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A Review of Research on Acoustic Detection of Heat Exchanger Tube

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Abstract

Leakage in heat exchanger tubes can result in unreliable products and dangerous situations, which could cause great economic losses. Along with fast development of modern acoustic detection technology, using acoustic signals to detect leakage in heat exchange tube has been gradually accepted and considered with great potential by both industrial and research societies. In order to further advance the development of acoustic signal detection technology and investigate better methods for leakage detection in heat exchange tube, in this paper, firstly, we conduct a short overview of the theory of acoustic signal detection on heat exchanger tube, which had already been continuously developed for a few decades by researchers worldwide. Thereafter, we further expound the advantages and limitations of acoustic signal detection technology on heat exchanger tube in four aspects: 1) principles of acoustic signal detection, 2) characteristics of sound wave propagation in heat exchanger tube, 3) methods of leakage detection, and 4) leakage localization in heat exchanger tube.

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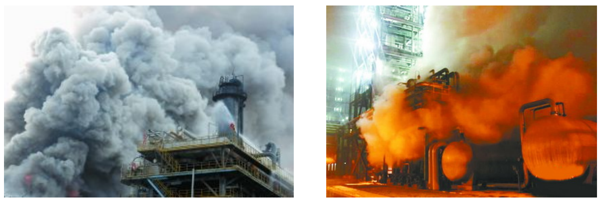
1. Introduction

Accidents caused by heat exchanger tube leakage have frequently occurred in various industrial plants, which have seriously damaged the security of factories and increased their running cost [1], e.g., a fire can be caused as shown in Figure 1. Furthermore, in terms of heat exchange tubes in boilers, the bursting-leakage of "four tubes" [1] is an important cause of unplanned maintenance on boilers. If we can predict the leakage location promptly, the maintenance time and economic losses will be significantly reduced.



(a) (b)

Figure 1. Fire caused by heat exchanger leakage

Various leakage detection technologies have been studied over the past decades. Nowadays, the most promising leakage detection technologies fall into the following three types: 1) Acoustics, 2) Conductivity, 3) Mass balance. As for the detection mechanism, these three types of technologies have different advantages and disadvantages, but only the acoustic detection can make

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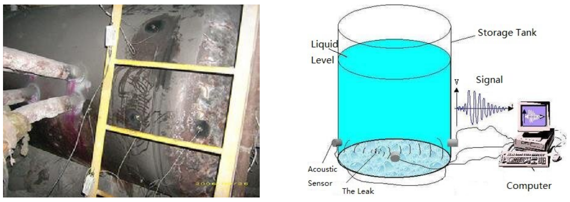
[1]Water wall tube, superheater tube, reheater tube and economizer tube as "four tubes".

use of the fluctuation information, which can achieve real-time remote monitoring and be applied to high-temperature and high-pressure environment in the heat exchanger [2]. Therefore, using the modern acoustic technology to detect the acoustic signal of leakage in heat exchanger tube plays an important role. Figure 2 [2] demonstrates an example of leakage detection by using acoustic signal.



(a) (b)

Figure 2. An example for leakage detection by using acoustic signal

Since acoustic signal detection is one of the means with most promising potential to forecast tube burst accidents, and studying the theory of heat exchanger acoustic signal will also promote the development of acoustic detection technology. In this paper, we summarize and analyze the theory of acoustic detection for heat exchanger leakage, including: 1) principles of acoustic signal detection, 2) characteristics of sound wave propagation in heat exchanger tube, 3) methods of leakage detection, and 4) leakage localization in heat exchanger tube, so as to provide a theoretical basis for further development of leakage detection technology in heat exchanger tube.

Figure 3. shown in the following page gives the studied details of each aspect, in which we provide and summarize the related information towards the similarities of different researches. As the analyzing results are given in this paper, we believe that this research work has already made the following contributions to both industrial and research communities:

- This paper summarizes the heat exchanger acoustic signal detection theory, which can provide the basis for fault diagnosis of heat exchanger.
- The comparison between the advantages and disadvantages of the heat exchanger's sound signal detection methods can help researchers to select and perfect the methods of leakage acoustic signal detection.

[2]When pipeline leak occurs, the fluid flows through the leak will make noise. We can use sound sensors to collect sound waves, to determine whether the pipeline leakage.

2. Basic principles of acoustic detection

Leakage in heat exchange tube is mainly due to corrosion of metal material and cracks in pipelines, which are caused by chemical reactions, aging and other external forces. When leakage occurs, high-temperature and high-pressure fluid within the tube will squirt out from small cracks and become jet [5], which will further cause acoustic signal. Commonly, an acoustic detection technology system is made up of multiple microphones or sound sensors installed on/in the detected equipment with an expert system for signal processing. For example, researchers in paper [5] used sonic sensor with the follow features to conduct their experiments: 1) the sensitivity is less than 25mv/pa; 2) the frequency response is between 20Hz to 4000Hz; 3) the dynamic range is between 30dB to 160dB; 4) the operating temperature is between -20°C to 105°C. The expert system can analyze the characteristics of gathered sound spectrum and intensity in the equipment, and further determine whether heat exchanger pipe leaks or not [3], [4].

In literatures, James Lighthill has published two papers on aerodynamic-noise as [6], [7]. After that, researches on mechanism of jet flow develop along Ligthtill's acoustic analogy theory, which puts forward that the process of pipeline leakage meets the mass and momentum conservation of fluid. Therefore, we can use the aerodynamic equation of Lighthill [8] to describe how the noise produced by flow field. Aiming at the effects of the jet noise, Guan Dai *et al.* [9], [10] used the finite different time domain method to correct the aerodynamics equations of Lighthill. In order to simplify the calculation and analysis, [11], [12], [13] proposed a simplified-idealized jet-flow physical model. Based on the researches of the frequency spectrum regularity of leakage acoustic signal, [14], [15], [16], [17] have studied on the experimental data and the flow mechanism. After that, they put forward the function relationship among the most probable frequency of sound radiation, jet speed and the leakage of mouth diameter, which laid the foundation for abstracting spectrum and intensity from the background noise. According to the above analysis, we compared the major existing heat exchanger pipe theories of the basic acoustic detection principle, and listed our analysis, as shown in Table 1. All in all, each method has its own advantages and limitations. It is crucial to consider the vocalization problem of the turbulence structure at all levels under the condition of three-dimensional high Reynolds number. It will further provide research directions for developing the heat exchange tube's acoustic detection technology.

3. Propagation characteristics of sound wave in heat exchanger pipe array

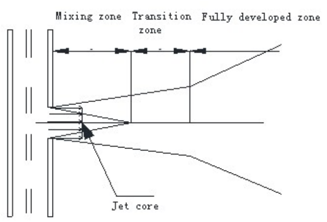
Name	Expression (Model)	Advantage	Limitation
The aerodynamic equation of Lighthill [8]	$\frac{\partial^2 p}{\partial t^2} - c_0^2 \frac{\partial^2 p}{\partial x^2} - c_0^2 \frac{\partial^2 p}{\partial y^2} = f(x, y, z)$ Formula: p - acoustic pressure, Pa; c_0^2 - the speed of sound in a homogeneous medium, m/s; f - sources of stress. As an external sound source processing, $f = 0$.	It can describe the mechanism of the jet and provide an expression to estimate some physical quantities of jet preliminarily by using the conservation of mass and momentum.	1. It can't describe the problems of the sound field and the flow field coupling when the furnace tube in the process of leakage. 2. It doesn't consider the acoustic scattering effect of the mean flow field and the disturbance of uneven flow of sound propagation.
The correction of the aerodynamics equations of Lighthill [9], [10]	$\frac{\partial^2 p}{\partial t} - (c_0 + u_x)^2 \frac{\partial^2 p}{\partial x^2} - (c_0 + u_y)^2 \frac{\partial^2 p}{\partial y^2} = 0$ Formula: u_x, u_y are the disturbance velocity of plumes along with the orientation of x, y. (m/s).	1. It has employed finite different time domain and the numerical simulation of the sound field, which was built in the qualification of total reflection and non-reflective correct the aerodynamics equations of Lighthill. 2. It not only considers the influence between the jet's velocity perturbation and acoustics thoroughly, but also gives the equation to calculate the jet's physical quantities.	1. The method does not take into account non-linear mechanism of action in the flow field and the sound field. 2. It doesn't consider the vocalization's problem of the turbulence's structure at all levels under the condition of three-dimensional high Reynolds number.
A physical model of cascade [11], [12], [13]		1. It simplifies the analysis and calculation of the physical quantities during the flow-jet process, which is an idealized model. 2. The process is divided into the mixing zone, transition zone and the fully developed zone. It shows that the sound of the jet depends on the velocity field of the jet, and the peak frequency of the spectrum produce was near the tip of the jet core.	1. It ignores that the shapes of the furnace pipe leakage holes are different. 2. It does not take into account the complexity of the jet's mechanism, which is an idealized model.
The spectrum of the leak sound [14], [15], [16], [17]	1. $f_{\max} = St(\frac{u}{D}) = 0.2\frac{u}{D}(\frac{c_0}{c})$ Formula: f is the most probable frequency of sound radiation, u is the velocity of the jet, D is the diameter of the leak hole, St is Strouhal number, which is dimensionless and its value is based on the experiment, general $St =$ 0.15 and 0.2 near equivalent. 2. For non-isothermal jet, e.g. superheated steam is injected into the high temperature flue gas with a higher ambient temperature and it needs to consider the influence of the temperature on the jet's noise spectrum. The estimation of peak frequency becomes as follows: $f_{y\max} = St\frac{u}{D}(\frac{T_0}{T})^{0.5}$ Formula: T_0 is the absolute temperature of the medium's surrounding (K), T is the absolute temperature of the jet's exports, (K).	1. This formula provides function relationship among the most probable frequency of sound radiation, jet speed and leakage of mouth diameter. 2. In the case of the furnace, the internal pressure of the pipeline is between 0.2 and 0.7 MPa. Therefore, the leakage of sound spectrum's distribution is in the range of 1000-4000 Hz. 3. It can be used in real-time monitoring of the pipelines leak state by listening to the sound signal in the furnace.	1. The formula estimate the peak's frequency roughly, and can only qualitatively describe function relationship among the most probable frequency of sound radiation, jet speed and leakage of mouth diameter. 2. The Strouhal number is dimensionless and its value is based on the experiment, which limits the formula's universality to estimate the jet's frequency and increases the difficulty of measuring.

Table 1. Major existing heat exchanger pipe theories of the basic acoustic detection principle

<table>
<tr><th>The number rows of tubes</th><th>Theoretical content</th><th>Significance and limitations</th></tr>
<tr><td>A row of tubes</td><td>1. Sound wave transmission and reflection.
2. When the tube's array geometry and the physical parameters are certain as well as $f \geq f_{crit}$ (f_{crit} the fixed threshold frequency), the summations of reflection coefficient and transmission coefficient is $|T_0 + R_0| < 1$. While $f < f_{crit}$, the acoustic wave has only transmission and reflection wave, that is $|T_0 + R_0| \equiv 1$.
3. The transmission of sound waves have two stopband in the range of audible sound. The center frequency is $3.635kHz$ and $14.22kHz$ and the bandwidth is $1.45kHz$ and $0.98kHz$.
4. While the tube spacing tends to infinity and the tube diameter tends to 0, the reflection coefficient tends to 0 and the transmission coefficient tends to 1.
5. When the tube spacing and diameter ratio equals to $\frac{\pi}{2}$ and incident wavelength equals to $\frac{d_x}{4}$ tube spacing, a strong resonance will appear. And the summations of reflection coefficient and transmission coefficient is greater than 1.</td><td rowspan="3">1. This theory is to study the characteristics of the sound transmission emission from the single row to N rows of heat exchanger tube's array. And it reveals the influence of acoustic's reflection and transmission from the multi-row bundle.
2. Its phenomenon is similar with the phenomenon which was known from the international institute as"Phononic's crystals". It confirms the truth of existence of passband and band gap through theory and experiment.
3. It is an important theory and practice for the technology of the leak's acoustic detection as well as the crystals.
4. The boundary of furnace wall and interference of background's noise would affect the directivity of sound wave, the law of the spectrum, the direction of propagation and the wavefront of sound wave. Therefore, it is necessary to further perfect it.</td></tr>
<tr><td>Double row of tubes</td><td>1. When the tube array geometry construction and the physical parameters of a certain, it has the critical frequency fixed (f_{crit}). While $f \geq f_{crit}$ (f is the sound frequency), the summations of reflection coefficient and transmission coefficient: $|T_0 + R_0| < 1$. While $f < f_{crit}$, the summations of reflection coefficient and transmission coefficient: $|T_0|^2 + |R_0|^2 \equiv 1$, the tube array's transmission weakening while the reflection has strengthened and the transmission's Stopband is reflection's conduction band exactly.
2. The tube array of double row has 7 bandwidth ranging from Stopband for the transmission of sound waves in the range of audible sound. Especially nearby the $3.745kHz$ and $14.21kHz$, the transmission coefficient of tube array is 0, which"the band gap" appear.
3. When the furnace temperature is $t = 1370^0 C$, the diameter is d =57mm and the transverse and longitudinal ratio of the diameter is 1.25 and 15.0, the critical frequency of the tube array is $f_{crit} = 16.1kHz$.
4. It has the effects of transmission and reflection for the sound's wave.</td></tr>
<tr><td>Multi-row of tubes</td><td>1. When the tube spacing/diameter ratio equals to $\frac{\pi}{2}$ and incident wavelength equals to $\frac{d_x}{4}$ tube spacing, the phenomena of the interference will appear, And the summations of reflection coefficient and transmission coefficient is greater than 1.
2. When the furnace temperature is $t = 1370^0 C$, the diameter is d =57mm and the transverse and longitudinal ratio of the diameter is 1.25 and 15.0, the critical frequency of the tube array is $f_{crit} = 16.1kHz$.
3. Within the scope of the audible sound, the Multi-row of tube arrays have two frequency's band ditch for the leakage acoustic, and the leakage acoustic's frequency which in the frequency's band ditch would be cut off.</td></tr>
</table>

Table 2. The sound wave propagation characteristics of different kinds of heat exchanger's pipe array

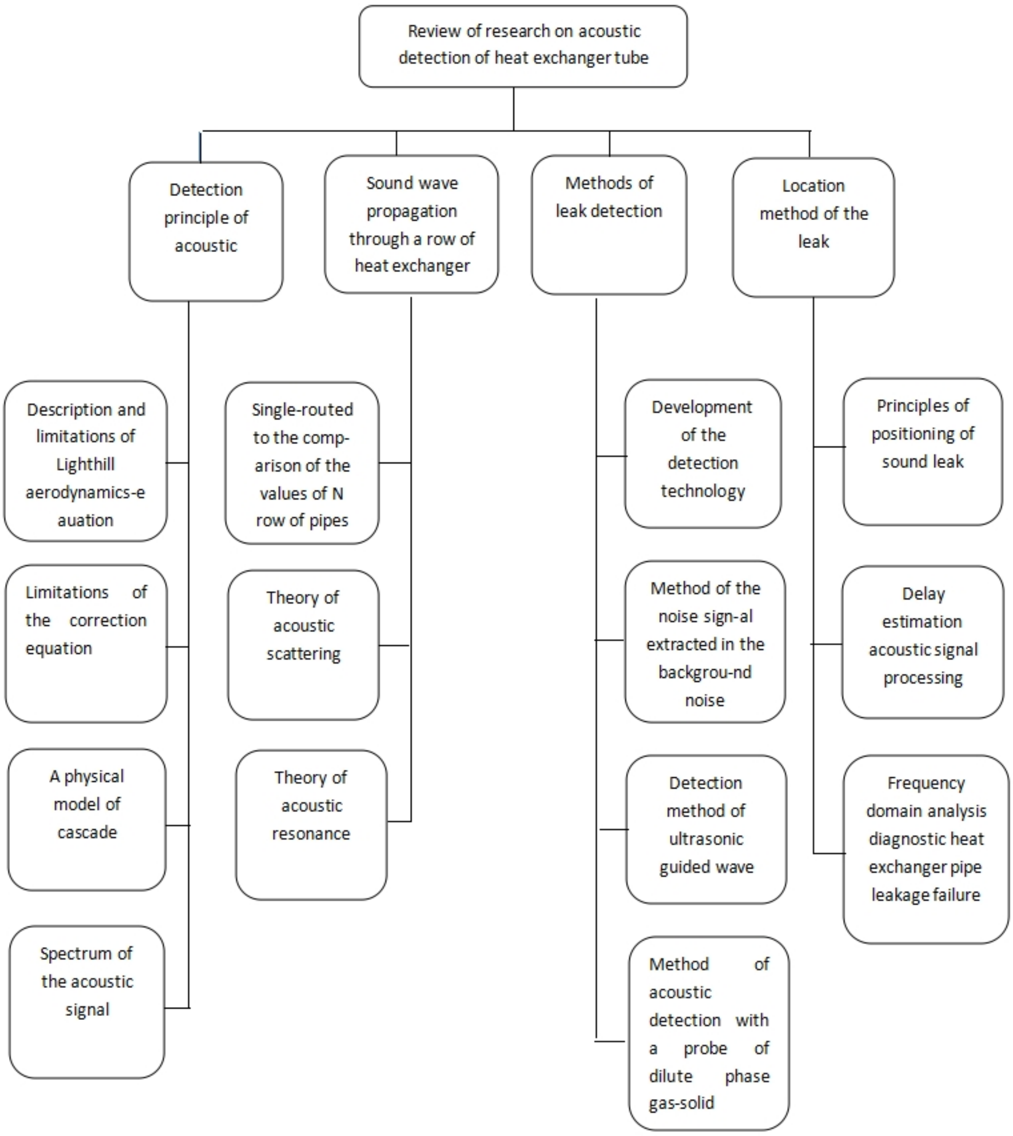


Figure 3. The content structure diagram of this review

3.1. Propagation characteristics of sound wave in different kinds of heat exchangers pipe array

The heat exchanger pipe array of acoustic wave propagation characteristics is a "bottleneck" in the development of leakage detection technology. Papers [18], [19], [20] used the Twersky's sound scattering theory [21] and the FabryParot optical interference principle [22] to calculate the mathematical model of the furnace's multi-row tube array acoustic reflection and transmission coefficients. And they also discussed the sound transmission characteristics from the array's single row to N rows of heat exchanger tubes. The researchers also revealed the relationships between the multi-row tube array's acoustic reflex as well as transmission coefficient with the acoustic's frequency and the count of tube rows as well as the structural's parameters of tube array [20]. Genshan Jiang in paper [16] used the BSWA VS-302USB sound-measuring device and the computer software was spectraLAB to do the experiment. Here, we list to compare these theories, as shown in Table 2.

3.2. Compare the current situation on the development of the acoustic scattering and acoustic resonance theory

When two sound waves spread in the medium and interact on each other, the scattering of sound occurs. Heat exchanger's acoustic signal detection that makes use of the acoustic scattering is a hot spot in the

Ways	Representative personage	Main theories	Weakness
Acoustic scattering theory	D. Firth and X.Y. Huang [23], [24]	For the nuclear power unit, they research the problem of acoustic scattering about the heat-exchanger tubes array in the water, got the water tube array acoustic transmission characteristics as well as the acoustic's resonance distribution frequency of the tube wall.	This theoretical model is based on cross-correlation function application in the acoustic temperature measurement technology [36]. It has superior processing technology difficulties when the stable periodic signal works as acoustic temperature measurement of the sound source. The model is based on a variety of assumed conditions, which become a gap between theory and reality. So, the theory of acoustic scattering remains to be further improved.
	Genshan Jiang eal [25], [26], [27], [28]	They used the Helmholtz equation to study the calculation model on the pipe wall of the sound field's distribution in the heat exchanger tubes array. From this model, they got the theory that the frequency response of pipeline wall scattered acoustic field has sharp peak's characteristics. This sharp peak's characteristic is the result of the multi-tube scattering of mutual interference. And the pipe wall of the sound field's distribution in the heat exchanger tubes array is by each pipeline which is the result of the incidence sound wave multipole scattering.	
	Xiaojun Zhang eal [29]	They came up with a new method which coupling acoustic's infinite element and finite element method (FEM) for exterior acoustic scattering calculations. They used the shape and weight function which consider the fundamental feature of exterior acoustic spread and infinity radiation boundary conditions. They also deduced the stiffness matrix and mass matrix of acoustic's infinite element method by using Weighted Residual Method (WRM).	
	Zeyuan Zhou eal [30]	According to the research of numerical method for the calculation of acoustic scattering's characteristics, they got the numerical calculation expression of singular integral and nearly singular integral by using the global approach. To improve numerical calculation accuracy and computation speed of boundary element method.	
Acoustic resonance theory	D. Firth eal [23]	They studied the sound wave's transmission characteristics of the heat exchanger tubes array in the water and the pipes' wall of the distribution of acoustic resonance frequency.	The tube spacing will change in different media, and it will affect the resonance peak, so it is very difficult to study. And the interaction between the modal is a problem to be solved.
	Genshan Jiang eal [27], [31], [32]	They studied the problems of the heat exchanger tube wall acoustic resonance, and came up with the pipes' wall acoustic resonance frequency of the distribution modes. From this model, they show that the acoustic resonance frequency of the tube wall in the heat exchanger tubes array is the same as the resonance frequency of independent pipe. They got the conclusion that the resonance frequency (ka) is inversely proportional to medium density.	

Table 3. The development status of the acoustic scattering and acoustic resonance theories

acoustics research field. Papers [23], [24] research the acoustic scattering phenomenon. The results show the sound wave transmission characteristics. Papers [25], [26], [27], [28] used the Helmholtz equation to research the sound fields distribution, which is on the tube walls surface in the heat exchanger tube array. Papers [29], [30] used a numerical method for the calculation of acoustic scattering characteristics which came up with a simplified method to calculate of acoustic scattering. For the problem of acoustic resonance, papers [23], [24] put forward the distribution of acoustic resonance frequency in the pipe wall, and papers [27], [31], [32] got the pipe

Representative personage	Main theory contents
J.A.Kleppe [38]	When they study acoustic detection technology in boilers, they came up with frequency of the sound source setting in MID which was used for furnace physical quantity detection technology and should not be using ultrasound. Because it is beneficial to reduce acoustic wave attenuation, on the other hand the sound sensors must be placed in a specific location, otherwise, it can't receive acoustic signal easily.
Helmut sielshcott [39]	They used sound waves in the sports transmission medium frequency and velocity relationship to study the flue gas velocity measurement technology in boilers.
J. Lu [40]	They studied theoretically that the sound propagation path"bending effect" will affect the measurement result in the temperature gradient field. According to this research, they came up with a theory that sound propagation must be considered as"sound ray bending" to improve the accuracy of a real-time temperature field measurement.
R.I.Sujith [41], [42]	They studied the sound propagation problems which in one dimensional temperature gradient field in the tubes and the area of gas burning. And they did the numerical calculation about an index and linear temperature field distribution.

Table 4. The research and development situation of the theory of tube leak detection technology for the heat exchanger in boilers

wall's acoustic resonance frequency of the distribution modes. The development statuses of these two theories are listed to make a comparison, as shown in Table 3.

The theories of acoustic scattering and acoustic resonance can provide a reference for the heat exchanger tubes acoustics non-destructive testing (ANDT) and acoustic energy saving technology [33], [34], [35]. But most of these theories are based on a variety of hypothetical situations, which are very different from actual conditions. For example, there is strong background noise existing in the actual environment. Therefore, the research on the heat exchanger sound theory is expected to have a further development.

4. Leak sound detection method of the heat exchanger

4.1. The development of the theory of pipeline leak detection technology for heat exchanger in the boiler

The leak detection technology-Acoustic Detection Method (ADM) is divided into two main categories [31], [32], [37]. The first one is passive technologies, relying on the source of the leak which produces acoustic signal to determine whether the pipeline leaks or not and determine the leak position. The other is active technologies, which rely on the physical factors (e.g. temperature variation, air bubbles or residue suspended) nearby the source of leak, by affecting the external acoustic signals to get tubes leakage signs, locations, etc. The research and development situation of the theory of tube leak detection technology for the heat exchanger in boilers [38], [39], [40], [41], [42] are shown in Table 4.

4.2. Compare different sound detection methods when the heat exchanger leak

All in all, when the tubes leak, the complex pipeline environment will influence the propagation path of sound. It may cause alarm omission, misstatement and delays. So, it is very important to research and perfect the theory of the heat exchanger tube leak detection technology. Sound detection, an important method of heat exchanger nondestructive testing, is a hot topic of research. Papers [43], [44], [45] used a method of Wavelet Transform and Mal-lat algorithm extracting the noise from background noise to meet the requirements of realtime monitoring of pipeline leakage. To improve the accuracy and efficiency of the acoustic signal detection, papers [46], [47], [48], [49], [50] used the propagation characteristics of ultrasonic guided waves in pipes to test the leaking pipe. To reduce the cost of the heat exchanger acoustic signal detection, papers [51], [52], [53], [54] designed the probe-based method and the gas-solid two-phase flow detection sensor structure that the sound sensors are installed on the pipe outside. At present, the model of gas-solid two-phase flow measurement based on sound detection is still not sure. The method of detection analysis of gas-solid two-phase flow parameters by using solid particles hit against the probe to produce the acoustic signal will become the focus of many researchers. Therefore, we list to compare the different methods for sound detection, as shown in Table 5.

5. Sound source localization of the heat exchanger tube leak

Methods	Principles	Advantages	Boundedness
The wavelet transform method treatment of background noise	The researchers used different center frequency bandpass filter for signal filtering. It mainly reflects the scale of the noise frequency wavelet function. Then combined the rest of each scale wavelet function to make an inverse transform. After we do that, we can get the acoustic signal. This process including decomposition course, threshold effect and the reconstruction process. The expression is: $WT(a, \tau) = \frac{1}{a}\int x(t)\psi^*(\frac{t-\tau}{a})dt =< x(t), \psi_{az}(t) >$ Formula: a is the scale factor, τ is the scalability factor, $\psi^*(t)$ is the conjugate function of $\psi\,(t)$.	At the moment, using the method of wavelet transform to process the leak signal is the dominant method to extract acoustic signals from background noise. Using Mallat algorithm can implement the decomposition of leak signal and noise, and speed up the calculation. All in all, using the method of wavelet transform and Mallat algorithm to process the leak signal adapted to the requirements of real-time monitoring, can reduce the system error caused by noise signal interference and omission probability.	Not on each scale it can be well estimated the time delay.
The pipeline ultrasonic guided wave testing online	The pipeline ultrasonic guided wave detection which is to use the probe in the tube bundle emitting a pulse of ultrasonic energy. When ultrasonic guided wave in the process of encountered in the propagation of defects, it will return a reflected wave. According to the return signals, we can determine the size and the defect position of the tube.	The ultrasonic guided wave usually used less than 100 kHz frequency multiple probe of Axially symmetric torsion wave. It has the characteristic that the defective signal is clearly legible, and it can improve the test accuracy and efficiency.	At present, the technology of ultrasonic guided wave is not mature enough. Such as solving anti-jamming and accurate positioning of corrosion defects. It needs to be studied further.
Dilute phase gas-solid two-phase flow probe sound detection method	Using solid particles collision acoustic signal detection of gas-solid two-phase flow parameters to determine the location of the defect.	On the one hand, its characteristic is detection sensitivity, simple structure and low cost. On the other hand, for the obvious features of sound signal, it may reduce the influence of outside interference.	At present, the model of gas-solid two-phase flow measurement based on noise detection is still not for sure, this method will be the focus of many researchers.

Table 5. The different sound detection methods for heat exchanger leak

5.1. The sound source localization principle of the heat exchanger tube leak

In daily life, we always use more sound sensors for the sound source localization. Its basic principle is to analyse the characteristics of electrical signals converted from acoustic signals collected by the sound sensors, including the active positioning and passive positioning [55]. Theoretically, as long as there are three positions of sound sensors' array not in the same line that has received acoustic signal, we can determine the sound source location according to the geometric relationship of the target and motify position [56].

5.2. The sound sensors array of choice

The position of sound sensors in different sensor array determines the position performance of their characteristics. It is directly related to the location of the heat exchanger pipe leak. Now, we compare six kinds of sensors array widely used and their application range [55], [57], [58], [59], [60], as shown in Table 6.

5.3. Time delay estimation for acoustic signal processing

Time delay estimation of acoustic signal processing is an important part of the positioning. With the development

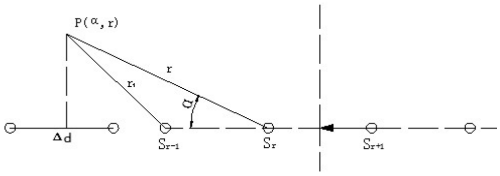
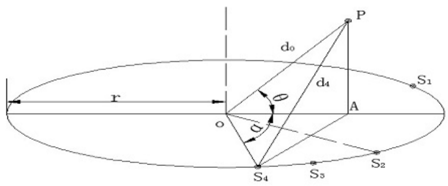
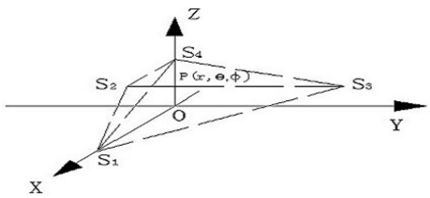
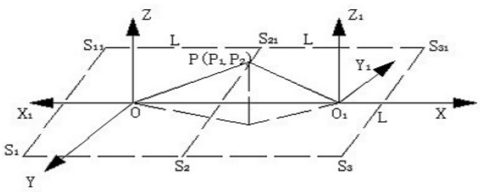
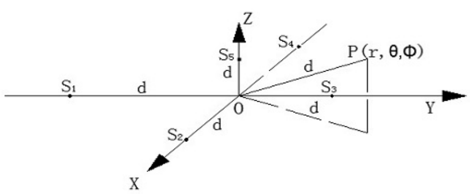
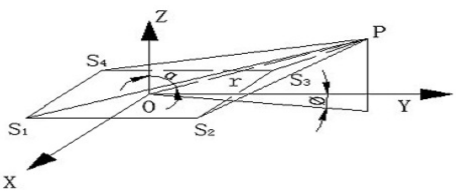
Name of the arrays	Array of schematic diagram	Use characteristics
Uniform Linear Array		The geometry structure is relatively simple, which is the first array. It is suitable for simply pipeline design.
Uniform circular array		It has a good performance measure. The variance of the measuring distance and direction is relating to the time delay estimation and the speed of sound as well as the array aperture, which has nothing to do with the orientation of the target. To some extent, it inhibited the influence by time delay estimation variance on the accuracy of the measuring of distance and direction.
Regular tetrahedron array		It can eliminate the influence of effective sound velocity.
Double right-angle triangular matrix		Using less sound sensors completes the positioning of master-slave four square matrices, which solved the problem of the regular tetrahedron microphone array cannot positioning for long distance. This model also effectively improve the measurement accuracy.
Solid five-element cross array		It can overcome the measuring blind area when positioning, and it has good directional property.
Quaternary cross array		This model can avoid the influence of effective sound velocity, but cannot position remotely.

Table 6. Contrast table of sound sensor arrays

Method names	Theories	Advantages	Boundedness
Generalized correlation method	First, filter the two discrete signals received by the two sensors. Then, determine the cross-correlation function of two discrete signals. The time that corresponds to the peak value of the function is the time delay value.	The generalized correlation method is currently the most widely used method. Thereinto, time delay estimation based on Wavelet Transform is widely used in non-stationary signal processing. It can expand the application scope of time delay estimation and improve the accuracy.	The generalized cross-correlation function is based on a variety of assumptions, which limit the use of it. The time delay of wavelet transform may not be always well estimated in every scale.
Adaptive algorithms	This algorithm uses adaptive filter instead of pre-filter of the generalized correlation method or directly implement the adaptive estimation of time delay with generalized correlation algorithm.	It is the optimal time delay estimation method, which may be exempted from the limit of the input signal and the conditions of the additive noise, and overcome the defects of the generalized correlation method.	The adaptive filter has high production requirements, materials and costs, which limits the widespread use of this algorithm.

Table 7. Comparison sound sensor arrays

of the signal processing technology, there are a lot of time-delay estimation methods, e.g., the method of phase data, generalized correlation method, parameters model method based on adaptive filter, spectrum refinement method and correlation peak interpolation method, etc [59], [61], within which the generalized correlation method and adaptive algorithm are most widely used, and their advantages and disadvantages are shown in Table 7.

5.4. Frequency domain analysis method applied in the heat exchanger pipe leakage fault diagnosis [62]

Engineers often use the method of frequency domain analysis for fault diagnosis of the heat exchanger pipe based on the frequency distribution of the sound source, composition and amplitude. The method of frequency domain analysis is through Digital Signal Processing technology. There are two kinds of methods,which are amplitude spectrum analysis and power spectrum analysis [2]. In practice, we often combine these two methods with process sound signal to get more accurate results. On the whole, at the mention of the heat exchanger's pipe leak sound source localization, it generally needs to consider the environmental impact. According to the environment, we can determine the sensor layout and sound signal's processing method, so as to determine the position of the heat exchanger leakage more accurately. Because the heat exchanger of acoustic detection is easily affected by the external environment, we can collect information of the external environment while collect the heat exchanger's running sound. The impact caused by the external environment is relatively large. So the technology that detects heat exchanger failures by using sound has not been widely adopted yet at present.

6. Sound detection research direction of the heat exchanger

The pipeline sound signal detection can be used to locate and detect the heat exchanger pipe leakage rapidly and accurately, and it is an effective measure to prevent boiler tube from explosion. But there is still no breakthrough on some technical problems of the system in the producing, which is a direction of the future research, especially for the pipeline's leak location technology, which is much behind the detection technology [63]. Therefore, there are some follows we must consider.

- Studying the sound signal propagation characteristics.
- Solving the problem of turbulent flow in the heat exchanger.
- Solving the problem of the effect on leak-sound propagation path caused by the complex non-uniform temperature and dynamic field in the furnace (Including the leakage of directivity of acoustic waves, frequency spectrum regularity and wavefront, etc. That will be the focus of the studies on the sound signal detection of heat exchanger's fault diagnosis [64], [65]).

- In the process of actual operation, we need to correct the calculation formula according to various uncertain factors.

7. Conclusion

In this paper, we summarize the acoustic signal detection of heat exchanger tube's theory. We thoroughly state the following four aspects to this paper, which are, the principle of acoustic signal detection, the characteristics of sound wave propagation in heat exchanger tubes, methods of leak detection and leak location in the heat exchanger. According to our research, the acoustic signal detection technology of heat exchanger tubes in boilers has wide application. More and more researchers are researching the theory of signal detection technology. But it has great limitation, such as affected by the environment. All in all, we researchers are expected to do further research in the technology of heat exchanger tubes in boilers sound detection, and improve on it.

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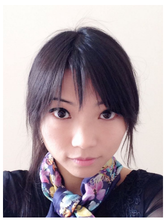

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