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Leakage monitoring research and design for natural gas pipelines based on dynamic pressure waves

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ABSTRACT

Many types of gases, such as natural gas, hydrogen, and so on, are transported via pipelines using a chemical process, though leakages in these pipelines create waste and pose hazards and risks to industries, the environment and people. To monitor gas pipelines, a new leak detection and location method based on the amplitude attenuation model of dynamic pressure waves was designed and researched by experiments, compared with traditional method based on the propagation velocity and time differences as determined by the waveforms of the upstream and downstream signals. Both methods are achieved based on the propagation law of the dynamic pressure waves in the fluid flow. First, the fundamentals of the newly proposed method are clarified by considering the influence of gas flow on the waves. The experiments are then conducted in gas pipelines with 42 mm internal diameters. Finally, the results of the experiments are discussed and analyzed. The results indicate that all leakages can be detected by both methods but that the largest location error of the traditional method is −0.780%, whereas the largest location errors with respect to the new method are 0.054% with the experimental attenuation coefficients and 2.055% with the theoretical attenuation coefficients. It is further determined that the influence of the gas flow effects cannot be ignored by either method. Accordingly, the conclusions drawn suggest that the proposed methods can be applied to monitor gas pipelines.

1. Introduction

With the rapid development of the pipeline industry, chemical gases, such as natural gas, hydrogen, etc., are being transported via pipelines, and thus, leakages in these pipelines occur occasionally that pose hazards and risks to the environment and the people. Taking into account that natural gas availability is not inexhaustible, its cost is extremely high. Therefore, to monitor pipelines, many leak detection and location methods [1] have been developed. For example, Alkhaledi [2] used the fault tree analysis to identify the source of leaking gas, and the results serve as a useful reference if any similar gas leak incidents occur elsewhere. Elaoud [3] presented a technique using transient negative pressure waves initiated by the sudden closure of a downstream shut-off valve. The presence of a leak in a pipe partially reflects these pressure waves and allows for the location of the leak. Scott [4] employed a method based on a real-time transient model that can detect small leaks, albeit it has the disadvantage of being very expensive. Moreover, as the models employed are complex, they require a trained user. Doothy [5] proposed a real-time pipeline leak detection method that incorporates volume balancing to detect and locate small leaks. However, if small leaks occur, it takes considerable time to detect them, and furthermore, Doothy's system is prone to false alarms during transient states unless thresholds are adapted. Zhang [6] proposed a novel hybrid technique for leak detection and location based on a real-time transient modeling method combined with a negative pressure wave method. The results of the experiments indicated that Zhang's hybrid technique successfully detects and locates gas pipeline leaks.

To describe the methods, the evaluation indexes are clarified as follows. (1) Sensitivity refers to the smallest leakage rate that can be detected. (2) Location accuracy equals the absolute differential value divided by the pipeline length, which equals the located leakage point minus the actual leakage point. (3) False alarms are those alerts that occur when there is no leakage. (4) Missing alarms

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Table 1
Evaluation indexes of leak detection and location methods.

The leak detection method	Sensitivity	Location accuracy	False alarm rate	Missing alarm rate	Detection time	Cost	Total score
Fault tree analysis	1	3	4	2	2	3	15
Negative pressure method	3	4	3	3	3	3	19
Transient model method	4	4	3	4	3	2	20
Mass/volume balance method	4	4	3	4	3	3	21
Hybrid technique	4	4	4	3	4	3	22
Acoustic method	5	5	3	5	5	3	26
Method based on dynamic pressure wave	5	5	4	5	5	3	27

refer to the failure of alarms to alert when a leakage does occur. (5) Detection time is the time the method takes to detect and locate the leakage point. (6) Cost is the money spent for facilities and maintenance charges. For each index, a score of 0 is awarded to the worst method, and a score of 5 is awarded to the best method, i.e., the larger the score, the better the method.

According to the evaluation indexes, the usual methods identified above including the acoustic method are presented in Table 1.

From among the presented methods, the acoustic method is found to be more promising. Lee [7] established an oil and gas pipeline failure prediction system using long range ultrasonic transducers (LRUT) and a Euclidean-support vector machine (E-SVM) classification approach. The results indicate that the E-SVM approach is ideally suited for classifying data from pipelines. Yan [8] proposed the gas leak detection technology of the spacecraft in orbit based on an acoustic sensor array. The detection distance and direction of the array are verified by the experiments. The method based on the dynamic pressure wave is one type of acoustic method that uses dynamic pressure sensors, where the acoustic waves measured by the dynamic pressure sensors have a wide frequency range of which the low frequency component can spread over a long distance. Thus, due to its advantages, it has been researched increasingly more frequently.

The key aspect of a leak detection system based on an acoustic method is the ability to extract the effective characteristics from the measured signals. Currently, the main filtering methods are based on time domain and frequency domain analyses, though the blind source separation method has also been studied. Yan [9] proposed an improved algorithm of median filtering based on extremum detection, and the results indicate that the proposed algorithm is superior to traditional ones with respect to noise removal and edge retention. Xu [10] proposed a denoising algorithm via Wiener filtering in the shearlet domain and found that the combination removes noises more effectively than other methods. Hu [11] proposed a new signal extracting method that combines a wavelet de-noising technique and the short-time Fourier transform method. The feasibility and accuracy of Hu's proposed method are verified by numerical simulation and practical experiments. Mostafapour [12] proposed a combination method of wavelet transform and a cross-time frequency spectrum to process signals. The resulting locating error indicates high precision of the proposed algorithm. Lu [13] applied fast independent component analysis (FastICA) to measure non-Gaussian independent components in blasting vibration signals as the approximation signals were separated, and the results indicate that the approximation signal close to the source signal can be precisely separated using the FastICA approach. Ni [14] proposed the combination of a wavelet packet and information entropy and the combination of empirical mode decomposition and information entropy. Under the condition of high noises, the proposed method is applied better. Sun [15] proposed a leak aperture recognition and location method based on the root mean square entropy of a local mean deposition and Wigner-Ville time-frequency analysis. The results indicate that the method can effectively identify different leak apertures and that the leak location accuracy is better than that of other methods. Liu [16] conducted the time-frequency analysis of the acoustic leakage signal measured by dynamic pressure sensors based on the Hilbert-Huang transform, and the results found that effective characteristics of dynamic pressure waves can be extracted.

After the leakage characteristics are extracted, they are applied to locate the leak, a task for which the time differences and velocities are important. Ye [17] developed an analytical model to predict the cross correlation function of leak signals in plastic water pipes, which can be used to calculate the time difference and improve leak location accuracy. Brennan [18] presented a new interpretation of the process of cross-correlation for time delay estimation and found that time delay estimations and their variances calculated using time and frequency domain methods are almost identical. Meng [19] established a formula using dynamic pressure waves to determine the locations of gas pipeline leaks. Meng's formula can be modified based on the influences of temperature and pressure. Liu [20] established a generation model of dynamic pressure waves to extract precise time differences and improve leak location accuracy.

Most of the extant studies have been conducted to improve the accuracy of velocity and time differences according to which the method is called the traditional leak location method. A dynamic pressure wave is generated, transmitted through fluid and acquired by sensors that are installed at both ends of the pipeline. It is then processed to extract specific characteristics to determine whether a leak has occurred and to calculate the time differences to locate the leak. Once leakage occurs, the computer sends out alarms and locates the leakage if accurate velocity and synchronized timing measurements can be achieved. However, it is difficult to confirm velocity due to different pressures and temperatures. Thus, velocity calculation requires more pressure and temperature sensors, especially for gas pipelines. Furthermore, if the method is applied to field or long distance pipelines, the time difference calculation requires the data be well synchronized, as presented in Fig. 1. Fig. 1 indicates that the variation in reporting times from one data acquisition device (DAD) to the computer can be quite large. Because the time-stamping is usually not performed at the level of the DAD but rather at the centralized computer level, this procedure yields uncertainty regarding the age of data that are collected in computer. This issue is also discussed by Magnis and Petit [21] as they considered the importance of data synchronization with respect to loss detection. They noted that the data should be carefully time-stamped with accurate and synchronized clocks, e.g., GPS or Rugby clocks, though they are not readily available and are subject to jamming in many areas. Unfortunately, these recommendations are far from optimal technical status observed in currently installed systems. Petit [22] analyzed problems induced by the imprecise dating of measurements, especially the mis-synchronization in oil and gas production. The results reveal that when signals with significant time variations are monitored, the impact of the dating of measurements can be troublesome or even worse than measurement noises. Accordingly, the above analyses suggest that the time difference calculation is a problem in the application of the acoustic method. Based on this perspective, the method without velocity and time differences can be considered to be more concise and easier. Thus, Liu [23] proposed a method based on amplitude, for which