Experimental Research on Detection of Internal leakage of Valves in Pressure Air Pipes based on Acoustic Emission Technology

Mengmeng Wu*, Xiuchen Dong, Jiaxuan Yang and Shunyan Xue

Naval Submarine Academy, Shan Dong, Qing Dao, China

*Corresponding author e-mail: caozewolong2006@163.com, yangjiaxuan89@126.com, xueshunyan99@163.com

Abstract. Valve leakage is a very important factor affecting the normal operation of pressure piping system. In this paper, based on the analysis of the mechanism of acoustic emission detection in the valve, under the condition of laboratory, the experimental platform and acoustic emission detection devices are designed and built. The experimental results show that acoustic emission technique can be used to detect leakage and evaluate leakage rate, which is very important for the real-time monitoring and quantitative detection of leakage in the pressure pipeline valve.

1. Introduction

Valve is the control unit of the pressure pipeline system, with the functions of truncation, regulation, backflow, stop, steady pressure, partial pressure and overflow relief [1]. The quality and reliability of the valve largely determine the working reliability of the whole pressure pipeline system. Facts have proved that many cases of failure of pressure piping system are caused by poor valve operation. Valve leakage, as a typical failure of valve, will bring great harm to the normal operation and indication of equipment and system, especially some key pipeline valves (such as steam pipeline, nuclear reactor pipeline, hydraulic pipeline, high pressure pipeline, etc.). One of the most important reasons for a nuclear accident in the United States is the leak in a release valve of the regulator.

At present, leakage of pressure line valves, especially internal leakage, has been difficult to solve in operation. The research on detecting valve leakage using acoustic emission technology has been carried out abroad since 1960s [2], some of the research results have been applied in practice. In 2010, Kaewwaewnoi, A. Prateepasen et al. [3-4] studied on the relationship between acoustic emission signal characteristic parameters and leakage rate. In 2012, E.Mland et al. [5] studied on the processing method of acoustic emission signal of leaked valves. In China, Dai Guang and Wang Bing of Northeast Petroleum University [6-7] carried out the acoustic detection of valve leakage by means of numerical simulation and experimental study. Yang Jing et al. explored the visualization of valve leakage fault [8], and Gao Qian-xia et al. [9-10] processed the acoustic emission signal of leaked valve leakage by using the least square method and adaptive filtering to remove noise, and the engineering verification was carried out.

In this paper, the experimental platform and acoustic emission detection system of valve leakage in pressure gas pipeline are set up under laboratory conditions based on the theoretical analysis of the acoustic emission detection technology of valve leakage. The acoustic emission signals under different
leakage conditions are collected, processed and analyzed. This paper has important reference value for remote, real-time and non-destructive monitoring of the working and running state of pressure pipeline valves.

2. Theoretical basis

Acoustic emission (AE) detection method [11] is to determine the leakage state of the valve or to quantify the leakage rate of the valve by collecting, recording and processing the acoustic emission signal emitted by the valve leakage. Acoustic emission detection method has the advantages of on-line, fast, dynamic, economical and environmental adaptability (especially for some high temperature, radiation, non-contact pipeline valves), and does not destroy the integrity of the valve. Therefore acoustic emission detection has become the main method and research hotspot of leak detection in valve [12].

For valve leakage rate quantification, it is generally estimated by the characteristic parameters of valve leakage acoustic emission signal, the main characteristic parameters include the effective voltage (\( (AE)_{RMS} \)) and average signal level (ASL) etc. \( AE_{RMS} \) is the mean square root value of an acoustic emission signal in the sampling time, with units of V. The formula is:

\[
(AE)_{RMS} = \sqrt{\frac{1}{T} \int_0^T (V(t))^2 dt}
\]  

(1)

\( T \) is the sampling time. For leak detection, the general \( T \) value is 0.5 s~5 s, \( V(t) \) is the time-dependent voltage value.

The ASL is the average value of the acoustic emission signal level in the sampling time, and the unit is dB. The formula is:

\[
ASL = 20 \log \left( \frac{AE_{RMS}}{1 \mu V} \right) - P_{re}
\]  

(2)

\( P_{re} \) is the preamplified gain in dB.

A study shows that the effective voltage (\( (AE)_{RMS} \)) and the average signal level (ASL) is related to the valve leakage rate [3].

\[
(AE)_{RMS} = C_1 \frac{1}{\alpha \rho D^4} \left( \frac{Q}{C_v} \right)^{3/4} P \left( \frac{S}{\Delta P} \right)^{4/3}
\]  

(3)

Because the dipole and quadrupole sound sources are the main noise fields of the jet turbulent flow field, the dipole sound sources are introduced into formula (3) to obtain the (AE)RMS value of the leakage acoustic emission of the valve. The formula is:

\[
(AE)_{RMS} = \frac{(C_1 P_1 + C_2) P_1^3}{\alpha \rho D^4} \left( \frac{Q}{C_v} \right)^{3/4} \left( \frac{S}{\Delta P} \right)^{4/3}
\]  

(4)

\( C_1 \) is the fluid parameters representing the influence of AE sensor, valve material, signal gain, etc., \( \alpha \) is the velocity of sound inside the fluid; \( \rho \) refers to the fluid density; \( D \) refers to the valve size; \( Q \) represents the volume velocity; \( \Delta P \) refers to the pressure drop through the valve; \( P_1 \) represents inlet pressure; \( C_v \) refers to the flow coefficient of the valve; \( S \) represents the specific viscosity of the fluid.
3. Experimental Device and Detection System

3.1. Experimental Platform

Figure 1 shows the schematic diagram of the simulated experimental platform for gas valve internal leakage. The device is mainly composed of an air compressor, gas cylinder, adjustable pressure relief valve, valve, flow meter, pressure gauge, etc. During the experiment, the air compressor is used to inflate the gas cylinder, and the pressure is provided to the system by the gas cylinder; the adjustable pressure relief valve is used to adjust the inlet pressure of the valve to be tested, and the pressure gauge 2 is used to measure and display the inlet pressure of the valve to be tested; the flowmeter 2 is used to measure and display the gas leakage of the valve to be tested; the end of the whole test platform is connected to the atmosphere, and the back pressure is standard atmospheric pressure.

The DN 25 conical globe valve is the valve to be tested in the experimental platform, and the core material of the valve is copper. Because the valve leakage is mainly caused by the valve closure is not tight, and generally occurs in the seat sealing surface, so in the experimental process, there are two ways to simulate the valve leakage. One is to open the valve to be tested slightly, to maintain a certain valve opening degree to simulate the valve leakage (hereinafter referred to as leakage mode 1); the other is to process a certain depth of scratches on the valve core sealing surface, as a fault unit, to simulate the valve leakage (hereinafter referred to as leakage mode 2). In leakage mode 2, the valve to be tested is closed, with one side of the valve being filled with pressure and the other side being connected to the atmosphere.

3.2. Acoustic detection system of valve leakage

Acoustic emission testing apparatus PAC produced by Acoustics Company of USA is mainly composed of acoustic emission sensor, preamplifier, signal acquisition card and industrial computer. The working principle of the leak detection device in the valve is to convert the mechanical wave signal emitted by the valve into a continuous electrical signal through the acoustic emission sensor, and amplify this electrical signal through the preamplifier and then transmit it to the main processor of the detection device, after processing, storage and waiting for subsequent signal display, processing and analysis.

Figure 2 shows the schematic diagram of leakage acoustic emission in gas valve.
(1) Sensors
The sensor is fixed to the pipeline near the valve by winding the film before the experiment. The sensor is a R15a acoustic emission sensor PAC by the United States. The resonant frequency is 150 KHz, the frequency range is 50~400 KHz.

Before fixing the sensor, the surface of the pipeline is polished and cleaned, and the surface of the sensor and the detection surface are coated with acoustic emission coupling agent to ensure good signal transmission.

(2) Signal conditioning and display
The signal collected by the sensor is firstly transmitted into the preamplifier. The preamplifier of this experiment is the type of 20/40/60 dB amplifier, which can realize three kinds dB gain of the signal. The 40 dB gain is selected in the preamplifier.

Signal acquisition card is a PCI-2 card. It is a high performance, low-cost acoustic emission card with two channels, which can simultaneously realize feature parameter extraction and waveform processing. The system has 18 bits A/D conversion rate, 1 KHz-3MHz frequency range, low noise, 40 MHz/18-bit real-time acquisition conversion, real-time AE feature extraction, built-in waveform processing, and built-in AE data flow and so on. After the acquisition of the signal in the industrial control computer, the AEwin™ software can be used to process, display, fast store and replay the AE signals and wave forms, and the real-time AE features of multiple 2-D or 3-D, as well as the plot active wave curves can be selected and viewed. During the experiment, the threshold of detection is set to 40 dB to eliminate the interference of environmental background noise.

4. Experimental results and analysis

4.1. Waveform analysis of acoustic emission signals in valves

Figure 3 shows the time-domain waveform of the acoustic emission signal under leakage mode 1, that is, the valve opening is set to simulate the leakage in the valve. Under this circumstance, the sensor measuring point is located on the right side of the valve (downstream), and the inlet pressure is 0.5 MPa. The abscissa in the figure is time, and the unit is seconds (s); the ordinate is the voltage value, and the unit is mV. The valve is closed during the first section and valve is without internal leakage; the valve is opened during the middle section, which has a certain opening with leakage rate of 0.32 m3/min; Several time later, the valve is fully closed, and the valve has no internal leakage. It can be seen from the diagram that when the valve has internal leakage, the time-frequency waveform of the acoustic emission signal will change, so the waveform diagram of the acoustic emission signal can be used to judge preliminarily whether the valve is leaking or not.
Figure 4 shows the time domain and spectrum of the acoustic emission signal in the simulated valve under leakage mode 2, that is, machining scratch in the valve spool, when the sensor measuring point is located at the center of the valve surface and the inlet pressure is 0.5 MPa. From the diagram, it can be seen that the acoustic emission signal of leakage in the valve is a continuous signal, which belongs to a non-stationary random wide band noise signal, with a frequency range of up to several hundred KHz and a peak spectrum of about 150 KHz.

4.2. Characteristic parameters of acoustic emission signals in valves

Figure 5 shows the effective value voltage (RMS) and average signal level (ASL) of the characteristic parameters of the leakage acoustic emission signal in the valve under leakage mode 1. The experimental working condition is the same as that in figure 1. From the figure, it can be seen that the change trend of the effective value voltage (RMS) and the average signal level (ASL) is the same, which can clearly show the process of valve closing-valve opening-hold opening-valve closing. Therefore, the effective value voltage (RMS) and the average signal level (ASL) are effective for the evaluation of this continuous signal for leakage in the valve and can be used for the detection of leakage in the valve.

4.3. Analysis of the influence of inlet pressure on acoustic emission signals

Table 1 is the change of the parameters of the acoustic emission signal in the valve under different inlet pressure under leakage mode 2 with the sensor measuring point being located in the center position of the valve. It can be seen from the table that with the increase of inlet pressure, the intensity of acoustic emission signal increases, and its amplitude, energy, average signal level (ASL), effective value voltage...
(RMS) increase, but it has little effect on the average frequency of signal, and the peak value of signal is mainly concentrated at about 150 KHz.

Table 1. Changes of acoustic emission signals under different inlet pressures.

| Inlet pressure (MPa) | AE hit number | Amplitude (dB) | Average frequency (KHz) | Power (eu) | ASL(dB) | RMS(V) |
|---------------------|---------------|----------------|-------------------------|------------|---------|---------|
| 0.05                | 1016          | 31             | 132                     | 61         | 23      | 0.001   |
| 0.1                 | 1002          | 46             | 147                     | 393        | 34      | 0.0036  |
| 0.2                 | 1002          | 53             | 148                     | 931        | 40      | 0.0072  |
| 0.3                 | 1025          | 50             | 150                     | 1228       | 42      | 0.0096  |
| 0.4                 | 1010          | 57             | 149                     | 1695       | 45      | 0.0134  |
| 0.5                 | 1002          | 56             | 148                     | 2354       | 48      | 0.0178  |
| 0.6                 | 1007          | 59             | 151                     | 3283       | 51      | 0.0254  |

4.4. Analysis of the influence of different measuring points on acoustic emission signals

Table 2 is the characteristic parameter value of the leakage acoustic emission signal in the valve at different measuring points under the same inlet pressure, as well as the same leakage rate. The measuring point 1 is on the valve upstream pipeline 5 cm; the measuring point 2 is on the valve body; the measuring point 3 on the valve downstream 5 cm, and so on. It can be seen from table 2 that the intensity of the acoustic emission signal of the measuring point 3 is the largest, the measuring point 2 is the second, and the measuring point 5 is the smallest. According to the vortex sound theory, when the fluid flows through the internal leakage valve, there will be vortexes of different sizes downstream, and the intensity of the vortex is directly related to the noise level, the noise downstream of the valve is higher than the noise upstream. Therefore, in the valve leakage acoustic emission sensor layout, the sensors are recommended to be installed on the test valve body or the the downstream pipeline nearby the test valve.

Table 2. Changes of different measuring points of acoustic emission signals in valves.

| Number | Location (cm) | ASL (dB) | RMS (V) | Amplitude (dB) | Power (eu) |
|--------|---------------|----------|---------|----------------|------------|
| 1      | -5            | 66       | 0.1472  | 74             | 19646      |
| 2      | 0             | 69       | 0.2214  | 76             | 15336      |
| 3      | 5             | 69       | 0.1966  | 79             | 25039      |
| 4      | 10            | 64       | 0.114   | 75             | 13620      |
| 5      | 20            | 62       | 0.0898  | 74             | 11675      |

4.5. Relationship between leakage rate and acoustic emission signal

Figure 6 is a diagram of the characteristic parameters of the acoustic emission signal ASL with the leakage rate in the valve under leakage mode 1, where the sensor measuring point is located 5 cm (downstream) on the right side of the valve, and the inlet pressure is 0.5 MPa. Horizontal coordinates are internal leakage rate of valve in m3/min; ordinate is the ASL value of the acoustic emission signal in dB. As can be seen from the diagram, when the leakage rate inside the valve increases, the average signal level ASL increases. Through polynomial fitting, the relationship between the ASL and the leakage rate can be represented by $Y = A + B1*X + B2*X^2 + B3*X^3 + B4*X^4 + B5*X^5$. 
Figure 6. The relationship between characteristic parameters ASL and leakage rate.

Figure 7 is a diagram of the relationship between the effective value voltage RMS of the acoustic emission signal and the leakage rate in the valve under leakage mode 1, where the sensor measuring point is located 5 cm (downstream) on the right side of the valve, and the inlet pressure is 0.5 MPa. Horizontal coordinates are internal leakage rate of valve in m.3/min; ordinate is the RMS value of the acoustic emission signal with the unit of V. As can be seen from the diagram, when the leakage rate inside the valve increases, the effective value voltage RMS increases. Through fitting, the RMS of acoustic emission signal is approximately linear with the leakage rate in the valve.

Figure 7. The relationship between characteristic parameters RMS and leakage rate.

5. Conclusion
(1) The fluid leaking through the valve generates turbulence at the leakage position and downstream piping system, and the continuous broadband noise is generated, which is very similar to white noise. The noise frequency range generated by the leakage is up to several hundred KHz, the leakage noise signal can be detected by acoustic emission sensor.
(2) Through the waveform diagram and characteristic parameters of acoustic emission signal, it can be inferred that the valve internal leakage, especially the effective value voltage (RMS) and the average signal level (ASL) is more effective to decide the valve internal leakage, thus verifying the feasibility of acoustic emission technology in the detection of valve internal leakage.

(3) The amplitude, energy, average signal level (ASL) and effective voltage (RMS) of the acoustic emission signal increase with the increase of the inlet pressure, but the inlet pressure has little effect on the average frequency of the signal.

(4) The selection, installation position, installation and coupling mode of the acoustic emission sensor have certain influence on the receiving and transmission of the acoustic emission signal. It is recommended to install the sensors on the valve center or downstream pipeline nearby the valve. Coupling agent is recommended to ensure the smooth and clean detection surface during installation.

(5) The characteristic parameters of the acoustic emission signal, including the average signal level ASL and the effective voltage RMS increase with the increase of the internal leakage rate of the valve, and the average signal level ASL is fitted to the valve leakage rate by a polynomial of five times, while the effective voltage RMS is approximately linear with the valve leakage rate.

(6) There is a strong correlation between acoustic emission and valve leakage rate. It is recommended that the database of characteristic parameters of acoustic emission detection in valve should be established on the basis of a large number of experiments and engineering tests.

References

[1] Yihan Zhang. Experimental Study on Monitoring Method of Leakage in Valve of Liquid Pipeline. Beijing University of Chemical Technology, 2015.
[2] Tonolini F, Saia A, Villa G. General review of develop in Acoustic Emission methods. International Journal of Pressure vessels and piping, 28 (1987) 179–201.
[3] Kaewwaewnoi W, Prateepasen A, Kaewtrakulpong P. Investigation of The relationship between Internal Fluid Leakage through A valve and Acoustic Emission Generated from the Leakage, Measurement, 43 (2010) 274–282.
[4] A. Prateepasen, Kaewwaewnoi, P. Kaewtrakulponng. Smart noninvasive instrument for detection of internal air leakage of a valve using portable acoustic emission signals, Measurement, 44 (2011) 78-384.
[5] E. Meland, N. F. Thornhill, E. Lunde, et al. Quantification of valve leakage rates, American institute of Chemical Engineers, 58 (2012) 1181-1193.
[6] Guang Dai, Bing Wang, Ying Zhang. Numerical simulation of leakage jet field in gas gate valve, Fluid Machinery, 35 (2007) 29-32.
[7] Bing Wang. Numerical simulation and experimental study of leakage in valve [D] Daqing Petroleum Institute, 2007.
[8] Jing Yang. A Study on Visual Diagnosis Technology of Valve Leakage Based on Acoustic Emission Detection, Changsha University of Technology, 2013.
[9] Qianxia Gao, Luping Li, Hongde Rao, et al. Experimental study on quantitative relationship between valve leakage fault state and acoustic emission signal characteristics, Thermal Power Engineering, 26 (2011) 582-587.
[10] Qianxia Gao. Extraction Technology and Engineering Application of Valve Leakage Fault Feature Quantity, Thermal Power Engineering, 33 (2018) 138-143.
[11] Gongtian Shen. Acoustic Emission Detection Technology and Application, Science Press, 2015.
[12] Guang Dai, Yanting Xu, Li Wei, et al. Application and Research Progress of Acoustic Emission Technology, Journal of Daqing Petroleum Institute, 25 (2001) 95-98.