Research on the Signal Characteristics of Internal Gas Leakage in Safety Valve

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Abstract. Based on the acoustic emission theory, this paper explores the signal characteristics of internal gas leakage in safety valve. In this paper, a simulation test-bed and an acoustic emission signal detection system for internal leakage in safety valve are designed and built. Through theoretical analysis and experimental research, the influence of factors such as inlet pressure of safety valve, size of leakage hole of sealing surface are explored, and the quantitative relationship between the gas volume leakage rate and the average signal level ASL of the characteristic parameters of acoustic emission signal is established.

1. Introduction

The safety valve is an automatic valve, which uses the pressure of the medium itself to discharge the specified amount of fluid to prevent the pressure of pressure bearing devices and equipment such as boilers, pressure vessels or pressure pipes from exceeding the predetermined safety value then causing overpressure and damage, so as to ensure the normal operation of the equipment and the personnel safety [1]. However, when the safety valve is affected by medium corrosion, erosion aging, improper operation and other factors, the sealing surface is easy to be damaged, resulting in internal leakage, causing medium loss and waste, even serious safety accidents. Traditional detection methods need experienced technicians to listen to the sound to judge or remove the safety valve from the pipeline for off-line detection, which is time-consuming and laborious, and cannot grasp the internal leakage of the safety valve in time.

Acoustic emission detection technology is a dynamic non-destructive detection method, with the advantages of convenient detection, no need to stop production and low cost [2-5]. It is of great significance to use this technology to monitor the internal leakage of the safety valve so as to repair and replace the damaged safety valve in time, prevent medium waste and reduce the probability of safety accidents.

2. Basic theory of acoustic signal detection for internal leakage in safety valve

2.1. Acoustic emission theory

Acoustic emission refers to a physical phenomenon [6] in which an object or material is subjected to deformation or external force, producing a transient stress wave due to the rapid release of elastic energy, as shown in Figure 1. When acoustic emission occurs in materials, each acoustic emission signal emitted by the acoustic source contains the information of the internal structure or defect
property and state change of materials. Therefore, sensitive instruments can be used to receive and process the acoustic emission signal. Through the analysis and research of the characteristic parameters of the acoustic emission source, the position, state change degree and changing trend of the internal defects of materials or structures can be inferred. The acoustic emission signal of internal leakage in safety valve carries the information of leakage point. The acoustic emission signal is picked up by the acoustic emission sensor, and the leakage degree of the safety valve can be judged by analyzing and processing the signal.

![Figure 1. Acoustic emission](image)

### 2.2. Time-frequency characteristics of acoustic emission signal of internal leakage in safety valve

The acoustic emission signal of internal leakage in safety valve belongs to the continuous acoustic emission signal. In order to extract the information representing the characteristics of internal leakage in safety valve from the acoustic emission signal in time domain, it is necessary to use the average value of signal characteristics rather than the instantaneous value. The average signal level ASL represents the average value of signal level in the sampling time, which can be used as the criteria for determining the internal leakage in safety valve [7]. The average signal level ASL is expressed as follows:

$$\text{ASL} = 20\log \left( \frac{\text{RMS}}{10^{-6}} \right) - \text{pre}$$  \hspace{1cm} (1)

Where: ASL is the average signal level of acoustic emission signal (dB), RMS is the effective value voltage (mV), and pre is the amplification factor of preamplifier.

The effective value voltage RMS is the mean square root value of the signal in the sampling time. For the discrete acoustic emission signal, there are N samples, which are $x[0], x[1], x[2], ..., x[n-1]$. The mean square root value equation can be expressed as:

$$\text{RMS} = \left( \frac{1}{N} \sum_{n=0}^{N-1} x[n]^2 \right)^{0.5}$$  \hspace{1cm} (2)

The leakage rate of safety valve can be estimated by the acoustic emission signal of internal leakage, and the acoustic power is needed as the intermediate variable. For the safety valve, the acoustic power of the internal leakage signal is approximately equal to the average energy of the leakage signal, and the relationship is simply defined as follows [8]:

$$P \propto \text{RMS}^2$$  \hspace{1cm} (3)

Where: P is the acoustic power, W.

The logarithm of acoustic power is linear with the logarithm of leakage rate [9], namely:

$$\log P = b \log Q + c$$  \hspace{1cm} (4)

Where: Q is the leakage rate, ml/min; b and c are coefficients respectively, and their values are related to safety valve type, leakage type, leakage hole size, inlet pressure, type of discharge medium, size of safety valve body and other factors.

According to equations (1) and (4):

$$\text{ASL} = b \log Q + c$$  \hspace{1cm} (5)

The characteristic frequency, peak frequency and other characteristic values of acoustic emission signal of internal leakage in frequency domain can also provide the characteristics of internal leakage.
in safety valve. These characteristic values can be obtained by conducting Fourier transform (FFT) on the acoustic emission signal of internal leakage in time domain.

3. Test device and detection system

The detection system for internal leakage in safety valve [10] consists of internal leakage simulation test-bed of safety valve and signal acoustic emission detection system for internal leakage in safety valve.

The internal leakage simulation test-bed is composed of nitrogen gas source, pressure regulating valve, pressure gauge, flowmeter and internal leakage simulation prototype of safety valve, as shown in Figure 2.

![Figure 2. The internal leakage simulation test-bed](image)

Spring loaded safety valve of HTO series of 3K4 specification developed by Beijing Aerospace Power Research Institute is selected as the internal leakage simulation prototype of safety valve, with nominal inlet pressure of 600 pounds. In order to simulate the different leakage state of safety valve, the safety valve clack is processed. There are four valve clacks used in the test: three of them have been slotted, with the size of 0.15mm * 0.5mm, 0.3mm * 0.5mm and double holes of 0.15mm * 0.5mm * 2, respectively, to simulate contact surface damage and particle accumulation; the other one has been manually polished on the sealing surface by sandpaper to simulate sealing surface scratch. Because the leakage rate of gas in safety valve is very small, the volume leakage rate of gas is measured by soap-film flowmeter.

The acoustic emission detection system for internal leakage signal of safety valve adopts the acoustic emission system produced by American Physical Acoustics Company, including sensor, preamplifier, acoustic emission acquisition card and supporting acoustic emission software. The center frequency of acoustic emission sensor is 30kHz, and the gain of preamplifier is 40dB.

4. Analysis of test results

For the internal leakage detection test of safety valve, first, fix the internal leakage simulation prototype of safety valve on the internal leakage simulation test-bed, and connect it to the internal leakage detection system of safety valve. Open the air source, adjust the pressure at the inlet of the prototype and control the gas flow. When the leakage is stable, measure the flow through the soap-film flowmeter, and record the acoustic emission signal of internal leakage in the safety valve through the acoustic emission system. Change the inlet pressure of safety valve (0.01MPa, 0.02MPa, …, 0.1MPa) to measure and test different leakage states. Finally, through the acoustic emission signal detection system for the internal leakage in the safety valve, the signal is collected, amplified and filtered to extract the required signal eigenvalues. Replace the leakage holes of different types and sizes of safety valves and repeat the above test process.

4.1. Time domain and frequency domain characteristics of acoustic emission signal of internal leakage in safety valve

The leakage holes of different types and sizes of safety valves are selected to carry out the internal leakage simulation test under different pressure. Collect the acoustic emission signals of internal leakage in time domain and frequency domain, and compare and analyze the signals. By analyzing the
acoustic emission signals of internal leakage in time domain and frequency domain, we can preliminarily judge whether the safety valve is in internal leakage state. Due to different types of leakage holes, the inlet pressure required for the test will change accordingly. Taking several cases in figures 3-7 as examples, the time domain waveform and frequency spectrum of the acoustic emission signal of internal leakage are selected to make a comparative analysis of the acoustic emission signal of internal leakage in safety valve.

Based on the analysis of the acoustic emission signals of internal leakage of the above types of leakage holes under different inlet pressures, the following conclusions are drawn:

(1) The peak frequency range of internal leakage in safety valve is 20-30kHz, which is related to the type of leakage holes. For square slotted leakage holes, the peak frequency is near 20kHz; for manually polished leakage holes, the peak frequency is near 30kHz.
(2) For the same type of leakage holes, the peak frequency of internal leakage signal in the safety valve does not change with the size of the hole diameter and the inlet pressure. But for the same leakage hole, the amplitude of peak frequency increases with the increase of inlet pressure.

(3) By observing whether the acoustic emission signal has peak value in frequency domain, it can preliminarily judge whether the safety valve has internal leakage.

4.2. Relationship between acoustic emission signal and leakage rate in safety valve

If the leakage rate of safety valve can be calculated according to the characteristic value of acoustic emission signal of internal leakage in the safety valve, the degree of internal leakage or damage of sealing surface of safety valve can be judged more directly. According to equation (5), the relationship between the ASL value of acoustic emission signal of safety valve and the logarithm of leakage rate is linear. Therefore, the leakage rate of safety valve can be estimated by measuring the ASL value of the acoustic emission signal of internal leakage in safety valve. Taking 0.15mm * 0.5mm square leakage hole as an example, by collecting the ASL value of acoustic emission signal under different leakage rates, and using origin to make a linear fitting between the two, the curve is fitted, as shown in Figure 8:

![Figure 8. The relationship of leakage rate and ASL of 0.15mm*0.5mm and 0.3mm*0.5mm square leakage hole](image)

Take the leakage rate and ASL value into equation (5), then obtain the coefficients $b = 47.5734$ and $c = -82.4719$. For square holes, the relationship between leakage rate and ASL is

$$ ASL = 47.5734 \log Q - 82.4719. $$

Therefore, for the internal leakage of safety valve, the leakage rate and average signal level can be fitted according to $\text{ASL} = b \log Q + c$, and the leakage rate of safety valve can be estimated by measuring the average signal level ASL of the acoustic emission signal of internal leakage.

5. Conclusion

Through theoretical analysis and experimental research, this paper explores the influence of factors such as the inlet pressure of safety valve, the size of leakage holes, the type and the number of leakage holes on the acoustic emission signal, and establishes the quantitative relationship between the gas volume leakage rate and the average signal level ASL of the characteristic parameters of acoustic emission signal in the process of internal leakage in safety valve, and draws the following conclusions:

(1) It is the first time to apply acoustic emission technology to the internal leakage detection in safety valve. The acoustic emission technology can effectively detect the internal leakage state in safety valve, which provides a new method for the internal leakage detection of safety valve.

(2) The peak frequency range of internal leakage in safety valve is 20-40kHz. The specific value is related to the type of internal leakage. The influence of hole size and inlet pressure is not significant. The peak frequency of contact surface damage and particle accumulation is about 20kHz, while the peak frequency of contact surface scratch is about 30kHz.
(3) For multi-hole leakage, the ASL value of acoustic emission signal is related to the leakage rate of single leakage hole, but it is independent of the total leakage rate, and there is no superposition of acoustic emission signals of each leakage hole.

(4) For internal leakage in safety valve, given the average signal level ASL value of internal leakage in safety valve, the leakage rate of safety valve can be estimated by equation.

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