scattering principle.

The temperature and strain sensing technology is based on the Raman and Brillouin optical time domain analysis technology, and the Brillouin frequency shift is only related to temperature and strain to realise pipeline leakage monitoring, and the distributed optical fibre strain sensing technology based on Brillouin frequency shift is relatively mature, while the distributed optical fibre temperature measurement system based on Raman scattering is widely used. The main scattering in optical fibres are Rayleigh scattering, Brillouin scattering and Raman scattering, among which Raman scattering is sensitive to temperature and easy to separate from incident light. The Raman scattered light reflected back to the incident end includes Stokes light, which is insensitive to temperature, and anti-Stokes light, which is temperature-dependent, and anti-Stokes light, which is temperature-dependent, and the relationship between anti-Stokes light and temperature is as follows:

$$\frac{L_m}{L_n} = \alpha e^{-\frac{hcv}{kT}} \tag{2}$$

Equation (2) is obtained by taking the logarithm and moving the term (3).

$$T = \frac{hcv}{k[\ln\alpha - \ln(\frac{L_m}{L_n})]} \tag{3}$$

In the above equation:

Lm——the light intensity of the anti-Stokes light;

Ln——the intensity of Stokes light;

h———Bronke coefficient;

c———speed of light, m / s;

α———temperature-dependent coefficients;

v———Raman translation, m-1;

k———Baltsmann's constant, J/ K;

T———temperature, °C.

Therefore, the scattered light is filtered, the physical parameters such as intensity, frequency, phase, and polarization that affect it are extracted, and the temperature distribution on the fibre can be obtained through calculation and analysis. When the pipeline leaks, it will cause the vibration of the pipe wall and the surrounding soil, as well as the change of medium and temperature. If the temperature-sensing optical cable is laid along the pipeline, the optical fibre senses the temperature change of the pipeline leakage, and the laser of the laser source produces a reflected light sensing signal, and the corresponding separation module separates the Stokes light and the anti-Stokes light in Raman scattering, converting it into an electrical signal through the photoelectric converter, and finally transmitting it to the computer. The computer compares the collected temperature data with the threshold set by the reference fibre to determine whether the pipeline is leaking. In terms of strain sensing technology, Kenneth et al. [7]studied the influence of the initial non-circular cross-section of the pipeline under internal pressure, and used a distributed fibre optic sensor based on Brillouin optical time-domain analysis to verify the ability of Brillouin optical time-domain analysis sensors to detect local stiffness irregularities on the outer circular pipeline subjected to internal pressure.

Ziguang et al. [8]developed a fibre Bragg grating (FBG) hoop strain sensor with higher sensitivity to measure the pressure drop caused by pipeline leakage during leakage transients, and added an integrated method of backpropagation (BP) neural network and hoop strain measurement to locate the leakage point of the pipeline, and its training error can be as low as 1.01%.

The distributed optical fibre detection method can detect pipeline leakage while sensing the surrounding environmental changes along the line, which is suitable for gas, liquid and multiphase flow pipelines, and its positioning and detection accuracy is high, and it is immune to electromagnetic interference. However, due to the fact that optical fibre laying needs to be buried at a certain depth to ensure the safety of operation, the cost is high, and it is easy to be disturbed by the surrounding environment, the system signal-to-noise ratio is reduced, and the accuracy is reduced, which is the difficulty of further research on this technology.

2.2.3. Negative pressure wave method

When a leak occurs in an oil pipeline, a transient pressure drop will occur at the leakage point to form a negative pressure wave propagating to both ends of the pipeline, and the pressure wave generated when the pipeline leaks is called a negative pressure wave when the pipeline leaks is used as a reference reference. The leak point is determined based on the velocity and time difference of the negative pressure waves collected by sensors at both ends of the pipe. Pressure wave-based leak detection locates leaks by analysing the propagation characteristics of the passive pressure wave caused by the leak or the reflection characteristics of the active pressure wave at the leak port, and is characterised by higher sensitivity, lower detection time and cost, and higher positioning accuracy compared to other methods[9]. In 2003, Yinghong et al. [10] designed a negative pressure wave pipeline monitoring system based on pattern recognition. For the first time, the idea of attaching a simulation system to a monitoring system was proposed.In 2008, Chuanhu et al. [11]derived a mathematical description of the amplitude change of negative pressure wave (NPW) and its attenuation along the pipeline propagation based on the physical model of the pipeline, and proposed a method to evaluate the minimum detectable leakage flow velocity and determine the sensitive points of the pipeline. In addition, Jiajian, Yupei, and Vorathin et al. [12-14]have done a lot of research work on negative pressure wave sensors and processing methods in recent years to measure the arrival time of negative pressure waves more accurately and quickly to obtain the highest positioning accuracy. The negative pressure wave method can effectively identify the location and scale of the leak by detecting the propagation characteristics of the negative pressure wave in the pipeline, and can maintain good performance in complex environments; however, it also has some shortcomings. The method is sensitive to environmental noise, and occasionally has the problem of false alarms or false negatives, and the negative pressure wave method requires high-precision sensors and complex data processing systems in the practical application of leak detection, and the initial investment and maintenance costs are relatively high. Secondly, the accuracy of the method is closely related to factors such as pipeline material, fluid characteristics, and installation location, which urgently need to be studied and optimised.

2.2.4. Ground penetrating radar method

Ground penetrating radar (GPR) is an important geophysical method developed in recent decades to detect shallow underground (usually less than 50 m) targets[15], which is a rapid and non-destructive detection technology that uses high-frequency electromagnetic waves to determine the underground medium or structure, mainly using the characteristics of the path, electromagnetic field strength, and waveform of electromagnetic waves propagating in the medium with the electrical characteristics and geometry of the passing medium[16-18]. As an efficient non-destructive detection technology, GPR is not only suitable for the identification of metal pipelines[19], but also can accurately detect non-metallic pipelines, and has the remarkable characteristics of high resolution, trenchlessness, and non-destructiveness, which makes it show unique advantages in the field of pipeline positioning and leakage area definition[20]. In pipeline leak detection, GPR plays a key role through its unique electromagnetic wave propagation mechanism and high-precision imaging interpretation technology. By emitting high-frequency electromagnetic waves and receiving reflected signals, this technology can accurately identify abnormal areas around pipelines, thus providing a scientific basis for locating leaks. Many scholars have conducted in-depth research on the propagation characteristics of radar electromagnetic waves in the medium and their data processing methods, which not only promote the wide application of ground penetrating radar technology, but also significantly improve its accuracy and reliability in leak detection. Cheung et al.[21]used an improved common-offset GPR antenna algorithm to measure changes in electromagnetic wave velocity and wave reverberation, sensing upward and downward leakage, respectively. Sagnar et al. [22]constructed a multifunctional pipeline detection experimental field, which used a variety of frequency, polarisation mode and signal processing techniques to interpret Bscan data and extract key parameters related to pipelines, which provided practical guidance for the application of GPR in the field of pipeline detection. Andrea Cataldo et al. [23]proposed a pipeline leak detection method based on the combination of time domain reflectometry (TDR) and ground penetrating radar, which overcame the limitations of the traditional electroacoustic method to environmental noise and pipeline material sensitivity through the time domain forward simulation technology, tested the effectiveness of the method on two leaking pipe sections, and optimised the configuration of TDR sensing elements, which significantly improved the implementation efficiency and detection accuracy of the system.

The echo signal of ground penetrating radar mainly characterises the round-trip time delay of electromagnetic waves from the antenna to the target, which is difficult to directly reflect the specific morphological characteristics of the target. In the GPR detection profile, different targets may exhibit highly similar echo signal characteristics, which brings significant challenges to the interpretation of the data. In recent years, deep learning technology has made breakthroughs in the field of structured data processing such as images, prompting researchers in the field of ground penetrating radar to gradually introduce deep learning methods to realise the intelligent identification and classification of targets in echo images[24, 25]. Zhu et al. [26]used the YOLOv7 target detection network to automatically detect hyperbolic features in GPR images, and proposed a two-stage curve fitting method according to the characteristics of the detection model. In this method, the buried depth and radius of the pipeline are quantitatively inverted by using some parameters of the ground penetrating radar system and the annotation of several key points of the hyperbolic mode. Barkataki et al. [27]converted the GPR data acquired in the time domain into the frequency domain through FFT, and used ANN for feature extraction to quantitatively locate the buried depth and size of the pipeline A-scan data collected by the FPGA array GPR system. De Coster et al. [28]developed a human-computer interface that supports 3D data visualisation by integrating near-field antenna effect removal, reflection detection and segmentation algorithms, and full-waveform inversion techniques, enabling end users to visualise the 3D imaging results of underground pipelines on mobile devices, so as to more accurately locate water leaks and assess the status of the pipe network. In summary, ground penetrating radar shows significant potential in urban underground space detection, and its equipment research and development is gradually evolving in the direction of multi-source data fusion, large-scale 3D imaging and intelligent real-time analysis. At the level of data interpretation, the dynamic modelling accuracy of key parameters such as dielectric constant and wave velocity distribution of underground media[29] directly affects the accuracy of pipeline positioning and the quantitative characterisation of leakage range. In the future, with the breakthrough of multi-physics fusion detection technology, adaptive signal enhancement algorithm and deep learning-assisted interpretation method, GPR will achieve a technological leap in the optimisation of signal excitation-reception mode and rapid inversion of the velocity

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field of underground medium, providing a more forward-looking solution for the safety monitoring of urban underground pipe network.

2.3. Software-based detection methods

2.3.1. Physical model-driven approach

2.3.1.1 Flow/mass balance method

The flow/mass balance method is the amount of gas flowing out of a section of a pipeline minus the amount of gas entering that section, and when the difference exceeds a certain threshold, the pipeline is in a leaking state. The flow/mass balance test method has been widely used in pipeline leak detection due to its low cost and easy equipment installation. However, this method may lead to a decrease in detection accuracy and even false alarms or missed detections under certain operating conditions. For example, when there are multiple spurs in a piping system, the flow and mass distribution of the fluid changes; In addition, parameters such as pressure, temperature, and density inside the pipeline can fluctuate under different environmental conditions, which can affect the accuracy of the inspection results. To address these challenges and improve detection accuracy, researchers are exploring a variety of improvements. Pascal Stouffs et al. [30]use a pipeline flow model in order to compute the change in pipeline inventory during a transient flow, where the packing term is a key parameter whose value is closely related to the sound velocity in the pipeline, which often depends on some parameter that is difficult to define accurately. The results of the study show that this has a significant impact on the setting of leak detection thresholds. Martins et al. [31]combined the acoustic principle with the flow/mass balance method, and the acoustic detection system alarmed and located the pipeline leakage, and used the flow/mass balance method to quantify the leakage, realising the complementarity of the acoustic and flow mass balance methods, and achieving better detection results. Zahra Fereidooni et al. [32]combined the mass balance approach with machine learning to optimise the leak detection model through a data-driven approach, which is applicable to pipeline systems under complex working conditions.

2.3.1.2 Transient model method

The transient model method uses the equations of state of fluids such as mass conservation, momentum conservation and energy conservation to establish a mathematical model of fluid flow in the pipeline, compares the calculated value with the measured value, and uses the difference to determine whether there is a leak in the pipeline. This method is usually based on the equations of conservation of mass, momentum and energy, combined with boundary conditions to solve the transient behaviour of fluids, which can accurately capture the propagation characteristics of pressure waves caused by leakage. Its advantages lie in high sensitivity and strong interpretability, especially in long-distance pipelines, demonstrating good leak location ability, and it is widely used in pipeline leak detection. Cai Xiuquan et al. [33]proposed a novel pipeline leak detection model based on real-time transient mechanism model fusion as well as data-driven inference. However, the transient model method also has some limitations, such as the high accuracy required for pipeline parameters (such as pipe diameter, wall thickness, and fluid properties), and the difficulty of modelling in pipe networks with multiple branches or complex topologies. Additionally, ambient noise and fluctuations in operating conditions can interfere with inspection results, leading to false alarms or missed detections. In recent years, researchers have been working to improve the robustness and applicability of the transient model method. Xiuquan et al. [34]proposed a new leak detection model based on real-time transient model (RTTM) and transfer learning (TL) (transfer learning multiple regression real-time transient model, t-RTTM) to overcome model generalisation issues. Shaheen et al. [35]investigated model-based sensor fault diagnosis techniques in natural gas pipelines under transient flow. In this paper, a fusion architecture based on distributed data fusion is used to implement the Sensor Fault Detection, Isolation and Regulation (SFDIA) mechanism.

2.3.2. Mathematical model-driven approach

2.3.2.1 Mathematical model-driven method

The mathematical model-driven method is guided by the system identification method, the filter method, and the pipeline flow balance method, etc., and the mathematical model is established based on measurement or real-time monitoring data (such as pressure, flow, vibration signal, etc.), and leakage detection is realised through data pattern recognition. As a typical method driven by mathematical models, support vector machine is a leakage anomaly detection method based on supervised learning to project low-dimensional data into high-dimensional space. Firstly, real-time data collection is carried out on the sensors arranged around the pipeline through a signal collection system, and noise reduction and feature extraction of the received data are carried out by wavelet packet decomposition or Hilbert transform[36, 37]. The SVM algorithm is used to identify the extracted feature vectors to determine whether leakage occurs. The support vector machine method has strong generalisation ability and is very suitable for processing nonlinear data, and in recent years, researchers have achieved good results in the application of pipeline leak detection. Qu et al. [38]used SVM to classify normal and abnormal vibrations caused by pipeline leakage based on fibre optic sensors. Tian et al. [39]used a support vector machine for multi-sensor data fusion to detect the corrosion degree of a submersible oil pipeline, and used these key attribute parameters as the input vector of the support vector machine. Li et al. [40]proposed a leak detection method based on the Moving Window Least Squares Support Vector Machine (MWLS-SVM) algorithm, which changed the nonlinear constraint in the SVM to a linear constraint, and used the sum of the squared error as the empirical loss function of the training set to improve the training speed. Jinhai et al. [41]proposed an online small leak detection method based on chaotic characteristics and least squares support vector machine (LS-SVM) to analyse chaotic characteristics and distinguish negative pressure waves (NPW) caused by small leaks, with a final recognition accuracy of 97.38% and a positioning accuracy of 99.28%. However, due to the complex calculation, verification set requirements and non-continuous monitoring of the SVM pipeline leakage identification method, it has not been widely used in the actual implementation and still needs to be further improved.

2.3.2.2 Artificial neural network method

Artificial Neural Networks (ANN) is a computational model inspired by the structure of biological neurons, which is composed of multi-level neuronal nodes with self-learning, dynamic adaptation and nonlinear mapping capabilities. As one of the core methods in the field of pattern recognition, ANN has gradually developed into a research hotspot in pipeline leak detection. In this method, the collected pipeline data needs to be used as the input of the network after feature extraction, and the final output is the leakage prediction result after the network is calculated layer by layer. BP (Back-Propagation) network is one of the classical artificial neural networks, and the BP algorithm realises network training through the two-stage mechanism of feedforward calculation and error backpropagation: the forward propagation stage completes the layer-by-layer transmission of the input signal and the result prediction, and the backpropagation stage is based on the gradient descent principle, and dynamically optimises the network parameters by calculating the partial derivative of the output error to the weight, which makes the BP neural network have a strong inclusiveness. Junhua et al. [42]used a nonlinear time series based on BP neural network and a long-tube leak detection model to establish an innovative model, and experiments verified the effectiveness of the proposed method. Hanxue et al. [43]performed wavelet decomposition through the acoustic emission signal of the internal leakage valve, and input the decomposed sample feature sets into the error backpropagation (BP) neural network quantitative model, and the results showed that the wavelet-BP neural network model predicted the leakage rate with good accuracy and an error of less than 10%. Although traditional shallow network learning has extremely high nonlinear representation ability, it is easy to fall into local optimum, and the training results may be unstable. Secondly, when processing large-scale data, it is necessary to increase the number of layers of the network, but too many layers of neural networks will lead to low network efficiency, so in recent years, many scholars have begun to use convolutional neural networks (CNNs) to identify pipeline leaks. Pengqian et al. [44] proposed a convolutional neural network-based transfer learning (CNN-TL) method for acoustic emission signals under different working environments, transport media, and fluid pressures, and the feature-based CNN-TL method obtained an average accuracy of 91.29% and an average computation time of 16.78 s. Jungyu et al. [45]proposed a Convolutional Neural Network (CNN) model to detect and classify water leaks based on vibration data collected using leak detection sensors installed in water pipes, and the proposed CNN model achieved a F1 score of 94.82% and a Matthew correlation coefficient of 94.47%.

3. Conclusion

The development of leak detection technology for oil and gas pipelines is the core demand to ensure the safety of energy transportation and reduce environmental risks and economic losses. At present, due to the significant differences in medium characteristics (such as viscosity and compressibility) and operating conditions (pressure and flow rate) between oil pipelines and gas pipelines, there are obvious differences in the applicability of detection technology: the acoustic emission method is more suitable for monitoring the vibration of the pipe wall caused by gas pipeline leakage due to its high sensitivity to high-frequency stress waves, but it is easily disturbed by fluid turbulence noise in liquid pipelines; Based on the propagation characteristics of pressure waves, the negative pressure wave method can achieve rapid leakage location in liquid pipelines (such as crude oil transportation), but it is sensitive to the signal attenuation caused by the compressibility of the medium in gas pipelines. Fibre optic sensing technology uses distributed acoustic or temperature sensing (DAS/DTS) to show unique advantages in long-distance, high-electromagnetic interference environments (such as natural gas pipelines), but there are bottlenecks such as high deployment costs and complex data analysis.

In the future, breakthroughs in oil and gas pipeline leak detection technology can be carried out from the following three aspects: (1) Detection accuracy and algorithm optimisation: In order to solve the problem of signal noise suppression of existing methods, it is necessary to develop adaptive filtering algorithms (such as deep learning-driven time-frequency analysis) and dynamic threshold calibration strategies to improve the identification ability of weak leakage signals and reduce the false positive rate under complex working conditions. (2) In-depth exploration of new detection technology: the development of new detection methods is an important direction to cope with complex working conditions and improve detection capabilities, as a non-contact and non-destructive detection method, ground penetrating radar shows significant application potential, and its non-contact detection characteristics can effectively solve the dependence of traditional methods on embedded sensors, combined with multi-frequency antenna arrays and three-dimensional imaging algorithms, it can realise the accurate identification of underground pipeline corrosion and small leakage, especially in areas with strong soil heterogeneity and large buried depth. (3) Multi-modal fusion and intelligent decision-making system construction: The traditional physical methods (such as negative pressure wave method, acoustic emission method) and advanced sensing technology (such as optical fibre sensing, GPR) are combined to build a leak detection system with multi-source data fusion. At the same time, artificial intelligence technologies (such as deep learning and neural networks) are introduced to realise the intelligent identification and prediction of leakage signals, improve the adaptive ability and real-time performance of the system, realise the leap from "single signal discrimination" to "multi-dimensional collaborative reasoning", and enhance the adaptability and real-time response ability of the system to complex leakage scenarios. To sum up, oil and gas pipeline leak detection technology is moving towards a new stage of high precision, intelligence, and multi-technology collaboration, and the deep combination of ground penetrating radar and artificial intelligence may become the key path to solve the problem of hidden leakage, providing full life cycle guarantee for pipeline safety operation and maintenance.

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