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Research Article

Application of EMD Technology in Leakage Acoustic Characteristic Extraction of Gas-Liquid, Two-Phase Flow Pipelines

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Nowadays, the exploitation and transportation of marine oil and gas are mainly achieved using multiphase flow pipelines. Leakage detection of multiphase flow pipelines has always been the most difficult problem regarding the pipeline safety. Compared to other methods, acoustic detection technology has many advantages and high adaptability. However, multiphase flow pipelines are associated with many noise sources that affect the extraction and recognition of leakage signals. In this study, the mechanism of leakage acoustic source generation in gas-liquid, two-phase pipelines is analyzed. First, an acoustic leakage detection experiment in the multiphase pipelines is conducted. The acoustic signals are divided into two classes in accordance with whether leakage occurs or not. The original signals are processed and analyzed based on empirical mode decomposition (EMD) processing technology. Based on the use of signal processing, this study shows that EMD technology can accurately identify the leakage signal in the gas-liquid, two-phase pipeline. Upon increases in the leakage aperture sizes, the entropy of the EMD information of the acoustic signals gradually increases. Finally, the method of the normalized energies characteristic value of each IMF component is also applied in leakage signal processing. When the liquid flow is maintained constant, the energy values of the IMF components change in a nonlinear manner when the gas flow rate increases. This verifies the feasibility of use of the acoustic wave sensing technology for leak detection in multiphase flow pipelines, which has important theoretical significance for promoting the development of safe and efficient operation in two-phase flow pipelines.

1. Introduction

The leak detection method's multiphase flow pipelines are generally divided into two classes through literature researches [1]. One model is based on real-time monitoring, and the other model is based on external sensor.

The model based on real-time monitoring is mainly achieved for leakage detection inside the pipes. This kind of method is used to estimate the flow state. That needs to es\ish the mathematical model that can accurately describe the flow process in the pipe. At present, there are transient models and pressure models. Due to the irregularity and unpredictability of multiphase flow, this kind of model is inefficient in leakage detection. The model based on external sensor is mainly achieved for leakage detection through measuring the parameters which included temperature, mass, pressure in the pipe. The sensors are laid along the pipelines. This kind of model mainly includes acoustic leakage detection, gas monitoring, and optical fiber detection and so on.

By comparing and analyzing various leakage detection methods through technical indexes such as sensitivity, positioning accuracy, false alarm rate, detection time, and the applicability [2], it is found that the acoustic detection has more advantages than others in multiphase flow pipelines.

Since 1991, many scholars have carried on studies in the leakage detection technology which based on acoustic leakage detection [3–5]. At present, these researches are successfully used in the single-phase pipelines. However, there is always two-phase fluid or multiphase fluid in the transport pipelines which is far more complicated than single-phase pipelines. Accurately identifying and extracting the leakage acoustic signal in the flow noise is the key technology of acoustic leakage detection in multiphase pipelines. In this study, the application of acoustic leakage technology in multiphase flow pipeline is studied. We have used EMD correlation technique to analyze the signals of leakage acoustic.

Researches on leakage acoustic signals are as follows. In 2004, Gao et al. [6] analyzed the interrelatedness characters of two kinds of acoustic signals by model of intercorrelation function model. In 2007, Brennan et al. [7] used the time-delay estimation to solve the signal time and improved the leakage location formula. In 2009, Aimé et al. [8] presented the spectrum analysis of acquisition acoustic signals based on the filtering diagonalization algorithm. In 2012, Ghazali et al. [9] compared different instantaneous frequencies of acoustic signals to distinguish and locate leakage. In 2014, Jin et al. [10] used the least squares support vector machine (LS-SVM) to analyze leakage scale. The same year, Li et al. [11] used the time-dependent spectrum (CTFS) method to deal with the leakage acoustic signals. In 2018, Glowacz describes an early fault diagnostic technique based on acoustic signals used for metallurgical equipment.

In order to analyze the characteristics of the acoustic signals when the pipeline leakage occurs, empirical mode decomposition (EMD) is used in this study. EMD technology [12–14] submitted by Huang in 1998. This method is suitable for analyzing nonlinear and nonstationary signals. The key EMD technology is empirical pattern decomposition. It decomposes complex signals into finite intrinsic mode function (IMF). The IMF components contain the characteristics of signals at different timescales of the original signal. The foundation of EMD technology is separate from the Fourier transform technology, which processes no stationary signals always resulting in false signals and redundant signal components. EMD technology has good adaptability to the signal itself. The significance is the instantaneous frequency of signal given by the characteristics of the time point. So, the frequency of the signal is based on the local characteristics and instantaneous Eigen values of the waveform. It is not necessary to form multiple oscillating periodic signal waveforms to give a frequency.

Because of the advantages of EMD technology, it has been widely used in mechanical fault diagnosis, characteristic extraction, geophysical detection, medical analysis, and so on. The researches of EMD technology used in acoustic signal filtering and noise reducing are followed. In 2003, Flandrin et al. [13, 15] presented the idea of EMD based filters bank that adaptive combination of high-pass, low-pass, band-pass, or band-stop filters by selecting the corresponding order of the IMF compo. In 2004, Wu and Huang [16] proved that the method has the characteristics of wavelet-like binary filter through a lot of experiments. In 2007, Boudraa and Cexus [17] realized the signal noise reduction by filtering and reconstructing each IMF with different values. In 2009, Wu and Huang [18] presented a new ensemble empirical mode decomposition method. In 2012, Li and He [19] developed a methodology for rotational machine health monitoring and fault detection using EMD-based AE characteristic quantification. In 2014, Amarnath and Krishna [20] describe the implementation of EMD technology for monitoring simulated faults using vibration and acoustic signals in a two-stage helical gearbox. In 2016, Sun et al. [21] proposed a small leakage characteristic extraction and recognition method based on local mean decomposition (LMD) envelope spectrum entropy and support vector machine (SVM). In 2016, Lu et al. [22] researched on a small-noise reduction method based on EMD that can be applied in pipeline leakage detection. At the same year, Guo et al. [23] carried out a study on adaptive noise cancellation based on EMD in water-supply pipeline leak detection. In 2018, Glowacz proposes an approach based on acoustic signals for detecting faults.

At present, there are many researches about EMD algorithm, such as increasing EMD speed, upgrading decomposition, expanding single-variables to double-variables EMD, and extending one-dimensional EMD to two-dimensional EMD. In this study, the leakage acoustic of signals in different flow patterns, different leakage positions, and five sizes of leakage apertures are collected.

Based on verified experimental data, this study shows that the leakage signal in the gas-liquid, two-phase pipeline is successfully recognized by the EMD technology and the information entropy of EMD. Further research also found the EMD information entropy of the leakage signal can well reflect the size of the leakage aperture, so as to provide a basis for judging the size of leakage. Through the normalized energy characteristics of each IMF energy component method, it is found that different flow patterns have different laws. It is necessary to study the propagation characteristics of acoustic leakage of signals in different flow patterns in subsequent research.

2. Theoretical Research

The composition of background noise in multiphase pipelines is much more complex than single-phase pipelines. The acoustic mechanisms of the background noise in the multiphase pipelines are very complicated. At present, there are few studies on the leakage acoustic source of multiphase flow pipelines. The study on leakage acoustic mechanism of pipelines mainly focuses on single-phase pipelines. The leakage occurs in multiphase flow pipelines and causes the complex interaction between gas and tube walls, liquid and tube walls, gas and liquid friction, phase separation, and the irregular motions of gas and liquid itself. All these functions can produce noise sources. The vibration and background noise caused by pressure pulsation also changes greatly when the flow field changes.

2.1. Mathematical Model. The leakage occurs in the pipeline and triggers a pressure jump of fluid at the leakage point on the tube at the same time. That also causes the vibration of pipeline which includes transverse, longitudinal, and ring vibrations of pipelines. These three kinds of vibration caused the production of horizontal, longitudinal, and surface waves. The model of tube wall vibration can be described by the theory of thin wall, infinite length, and ring. The tube is considered as free support. In the theory of thin wall of leakage occurrence, the tube wall is assumed to be an elastomer to describe the vibration of the pipe. The root of the cubic equation derived for the ideal vacuum pipe represents the vibration frequency in three directions [24]:

$$\Delta^3 + k_2\Delta^2 + k_1\Delta + k_0 = 0. \quad (1)$$

In the formula, Δ is vibration frequency, Hz, and k_0, k_1, k_2 are constant, which are obtained as

$$\begin{aligned} k_0 &= \frac{1}{2}\left(1-\sigma^2\right)(1+\sigma)l^4 + \frac{1}{2}(1-\sigma)b\Big[\left(l^2+n^2\right)^4 - 8l^2n^4 \\ &\quad - 2\left(4-\sigma^2\right)l^4n^2 - 2n^6 + 4\left(l-\sigma^2\right)l^4 + 4l^2n^2 + n^2\Big], \\ k_1 &= \frac{1}{2}\left(1-\sigma^2\right)\left(l^2+n^2\right)^2 + \frac{1}{2}\left(3-\sigma-2\sigma^2\right)l^2 + \frac{1}{2}(1-\sigma)n^2 \\ &\quad + b\Big[\frac{1}{2}(3-\sigma)\left(l^2+n^2\right)^3 - 2(l-\sigma)l^4 - \left(2-\sigma^2\right)l^2n^2 \\ &\quad - \frac{1}{2}(3+\sigma)n^4 + 2(l-\sigma)l^2 + n^2\Big], \\ k_2 &= 1 + \frac{1}{2}(3-\sigma)\left(l^2+n^2\right) + b\Big[\left(l^2+n^2\right)^2 + 2(1-\sigma)l^2 + n^2\Big]. \end{aligned} \quad (2)$$

Among them, b is a constant, usually $b = h^2/12d^2$; d is the average diameter of pipe, cm; l is the pipe length, m; n is the number of vibration waves for horizontal vibration of pipes; h is the thickness of pipe walls, cm; and σ is the Poisonby. The above models are significant in the study of mechanism of leakage acoustic source generation in gas-liquid, two-phase pipelines.

In the aerodynamic mechanics, the acoustic signals are mainly divided into three classes which are monopole, dipole, and quadrupole. In terms of the generation mechanism, the source is mainly divided into two parts. One is turbulent noise, produced in fluid by the vortex and its interaction, shock wave, and its interaction with the vortex, small scale turbulence, and other motion. This noise of multiphase flow pipelines has nonlinear characteristic. Another is the noise produced by the fluid flows on the moving or stationary boundary. That includes displacement noise, pulsation noise, noise caused by complex structure, and so on.

In the leakage process, the turbulent pulsation of quadrupole sound source is caused by the gas jet out of the leakage aperture. The dipole sound source is formed by the gas-solid coupling between compressible gas medium and the pipe wall, valve and leak aperture wall. The monopole source is formed by the fluid displacement distribution which caused by the fracture of the solid wall. In this study, the quadrupole is used as the main sound source of pipeline leakage, because the vortex is the most important quadrupole source.

The sound power of the quadrupole is proportional to the eighth degree of fluid velocity. The law of the eighth power of speed which is known as Lighthill equation is

$$W = \frac{KD^2\rho U^8}{c_0^5}, \quad (3)$$

where W is sound power, w; K is Lighthill constant, usually taken $K = 1 \times 10^{-5}$; D is leakage pore size, ρ is fluid density, kg/m^3; U is fluid velocity, m/s; and c_0 is sound velocity in local media, m/s;

The relationship between the total sound power of the quadrupole source and the sound pressure can be expressed as

$$W = \frac{1}{2}\frac{p^2}{\rho c_0^2}, \quad (4)$$

where p is sound pressure, Pa. Simplifying the above two formulas (3) and (4),

$$p = \sqrt{2Kc_0}\,\frac{D\rho U^4}{c_0^2}. \quad (5)$$

The surface acoustic pressure of the quadrupole source can be expressed as

$$p_{\max} = k\rho U^2 M^2 D, \quad (6)$$

where M is Mach number and k is constant, usually taken $k = \sqrt{2Kc_0} = 0.0825$.

We can know from formula (6), leak apertures size, mixture fluid density, and Mach number of gas-liquid mixture are all important factors that affect the intensity of the tetra pole sound source and the leakage sound source of pipeline. The relationship between Mach number and voidage of gas-liquid mixture affects the sound pressure of leakage source.

2.2. Experiment

2.2.1. Experimental Basis. This study relies on the discipline innovation platform of China University of Petroleum (East China) to construct the gas-liquid, two-phase flow experimental installation and the acoustic leakage detection experimental installation of multiphase flow pipelines. These experimental facilities are equipped with advanced acoustic sensor and data acquisition system, which can simulate various leakage and flow conditions.

Many researches of acoustic leakage detection technology have been done in the single-phase pipelines. Our research group also has done a lot of studies in the mechanism of leakage acoustic source generation in gas pipeline since 2012 [25–31].

In this study, we have conducted an acoustic leakage detection experiment in gas-liquid, two-phase pipelines. Then various methods are used to process the experimental data. The results show that the leakage signals are accurately identified. The influence factors of the acoustic leakage of signals are discussed.

The principle of leakage detection of multiphase flow pipeline based on acoustic method is shown in Figure 1 [9, 32]; leakage detection of multiphase flow pipeline based on acoustic method is achieved using the independent pressure and acoustic sensor network along pipeline.

The fluid jets out of the pipeline through the leakage aperture and produces the leakage acoustic source because of the inside and outside differential pressure of the pipelines. The leakage acoustic is radiating energy and produces the acoustic signals. Acoustic leakage detection is based on the leakage acoustics of signals that generated when leakage occurs. The leakage acoustic of signal travels from the leakage position to pipeline upstream and downstream. Acoustic sensors along the pipelines collect the acoustic signals. Leakage rate is estimated by the amplitude of acoustic wave, and it increases with the increase of amplitude of acoustic signals. Parallel probes are used to measure the liquid level height of stratified and wave flows in the pipeline and the gas-liquid length and frequency of slug flow.

2.2.2. Experimental Installation. We have designed the experimental facilities for gas-liquid, two-phase pipelines in accordance with the principle of acoustic leakage detection technology. The mediums in experimental pipelines are air and water under the standard conditions. The experimental objective is to verify whether acoustic leakage detection technology is used well in the gas-liquid, two-phase pipelines. It is necessary to study the mechanism of leakage acoustic source generation and spectral characteristics of acoustic signal in the gas-liquid, two-phase pipelines. The diameter of the pipe is 80 mm, and the leakage apertures are 3 mm, 4 mm, 5 mm, and 6 mm. The position of the acoustic sensor and the leakage orifice is as shown in Figure 2.

The experimental installation mainly includes air compressor, fluid pump, gas-liquid mixer, pressure maintaining valve, pressure sensor, flowmeter, dynamic pressure sensor, water pot, gas tank, and so on. Acoustic signal acquisition and processing systems mainly include the acoustic sensors and the high-speed real-time data acquisition system. The acoustic sensors are installed at the beginning and the end of the pipeline. The high-speed real-time data acquisition system is implemented based on the LabVIEW software.

The data sampling rate of conventional signals is only 100 Hz. The leakage process is completed instantaneously. In order to better capture the leakage signal, the data sampling rate of leakage acoustic signal is 3 kHz in the experiment. According to Nyquist sampling theorem, the original signal frequency band is 0–1500 Hz. The acoustic signal is collected in just 30 seconds each time. The acoustic sensor collects signals from ten seconds before to twenty seconds after the leakage occurs.

In the experiment, the gas and liquid flow rates are, respectively, controlled by the ball valve and flowmeter in pipe head. Gas and liquid flow into the air and liquid mixer. The mixture fluid flow developed in the pipelines and then entered the transparent pipe section and the test section. In order to ensure that pressure is stable, the system also has a 2 m^3 buffer tank. Several MPM480 pressure sensors are installed along the pipeline to test the pressure characteristics of the two-phase flow. Leakage simulation part of the experimental facilities mainly includes acoustic sensors, leakage orifice simulation system, data acquisition, and processing system. Acoustic sensors are the core components for collecting experimental data in the experiment. In this study, PCB106B dynamic pressure sensors are used which produced by the United States PCB to collect the acoustic signals. The measurement range of sensor is −57.2 kPa to 57.2 kPa and the sensitivity is 43.5 mv/kPa. The experimental installations are shown in Figures 3 and 4, in which the simulated leak orifice device is set on the observation tube segment. The leakage simulation is realized by controlling the opening and closing of the ball valve.

2.2.3. Data Acquisition. This study used the Mandhane flow pattern to select the range of gas-liquid flow rates for different flow patterns in horizontal pipelines. The gas and liquid flow rate are, respectively, controlled by the ball valve and flowmeter in pipe head. Then gas and liquid flow into the air and liquid mixer. A different gas-liquid, two-phase flow pattern simulated through observing the flow of transparent pipes after mixture fluid flow developed. In the actual pipeline, transportation process was mainly three-flow pattern, such as stratified, wave, and slug flows. So, the study of this experiment focuses on that three-flow pattern. We have selected liquid flow rate and gas flow rate as shown in Figure 5.

The experimental conditions include three-flow pattern. The leakage locations are at the top and bottom of the wall of the pipeline. The leakage apertures are 3 mm, 4 mm, 5 mm, and 6 mm. The experiment in each group was repeated three times. A total of 1728 sets of sample data were collected and processed in 576 sets conditions. The flow pattern of gas-liquid, two-phase flow in horizontal pipeline is shown in Figure 6.

3. Data Processing

Acoustic characteristics are the physical quantities of the leakage acoustic signals calculated by using some algorithms. Acoustic characteristics of signal change significantly according to whether leakage occurs or not. Therefore, the extraction and recognition of the effective characteristic of the leakage signal are the cure of the leak acoustic detection study. The eigenvalues of acoustic signals without leakage are used as thresholds value. The acoustic characteristic value obtained in the pipeline leakage process is compared with this threshold value so as to recognize the leakage.

Many traditional methods of signal processing are used in the early study, such as the signal mean, average amplitude, signal variance, and mean square value. But under three-flow pattern, the change of acoustic characteristics of leakage signal is not obvious by traditional methods. Through the research, it is found that the EMD can

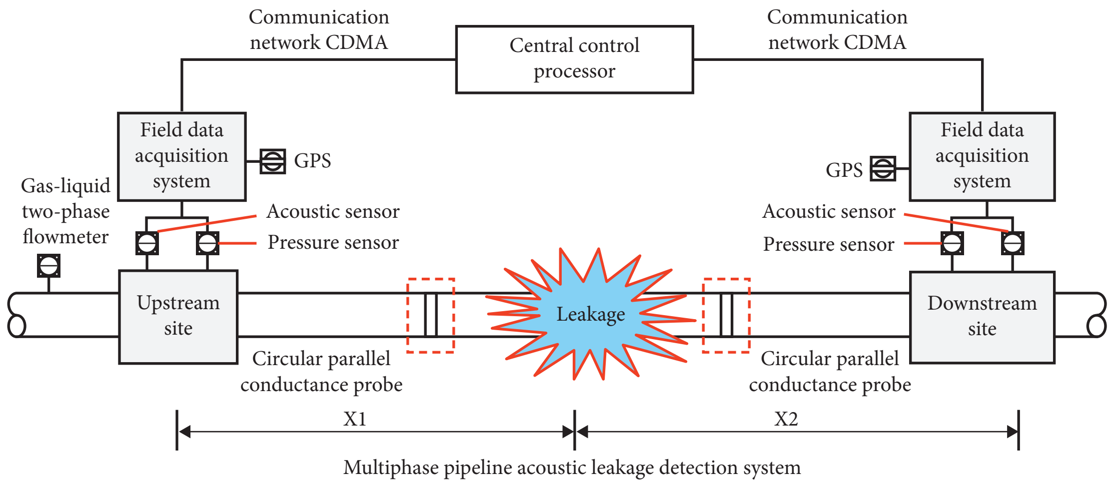


Figure 1: Acoustic leakage detection principle.

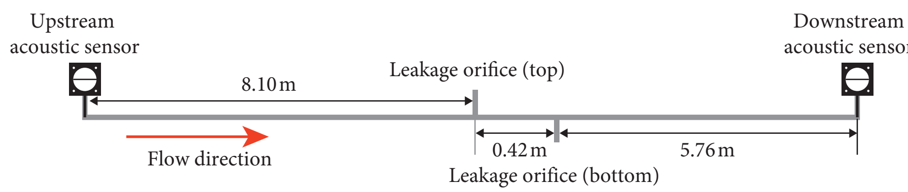


Figure 2: Acoustic sensor to leak orifice location.

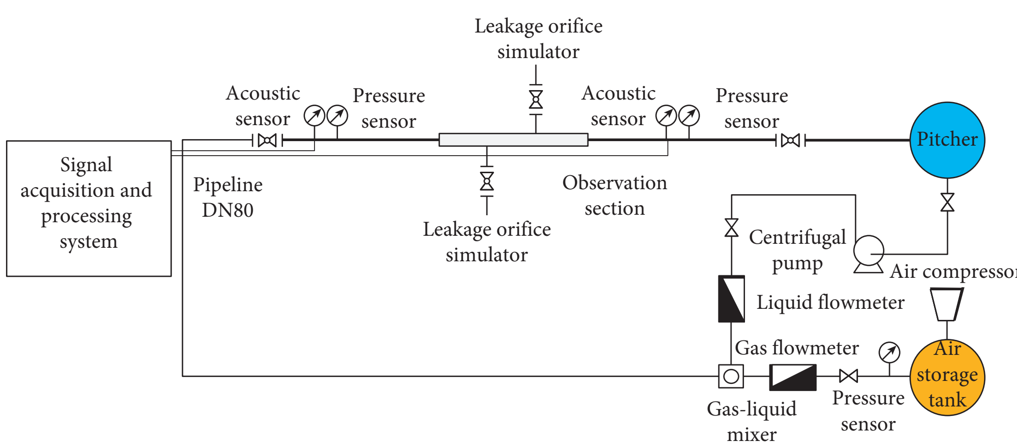


Figure 3: Flow chart of the acoustic leakage experiment.

Figure 4: Experimental facilities and equipment.

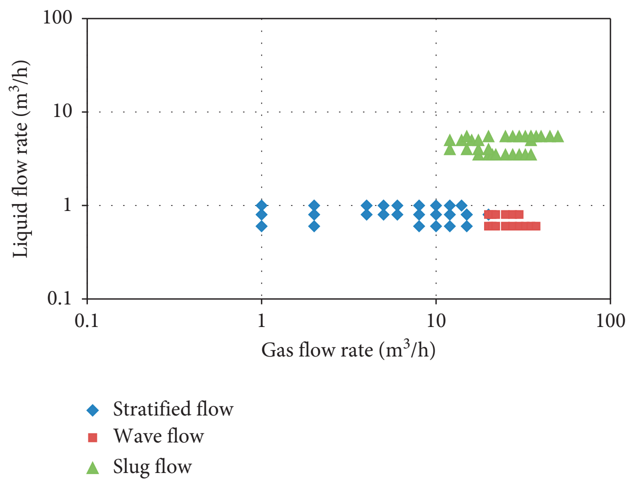


FIGURE 5: Selection of experimental data for gas-liquid, two-phase flow in horizontal pipeline (m/s).

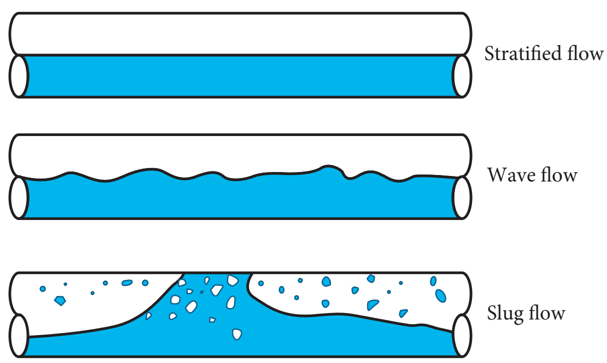


FIGURE 6: Flow pattern of gas-liquid, two-phase flow in horizontal pipeline.

effectively analyze the characteristics of the acoustic leakage of signals.

3.1. EMD Technology. The intrinsic mode function (IMF) obtained through EMD has two obvious characteristics [23]. First, in the whole data interval, the number of the extreme points is equal to the number of zero-crossing points or at most one difference. Then, the mean value of the envelope defined by the local maximum and minimum point is zero.

The effective EMD steps are as follows [23]:

(1) Find the position and amplitude of all the local maximum and minimum values in the signal.

Find all maximal points of the signal $x(t)$ and fit the envelope $E_{max}(t)$. Find the minimum points of the signal and fit the lower envelope $E_{min}(t)$ using interpolation method.

(2) In each time period t, calculate the average of the upper and lower envelopes $m_1(t)$:

$$m_1(t) = \frac{E_{max}(t) + E_{min}(t)}{2}. \tag{7}$$

(3) Extract the details of signal $d_1(t)$ and used as a new signal. This is an iteration of the screening process:

$$d_1(t) = x(t) - m_1(t). \tag{8}$$

This shows that $d_n(t)$ is the basic IMF component.

(4) Check if $d_1(t)$ is an intrinsic model function. In Huang's method, when the difference between two successive screen was less than a selected threshold SD, the screening process stopped, SD was defined as

$$SD = \sum_{t=0}^{T} \left[\frac{\left| d_{1(k-1)}(t) - d_{1k}(t) \right|^2}{d_{1(k-1)}^2} \right], \tag{9}$$

where, $d_{11} = d_1 - m_{11}$ if this is the kth iteration, then $d_{1k} = d_{1(k-1)} - m_{1k}$.

(5) When all the conditions are satisfied, the intrinsic mode function is defined as $c_1 = h_{1k}$, after deriving the intrinsic mode function $c_1 = h_{1k}$, the remainder is $r_1(t) = x(t) - c_1(t)$.

(6) Take the remaining amount as the input signal, then repeat the step 1–6.

$$r_1 - c_1 = r_2, \ldots, r_{n-1} - c_n = r_n. \tag{10}$$

Based on the acoustic signal processing of data generated from gas-liquid, two-phase flow pipeline leakage experiment, it is found that the original signals have their own

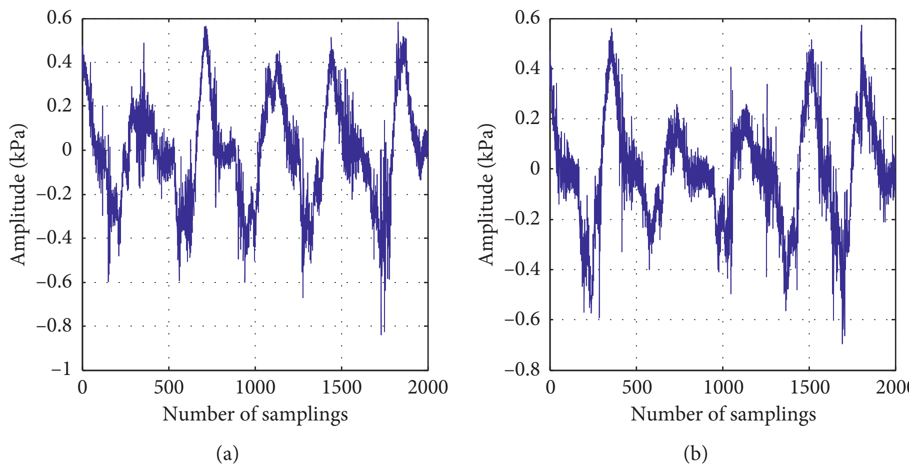


FIGURE 7: The original acoustic signals in stratified flow conditions. (a) No leakage. (b) Leakage.

characteristics as the flow pattern changes. This is mainly due to the background noise of fluid flow in the gas-liquid, two-phase pipelines changed greatly under three-flow pattern. The acoustic characteristics of signals under the three-flow pattern cannot directly reflect leakage. EMD technology is conducted to decompose two sets of signals whether leakage occurs or not under the three-flow pattern.

EMD technology can decompose the acoustic signals which collected under the three-flow pattern into the sum of several IMF components. Different IMF components contained different time scales and the signal characteristics of different resolutions. In order to describe the changes of acoustic leakage signals under the three-flow pattern, we analyzed and processed the signals in stratified, wave, and slug flows. In this study, we used the EMD technology to decompose original signals. The leakage apertures at this time are all 5 mm and remain unchanged.

3.1.1. Stratified Flow. When the gas flow rate is 10 m^3/h, the liquid flow rate is 1.0 m^3/h, and the original acoustic leakage signals collected are shown in Figures 7 and 8.

Before and after the leakage occurred in the stratified flow, the IMF component amount was obtained through the EMD technology which was without changing algorithm. In no leakage condition, that obtained 8 IMF components, while, in leakage condition, that obtained 9 IMF components. This is because when the leakage occurred, leakage acoustic source generated in the pipelines.

3.1.2. Wave Flow. When the gas flow rate is 15 m^3/h, the liquid flow rate is 0.6 m^3/h, the original acoustic leakage signals collected are shown in Figures 9 and 10.

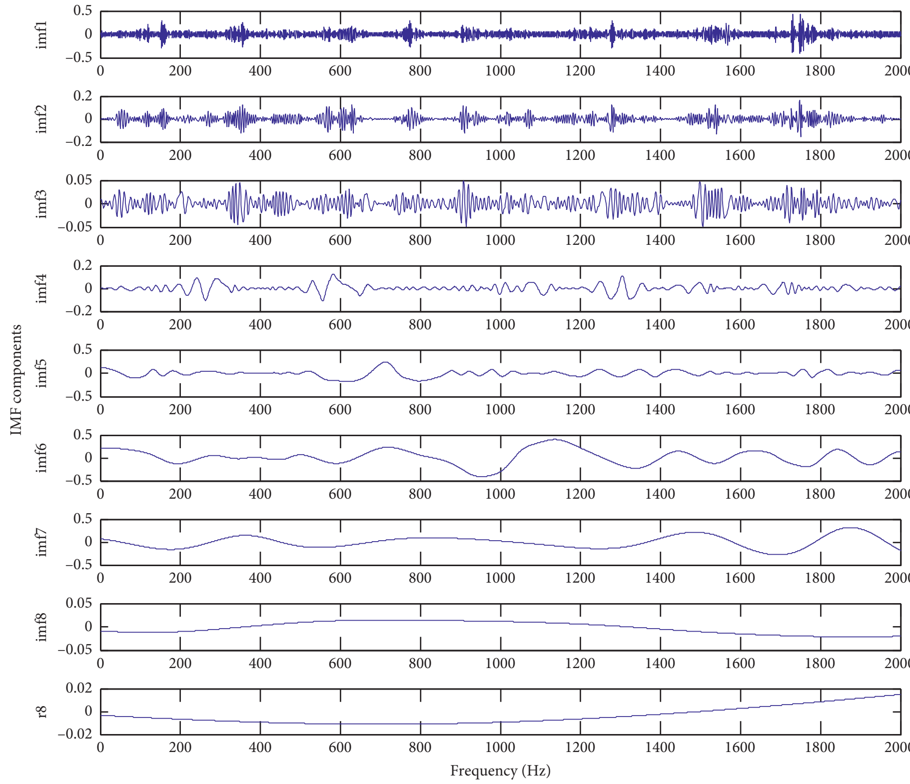
Before and after the leakage occurred in the wave flow, the IMF component amount was obtained through the EMD technology which was without changing algorithm. In no leakage condition, that obtained 9 IMF components, while, in leakage condition, that obtained 10 IMF components. The reason is that when the leakage occurred, leakage acoustic source generated in the pipeline.

3.1.3. Slug Flow. When the gas flow rate is 25 m^3/h, the liquid flow rate is 3.5 m^3/h, and the original acoustic leakage signals collected are shown in Figures 11 and 12.

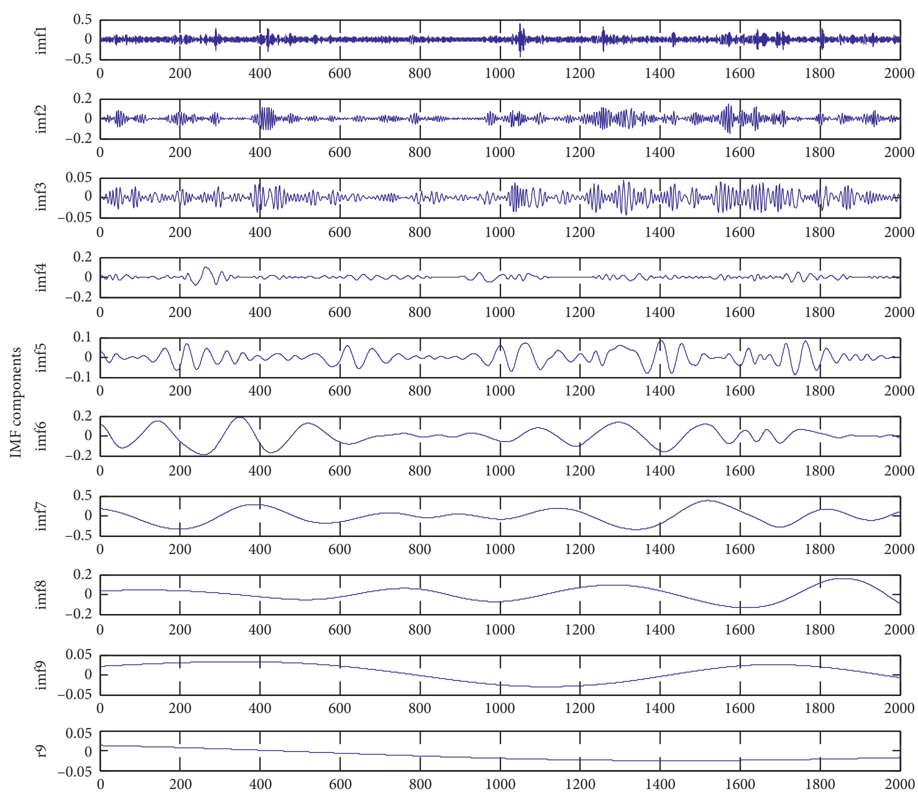
Before and after the leakage occurred in the slug flow pipeline, the IMF component amount was obtained through the EMD technology which changed nothing. In no leakage condition, that obtained 9 IMF components, while, in leakage condition, that obtained 10 IMF components. This is because when the leakage occurred, leakage acoustic source generated in the pipelines.

3.1.4. Comparison and Analysis. Acoustic signal whether leakage occurs or not was analyzed under the three-flow pattern based on EMD technology. The IMF components of the acoustic leakage of signals decomposed based on EMD technology had one more component than that of no leakage, since the acoustic signal of leakage pipeline had generated leakage acoustic source compared with the no leakage pipeline. Without other noises, it was easy to recognize whether leakage occurs or not based on the leakage acoustic signals processing. The study showed the EMD technology can accurately identify the leakage signals under the three-flow pattern in the gas-liquid, two-phase pipeline.

The acoustic signals under the three-flow pattern have the different IMF components characteristic. The interaction of gas-liquid, two-phase medium in the pipeline is different. Stratified flow is relatively stable, and the phase interface is continuous and smooth. Wave flow has a fluctuating phase interface and it generates interfacial wave. Slug flow is impacted by a liquid slug and forms a pulse wave. Therefore, the number of IMF components of wave and slug flow was one more than that of stratified flow. The amplitude range of the IMF components was directly related to the flow pattern in the gas-liquid, two-phase pipeline. Although the wave and slug flows had the same number of IMF components, the amplitude modulation ranges of each IMF component were different. The maximum IMF component's amplitude modulation range of wave flow was −0.5 to 0.5 and that for slug flow was −5 to 5.



(a)



(b)

FIGURE 8: The EMD of acoustic signals in stratified flow conditions. (a) No leakage. (b) Leakage.

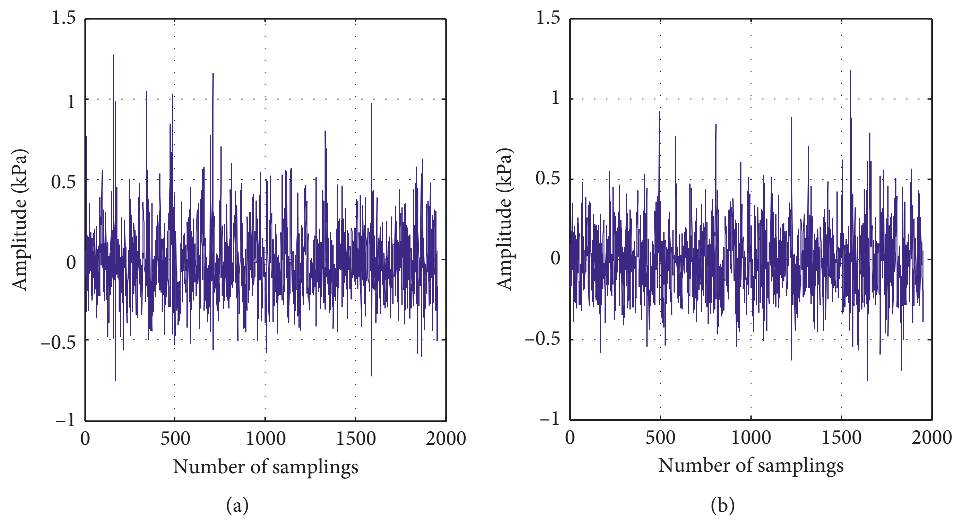


Figure 9: The original acoustic signals in wave flow conditions. (a) No leakage. (b) Leakage.

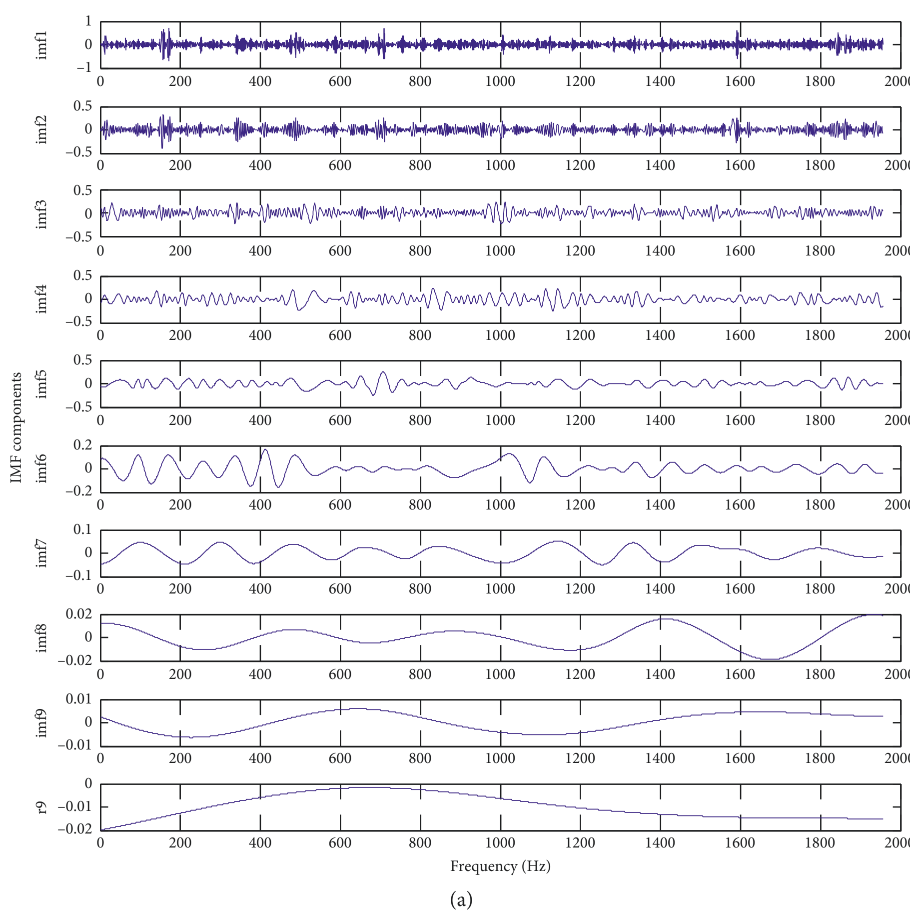
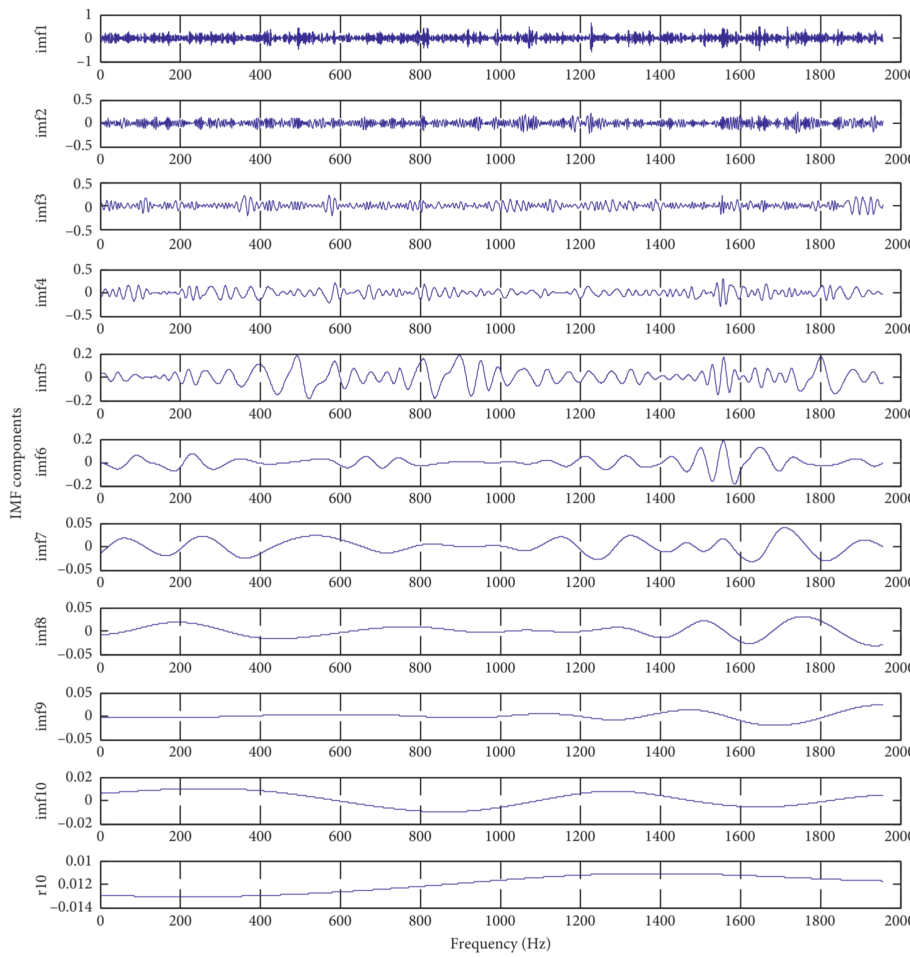


Figure 10: Continued.



(b)

Figure 10: The EMD of acoustic signals in wave flow conditions. (a) No leakage. (b) Leakage.

EMD-based acoustic signature analyses can successfully recognize more than 95% of the leakage signatures based on verified experimental data. These studies have built the foundation for a subsequent study on the propagation law of the acoustic leakage of signals and their positioning.

3.2. The Information Entropy of EMD. EMD-based acoustic signal processing can show the acoustic signal characteristics of the leakage source distributed in the IMF components and residual. The greater coefficient means the greater the correlation between the IMF components and the original signal is, the more leakage acoustic source characteristics the IMF component contains. The IMF component still contains a lot of noise no matter what the value is [33, 34].

The information entropy of EMD refers the amount of information contained in signal source. The energy distribution of the acoustic signals is changing with the flow conditions changing, such as the change of leakage position and aperture size. Information entropy is an indicator of uncertainty. In this study, we can identify different working conditions through data processing of the information entropy of EMD.

In the case of different flow rates, leakage aperture size, and other conditions under the three-flow pattern, the acoustic signal energy changes with frequency which expressed by the information entropy of EMD.

It is assumed that the acoustic signal is decomposed into n IMF components through EMD, and they expressed as $c_1(t), c_2(t), c_3(t), \ldots, c_n(t)$, respectively, which contained different frequencies. The energy of n IMF components is $E_1, E_2, E_3, \ldots, E_n$, respectively. In this way, the division of the acoustic signal is formed in frequency domain.

$$E = [E_1, E_2, E_3, \ldots, E_n] = \sum_{i=1}^{n} E_i, \tag{11}$$

$$E_i = \int_{-\infty}^{+\infty} |c_i(t)|^2 \, dt, \tag{12}$$

$$H_{E_i} = -\sum_{i=1}^{n} e_i \lg e_i, \tag{13}$$

$$e_i = \frac{E_i}{E}, \tag{14}$$

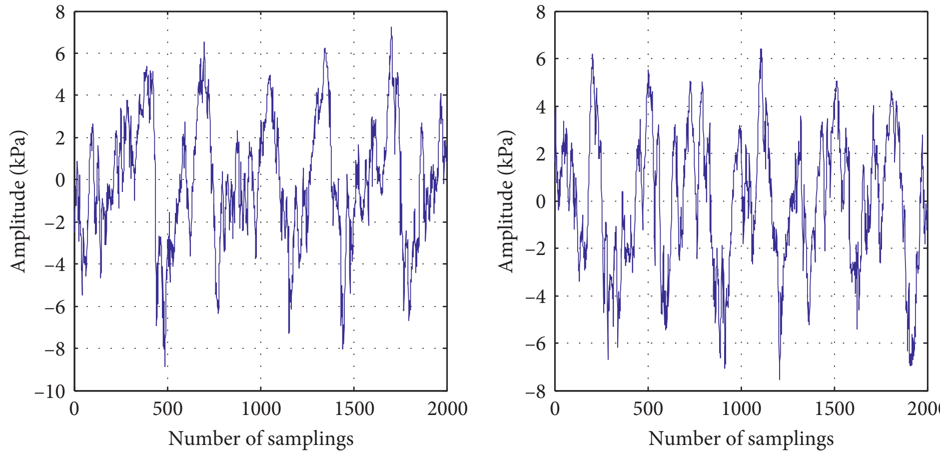
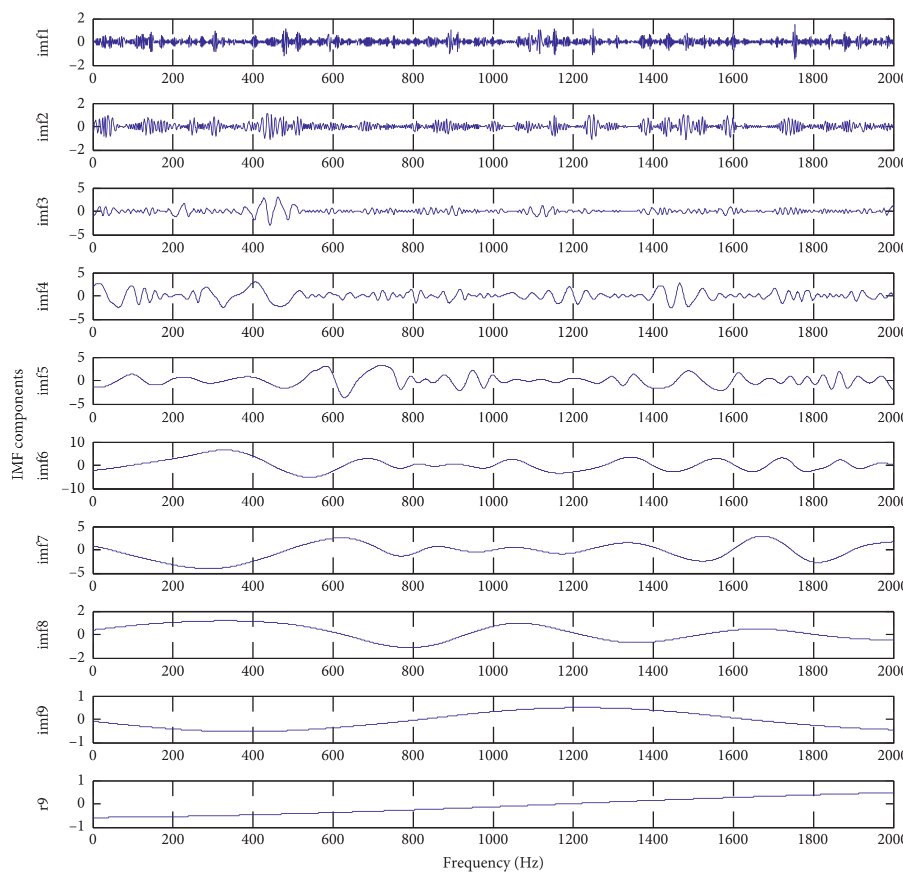
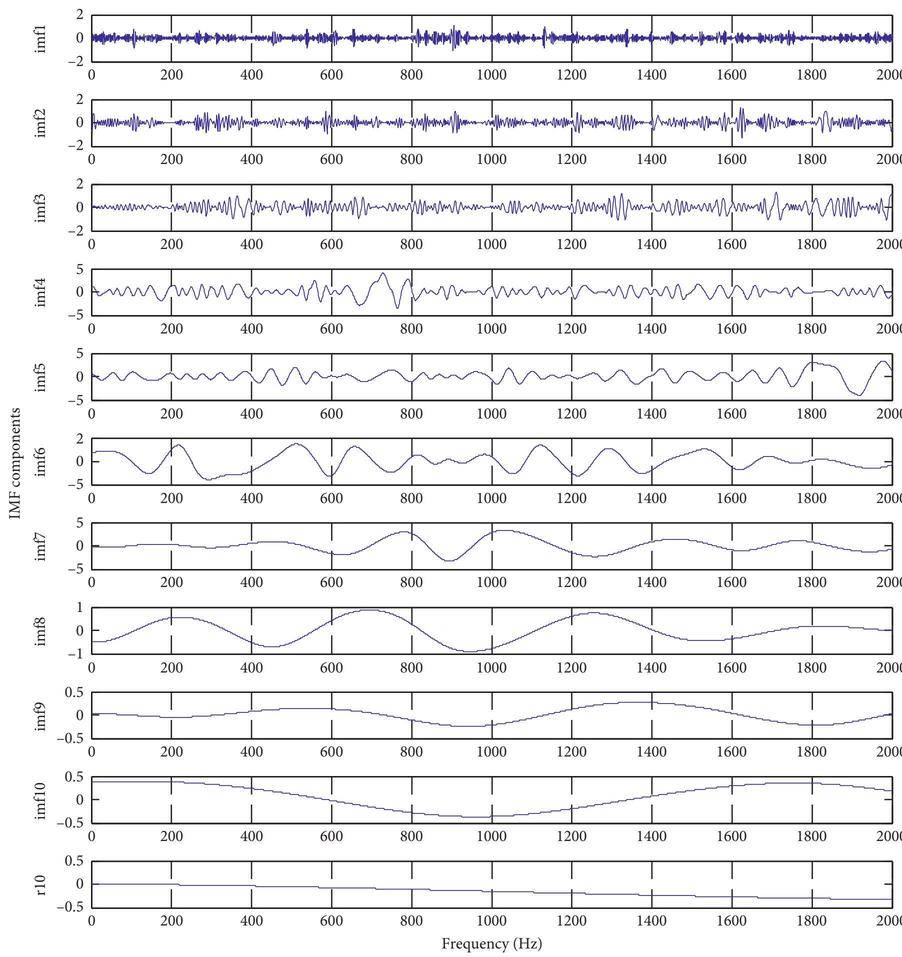


Figure 11: The original acoustic signals in slug flow conditions. (a) No leakage. (b) Leakage.



(a)

Figure 12: Continued.



(b)

Figure 12: The EMD of acoustic signals in slug flow conditions. (a) No leakage. (b) Leakage.

where H_{E_i} is the information entropy of EMD definition of each IMF component; E is the total energy of the acoustic signal; e_i is the percentage of the energy of the i^{th} IMF component in the entire energy, where $i = 1, 2, 3, \ldots, n$.

In this study, the acoustic leakage of signals under the three-flow pattern obtained by the experiment is analyzed and compared. The results show that the range of the information entropy of EMD obtained under the three-flow pattern is different. When leakage occurs, the information entropy of EMD of acoustic signals changed. We have used weighted average method to find the mean fluctuation caused by leak of each flow pattern, which is used to replace the fluctuation range caused by leakage. For each experimental condition is repeated three times, the data in the same condition is calculated by the average method. The experimental data in the same leak size 5 mm are chosen. The information entropy fluctuation range before and after each flow type leakage occur as shown in the following Table 1.

From Table 1, we known the range of the information entropy of EMD of acoustic signals changed in three-flow pattern whether leakage occurred or not. The table also shows that the information entropy based on EMD of acoustic signals had a certain relationship with the flow pattern. The fluctuation range of the information entropy EMD of acoustic signals in wave flow was approximately the same with the signal fluctuation range of stratified flow, but the fluctuation range which caused by leaking was slightly smaller than that of stratified flow. Slug flow had the biggest information entropy. This was a typical characteristic of slug flow. Using the traditional method, the researcher only selected the energy of the first IMF component scales as the main information to analyze each kind of energy.

Given the same conditions, the gas flow of the pipeline inlet is controlled at 15 m^3/h while the liquid flow rate is 1 m^3/h and it is steady stratified flow in the pipeline. The location of leakage is at the bottom of the pipeline. The leakage aperture sizes are 3 mm, 4 mm, 5 mm, and 6 mm, respectively.

Figure 13 is inferred based on the acoustic signal processing. The information entropy of EMD of acoustic signals gradually increased upon increase in the leakage aperture sizes. However, with the increase of the aperture sizes, the change of the information entropy of EMD of acoustic signals was relatively slow. However, using the same method

TABLE 1: The information entropy of EMD in leakage conditions of the three-flow pattern.

	Stratified flow	Wave flow	Slug flow
The information entropy of EMD	1.3619–1.8025	1.3313–1.5582	1.6782–1.7254
Fluctuation caused by leakage	0.155	0.148	0.186

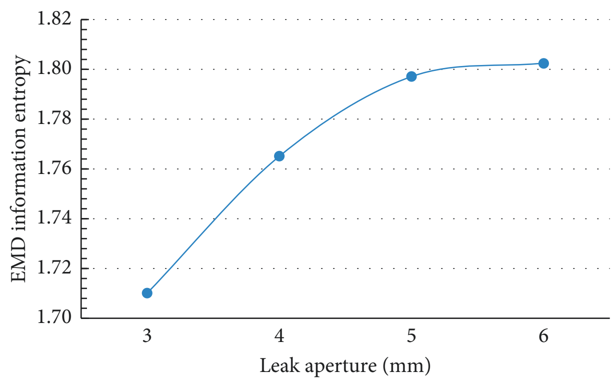


FIGURE 13: The information entropy of EMD of acoustic signals changes with different leakage aperture sizes.

to collect and analyze data of slug flow showed that the size of leakage aperture has no obvious effect on the information entropy of EMD of acoustic signals. The main reason was that the gas-liquid flow conditions in the pipeline are so complex. With the increase of gas and liquid flow rate, the interaction between gas and liquid phases became more and more intense.

3.3. EMD Energy Decomposition. Acoustic signals collected in the pipeline under three-flow pattern also have different energy distribution when leakage occurs, so the IMF components which decomposed by EMD are analyzed. EMD energy decomposition can be obtained using formula (12). We have performed EMD energy characteristics extraction method on the collected acoustic signals.

3.3.1. Flow Rate Change. In this study, EMD energy decomposition is used to study the effect of two-phase fluid velocity change on the acoustic signal collected when the liquid flow rate is maintained constant and gas flow rate is increased. In the case that the liquid flow rate of 1.0 m^3/h is maintained constant, gas flow increased to 15 m^3/h, 20 m^3/h, and 25 m^3/h, respectively. When the gas flow rate reached 15 m^3/h and 20 m^3/h, the flow pattern of the pipeline is stratified flow. When the gas flow rate was 25 m^3/h, the flow pattern in the pipe is wave flow. In the same leak location at the bottom of the pipe, the same leakage aperture size is 5 mm, and the distribution of their respective IMF energy values is shown in Figure 14.

As shown in Figure 14, there were two peaks of energy value of the IMF components, which was the first IMF component and the fifth IMF component, respectively. The

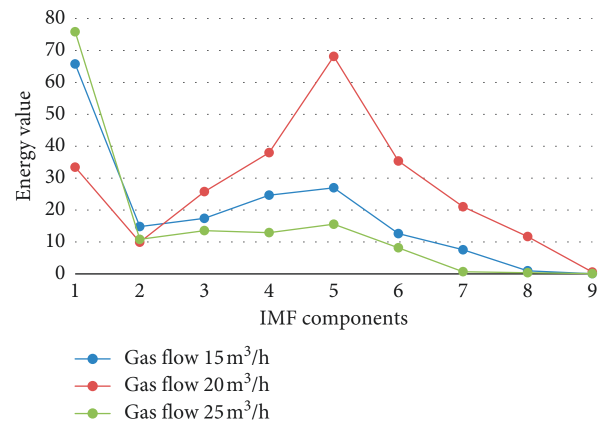


FIGURE 14: The IMF component energy values with different liquid flow rates.

energy values of the IMF components had different characteristic with gas flow rate increased. The energy value of the first IMF component had the characteristic peak and increases with increasing gas flow rate. So, subsequent study was needed. When the gas flow rate was small, the characteristic peak of energy value of the fifth IMF component was very distinct. With the increased of gas flow rate, the characteristic peak of the fifth IMF component became less and less obvious; that is, the energy value of the fifth IMF component decreased with the increased of gas flow rate. In the same flow pattern, a higher gas flow rate caused the less fifth IMF energy value as the second characteristic peak. When the gas flow rate reaches 25 m^3/h, the first IMF peak maintained and the fifth IMF peak almost vanished. When the liquid flow rate was constant, the energy values of the third to the seventh IMF components all decreased with the increased of gas flow rate.

3.3.2. Leak Aperture Change. EMD energy decomposition is also used to study the effect of leak aperture change. In the case that the liquid flow rate is 1.0 m^3/h and the gas flow is 15 m^3/h, the flow pattern of the pipeline was stratified flow. The acoustic signal collected when the leak aperture is 3 mm, 4 mm, 5 mm, and 6 mm, respectively. Further analysis of the variation of the IMF component energy values caused by leak aperture size is shown in Figure 15.

As shown in Figure 15, the energy values of the first IMF component and the fifth IMF component still had the characteristic peak. The energy value of the first IMF component in each aperture size was still the largest. The energy value of the first IMF component gradually decreases upon increases in the leakage aperture size. On the contrary, the energy value of the third to the seventh IMF components increased upon increase in the leakage aperture size. Among them, the energy value of the fifth IMF component had the maximum extremum. The size of the leakage aperture was estimated by analyzing the change law of the IMF energy value. Subsequent studies can focus on analyzing the change law between the energy value of the first and the fifth components and the leak aperture size.

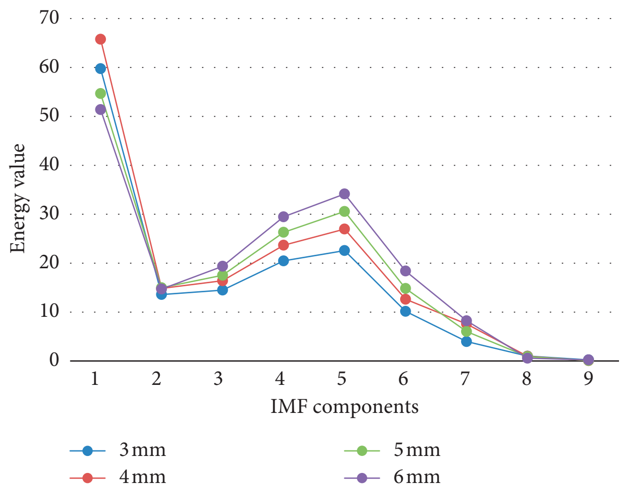


Figure 15: The IMF component energy values at different leak aperture size.

3.3.3. Flow Pattern Change. In order to better analyze the energy values of the IMF components caused by flow pattern changes, the normalized energies characteristic of each IMF energy component method is introduced.

Since the most important characteristic of EMD is smoothing and linearizing the data which non-stationary and nonlinear. The nature of the data itself is preserved during the decomposition process. Each IMF component represent the characteristics of a stationary signal at a certain set of characteristic scales. The energy change in the frequency band represents the characteristic of leakage in the pipeline. The ranges of total energy value of stratified and wave flows are from 100 to 200. The range of total energy value of slug flow is much higher than that of stratified and wave flows. It distributes in the range of 1000 to 10000 according to experimental results.

It is due to orthogonal nature of EMD, which is shown in formula (10). The normalized energies characteristic value was proposed in order to be universal in application. The fraction of each IMF component pattern in the total signal energy represents the individual characteristics, which is shown in formula (14).

Then the energy characteristics of the IMF can be expressed as:

$$E_e = [e_1, e_2, e_3, \ldots, e_n], \quad (15)$$

where E_e is the energy characteristic of the acoustic signal.

The normalized energies characteristic value of each IMF component under three-flow pattern can be obtained by processing data. When the EMD signal decomposition process does not have the ninth or the tenth IMF decomposition, the default of energy values is zero. The sum total of the normalized energies characteristic value of each IMF component of each flow pattern is 1.

The normalized energies characteristic value of each IMF component in the stratified, wave, and slug flows is obtained as shown in Figure 16. The peak of the normalized energies characteristic value of each IMF component existed under the three-flow pattern, which all were the seventh IMF component. The distribution ratio of each flow pattern was the same, but the proportion is quite different. The maximum normalized energies characteristic value of the IMF component of stratified flow was the biggest. This value of wave flow was the second characteristic peak. The fifth and the sixth IMF components of slug flow were bigger than others. The normalized energies characteristic value of the fifth, sixth, and seventh IMF components of slug flow took up most of the proportion which is more than others. Change rules of this value of stratified and wave flows were similar and that for slug flow needed studied separately. The subsequent study could focus on the spectrum changes and time-frequency changes of the fifth, sixth, and seventh IMF components.

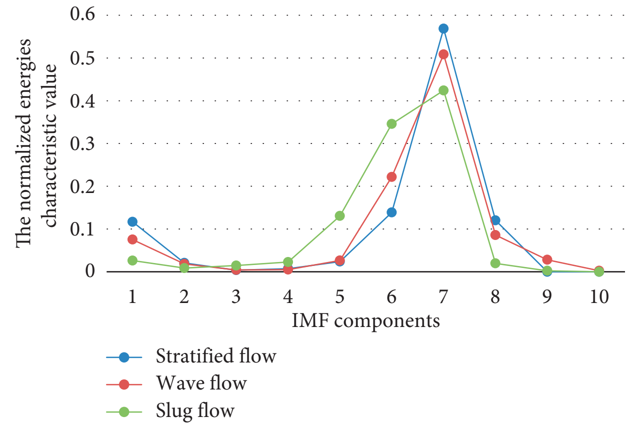


Figure 16: The normalized energies characteristic values of each IMF energy component in the three-flow pattern.

4. Conclusions

In this study, acoustic leakage detection combined with EMD technology was applied to gas-liquid, two-phase flow pipelines. The following conclusions were inferred based on the acoustic signal processing of data generated from gas-liquid, two-phase flow pipeline leakage experiments:

(1) EMD-based acoustic signature analyses could successfully recognize the leakage signatures based on verified experimental data. These studies had built the foundation for a subsequent study on the propagation law of the acoustic leakage of signals and their positioning.

(2) The information entropy of EMD of acoustic signals obtained in stratified, wave, and slug flows, have different characteristics. The fluctuation ranges of EMD information entropy of stratified and wave flows were approximately the same and were all smaller than that for slug flow. Given the same conditions, as the leakage aperture sizes increased, the entropy of the EMD information of the acoustic signals gradually increased.

(3) When the liquid flow rate was kept constant, the second characteristic peak of the energy values of the

fifth IMF components receded gradually, and the energy values of the third to the seventh IMF components all decreased with gas flow rate increased. Except for the energy value of the first and the second IMF components, the energies of the other IMF components increased with leakage aperture increased.

(4) The normalized energies characteristic value of each IMF component under the three-flow pattern all yielded maximum values at the seventh IMF component. The laws of the normalized energies characteristics value of each IMF energy component under the stratified and wave flows were all similar and different from that for slug flow.

The successful application of acoustic leak detection technology in gas-liquid, two-phase flow pipelines was discussed in this study. This study had provided the theoretical significance for safe and efficient operation of gas-liquid, two-phase flow pipelines.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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