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Internet of Things Acoustic Emission for Unattended Quantitative Leakage Monitoring

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ABSTRACT

This paper analyzes the theoretical basis of acoustic emission monitoring of leakage in principle. Based on the actual field leakage experiments, the following quantitative relationships are obtained: the quantitative relationship between the amount of leakage and the acoustic emission parameters under the same pressure; the quantitative relationship between different pressures, acoustic emission parameters and leakage rate under the condition of the same valve opening; the characteristic relationship between different leakage openings and acoustic emission parameters under the same pressure difference (tank wall plug). An online experimental demonstration system of leakage rate of water pipes is established. The acoustic emission collector automatically detects the leakage and leakage rates, and transmits the data to the cloud server. After the alarm conditions are set, the alarms will be pushed to the mobile phone if the alarm conditions are met. The cloud server is open for readers to view the results.

Keywords: *acoustic emission, leakage, quantitative, Internet of Things, unattended, alarm*

1. Introduction

Valves and pipelines are widely used in all walks of life, ranging from aerospace industry, marine industry, petrochemical industry to domestic water supply and gas supply. However, in the long-term effects of erosion and corrosion in valves and pipelines, it leads to the untight seals in valves and the reduced wall thickness, which often occurs leakage accidents. Although conventional detection methods (such as direct observation method, flow balance method, negative pressure wave method, operating pressure method, etc.) have been widely used, their deficiency is that they rely on professionals to go for the site inspection, and need to scan point by point or even need to dig and check the buried pipeline, which involves high labor intensity and low work efficiency.

As one of the important branches of the applications of acoustic emission (AE) technology, acoustic emission leakage detection technology has been widely recognized in recent years due to its advantages of dynamic, high sensitivity and wide coverage. However, the current technology and equipment still rely on acoustic emission technical experts to analyze acoustic emission data in order to determine whether and how much leakage there is. Thus it limits the wide range of industrial applications of this technology. This paper analyzes the theoretical basis of acoustic emission monitoring of leakage in principle. Based on the actual field leakage experiments, the following quantitative relationships are obtained: the quantitative relationship between the amount of leakage and the acoustic emission parameters under the same pressure; the quantitative relationship between different pressures, acoustic emission parameters and leakage rate under the condition of the same valve opening; the characteristic relationship between different leakage openings and acoustic emission parameters under the same pressure difference (tank wall plug). An online experimental demonstration system of leakage rate of water pipes is established. The acoustic emission collector automatically detects the leakage and leakage rates, and transmits the data to the cloud server. After the alarm conditions are set, the alarms will be pushed to the mobile phone if the alarm conditions are met. The cloud server is open for readers to view the results.

2. Acoustic Emission Principles and Theoretical Basis of Leakage Monitoring

The principle of acoustic emission signals produced by leakage is that when the medium is ejected from the gap due to pressure difference to form turbulent flow, the medium in the turbulent flow has impact and friction with the sealing surface of the medium, which stimulates the elastic stress waves. The signal strength and frequency range of the elastic stress waves are closely related to the turbulent velocity of the medium, which is pressure difference, the leakage rate, the valve medium and the structures. The generated leakage signals propagate along the pipe walls and in the medium. When the acoustic emission sensor is coupled on a reasonable position on the surface of the pipe, the signal can be received. The piezoelectric effect of the sensor is used to convert the elastic wave signals into voltage signals, which are then amplified, analyzed and displayed by the acquisition AE equipment.

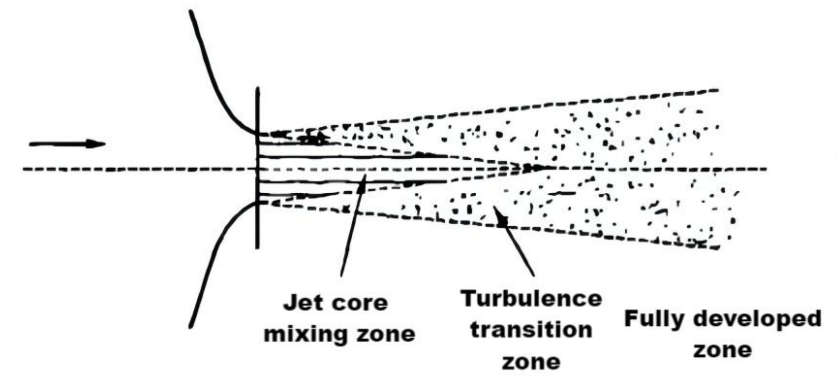


Fig. 1: Pipe jet leakage model

Typical leakage signals have continuous and random non-stationary characteristics and their frequency distribution has an obvious steep peak, so that it has a certain anti-interference ability. It can be seen from the jet leakage model that the leakage signals are mainly generated in the turbulent mixing zone and the transition zone. The high frequency frictional impact signals are mainly generated near the leakage outlet while the low frequency oscillation signals are mainly generated in the position far from the leakage outlet. Generally speaking, the larger the leakage amount, the greater the energy density of the acoustic emission signals generated from the leakage. When the pressure difference increases, the impact sound caused by the leakage blockage will be generated, which is much higher than the turbulence signals, and these signals can be used as meaningful signals for detection.

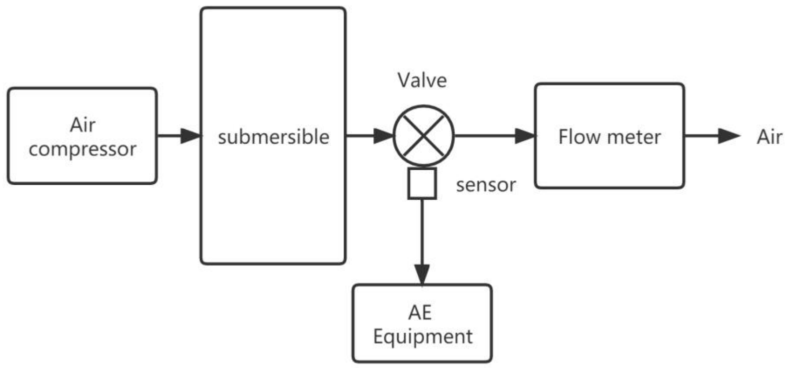
When the gas or liquid leaks from the leak hole under a certain pressure, continuous mechanical waves are stimulated at the leak hole. When the acoustic emission waveform stimulated by the leak is observed by the oscilloscope, its shape is continuous waves with small amplitude fluctuation without following any patterns. The frequency band distribution of leakage acoustic emission wave varies from several Hz to several hundred kHz depending on the size of the leak hole, the leakage speed and the leakage medium. The suitable acoustic emission sensors are chosen to receive the acoustic emission waves from leaking location, then the mechanical waves are transformed into electrical signals followed by amplification and then are transmitted to the acoustic emission host equipment. After signal processing and analysis, the amount of leakage information is obtained. After the appropriate threshold is set, when the AE signal reaches the threshold, it outputs an alarm. Through the Internet of Things (IoT) communication, the amount of leakage and the alarming AE parameters are transmitted to the Internet cloud platform, following by pushing the messages to the administrator user terminals, to achieve the purpose of intelligent alarming for unattended quantitative leakage monitoring.

3. Quantitative Experiments of Acoustic Emission Leakage

3.1. Experiment Background Introduction

The experiment was carried out at a submersible manufacturing company in Shenzhen. The submersible, the external valve and the flow meter used in the experiment are shown in Figure 2 and Figure 3. There is enough volume inside the submersible to pump air at a certain pressure, so that the pressure can be stabilized in a small range for the subsequent leakage tests. The valve inspected is a ball valve, whose nominal diameter is 15 mm. There is no leakage when the valve is completely shut. A gas flow meter is connected to the rear end of the valve to quantify the leakage rate.

The SAEU3H-4 digital acoustic emission detector from Qingcheng AE Institute (Guangzhou) was used in the experiment, with the compatible acoustic emission sensors, coaxial cables, acquisition AE cards and the analysis software to form the whole acoustic emission detection system. The acoustic emission sensor was the SR40M resonant sensor (the center frequency was 40 kHz and the frequency range was 15 kHz-70 kHz), and the external preamplifier had 40 dB gain. Details were shown in the figures below. The pencil lead breaking sensitivity test was 99 dB.



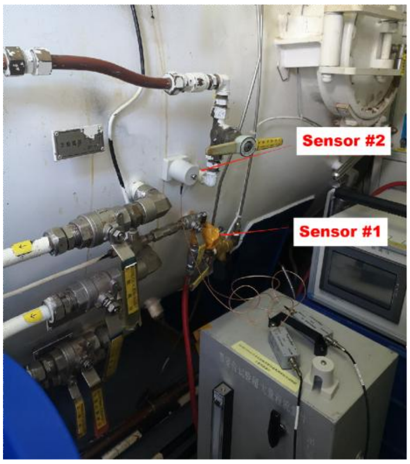


Fig. 2: Experiment connection and the field picture

Table 1: Acquisition settings

Sampling rate 1000kHz	EET: 30ms	Filter 20kHz~400kHz
HDT: 300us	HLT: 1000us	Threshold 23dB

3.1.1. Quantitative relationship between different leakage amounts and acoustic emission parameters under the same pressure difference

Tank gauge pressure: 0.1 MPa.

Kept the acoustic emission equipment sampling the signals continuously. Different valve openings were obtained by manually turning the ball valve, and the leakage rate was measured by the flow meter. The flow meter remained stable in the following stages: 0 L/h - 42 L/h - 64 L/h - 310 L/h - 540 L/h - replacing with a large range flow meter - 650 L/h - 430 L/h - 230 L/h - 110 L/h - 38-6 L/h - 1.7 L/h - 0 L/h.

The leakage rate ranged from 0 to 650000 mL/h in a continuous process, and the relationships between the leakage and acoustic emission were shown in the figures below:

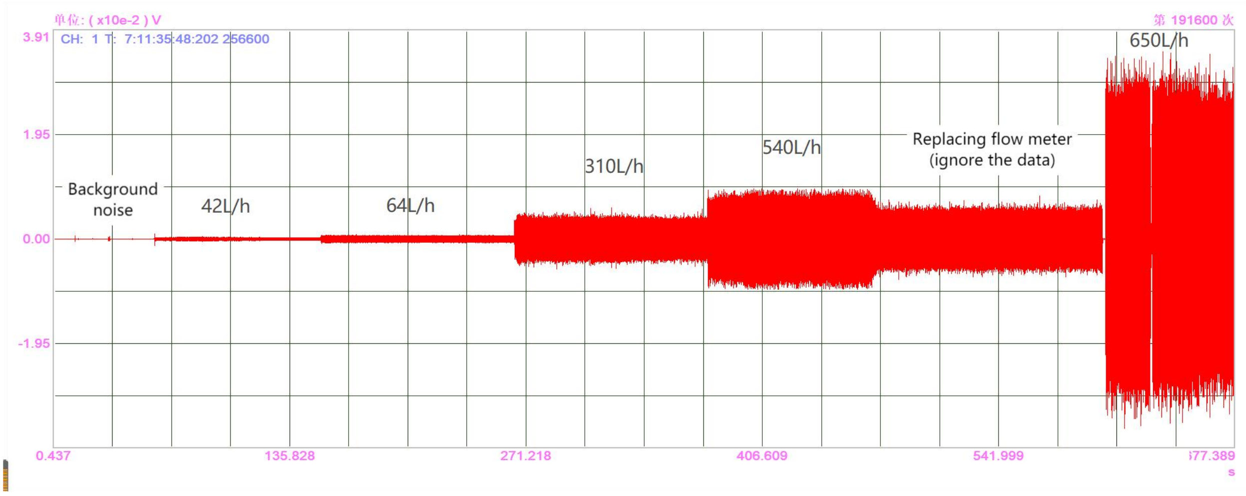


Fig. 3: Continuous waveform in time domain (different leakage rates at the same pressure)

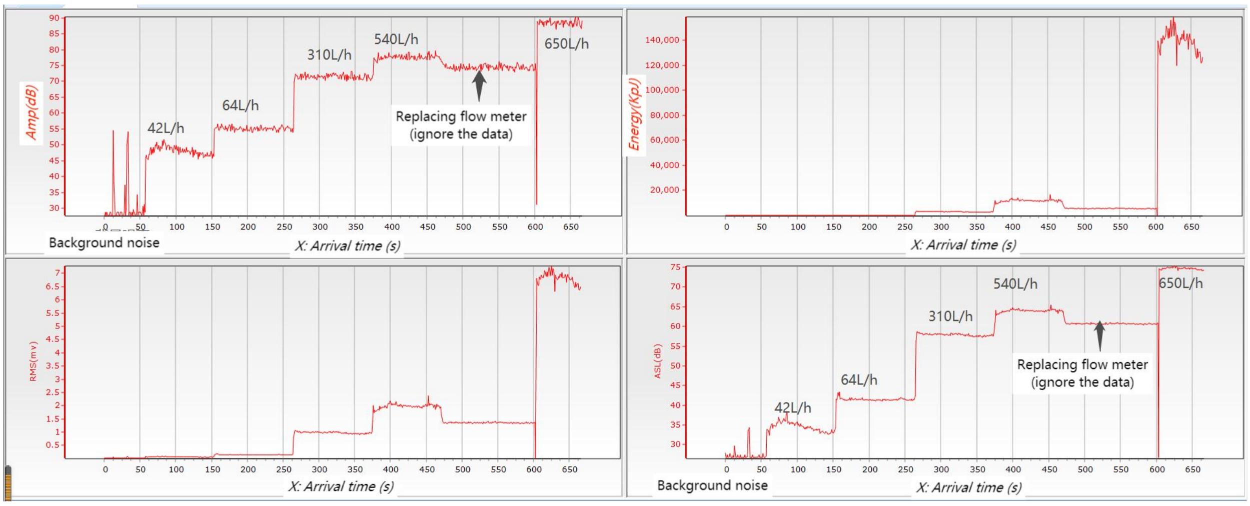


Fig. 4: Different AE feature parameters in time domain under different leakage rates

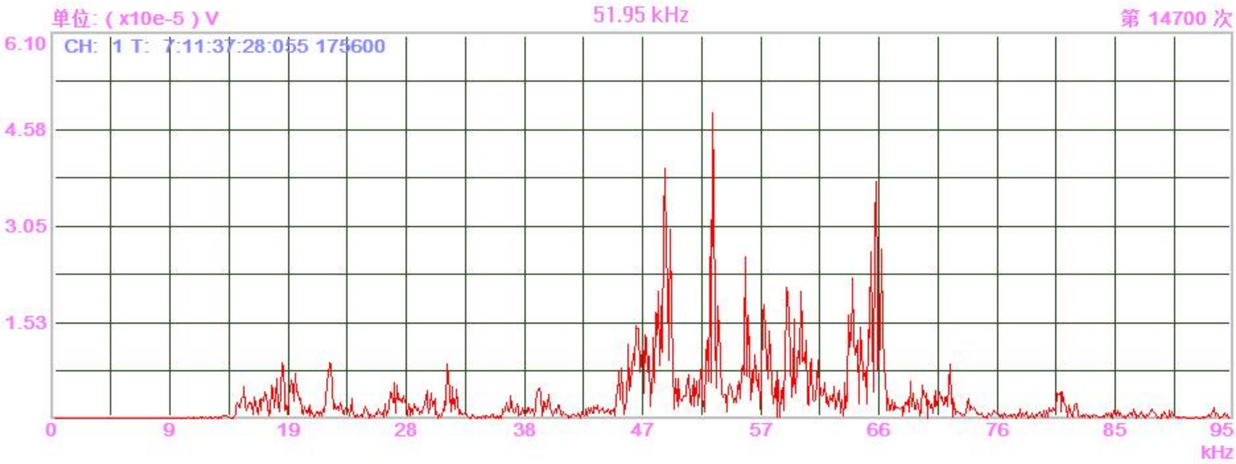


Fig. 5: Typical frequency domain view of leakage

Statistical AE characteristic parameters at each stage are shown in the following table:

Table 2: Different leakage rates and AE characteristic parameters

No.	Leak rate (mL/h)	Wave Amp. (mV)	Amp. (dB)	Counts	Energy (KpJ)	RMS (mV)	ASL (dB)	Freq. Range (kHz)
1	0	±2 (burr)	26.6-30	1-80	0-1	0.007-0.023	14-25	40-60
2	42000	±26	46-51	1530-1680	9-22	0.055-0.085	33-37	40-60
3	64000	±54	54-56	1600-1700	65-75	0.14-0.16	41-43	40-60
4	310000	±420	68-72	1700-1800	2500-3200	0.95-1.05	57-58	40-60
5	540000	±900	76-79	1750-1850	11000-13000	1.9-2.1	64-65	40-60
6	650000	±3000	85-90	1300-1450	120000-140000	6.5-7.5	74-76	40-60
7	430000	±820	72-76	1750-1850	8000-10000	1.7-1.85	62-63.7	40-60
8	230000	±600	70-74.5	1560-1724	4680-6480	1.25-1.46	60-61.1	40-60
9	110000	±300	63-70	1733-1800	1440-1980	0.7-0.8	54.9-56.3	40-60
10	38000	±102	56-60.7	1656-1756	138-185	0.21-0.25	44.6-46	40-60
11	6000	±6.1	38-45	1390-1560	3.3-8.8	0.035-0.045	29.2-30.7	40-60
12	1700	±4.2 (burr)	26.6-44	1-1529	0-8.3	0.006-0.2	11-32	40-60
13	0	±2 (burr)	26.6-30	1-80	0-1	0.007-0.023	14-27.4	40-60

The above data were drawn as follows: X axis (leakage rate) - Y axis (acoustic emission parameters) coordinate scatter diagrams:

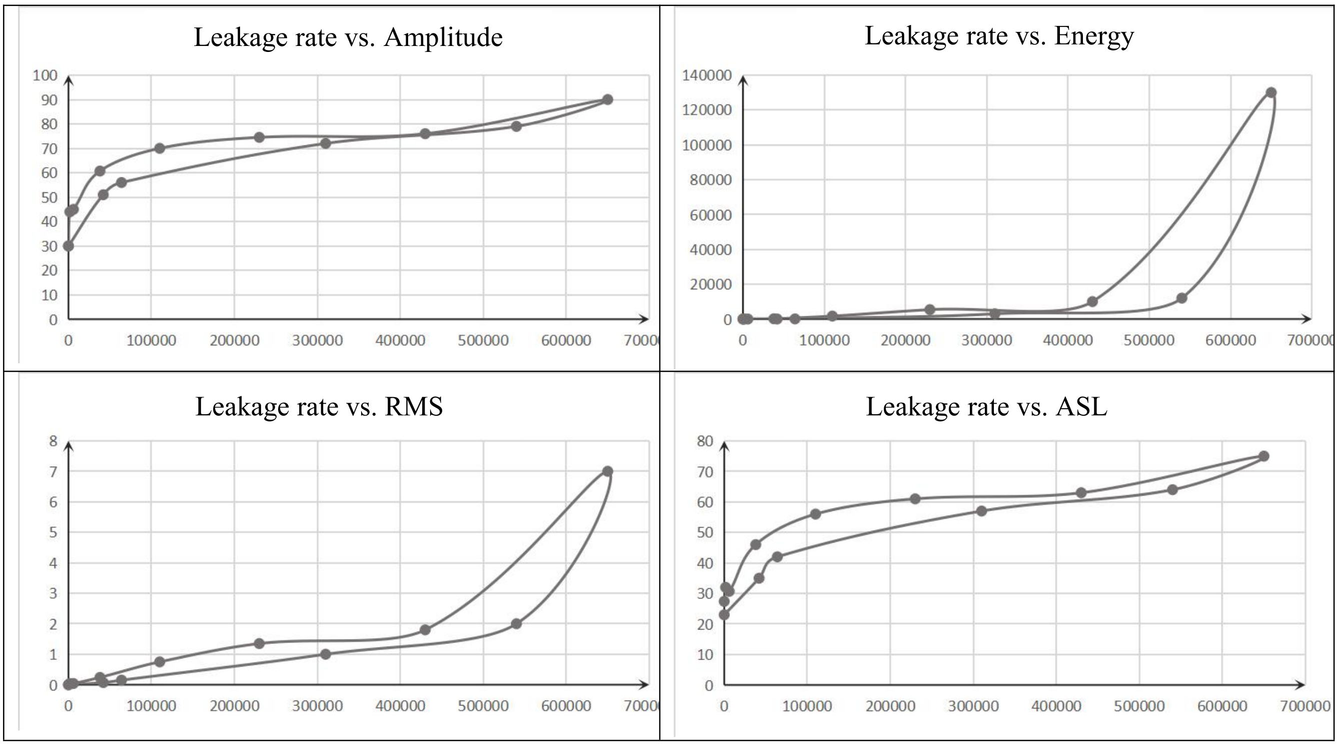


Fig. 6: Correlation graphs of different leak rates and AE characteristic parameters

Note that since the leakage rate from 540 L/h to 650 L/h was replaced with a large-range flow meter and there was some deviations between the flow meters, the 0-650 curve could not be completely consistent with the 650-0 curve. With the leakage pressure differences, the trending (slopes) was basically the same.

3.1.2. Quantitative relationship between different leakage amounts and acoustic emission parameters under the valve openings but different pressure differences

The valve opening was kept consistent throughout the process. The leakage rate was measured by the flow meter. The pressure in the tank increased to different pressures, and it was gradually reduced from high to low through other exhaust ports to maintain at several stable pressure stages: 0.42MPa, 0.31MPa, 0.21MPa, 0.1MPa, 0.05MPa, 0.02MPa, 0.02MPa (the valve was closed).

The continuous process diagrams were: (arrows showing the decompression process, and the value was not for reference)

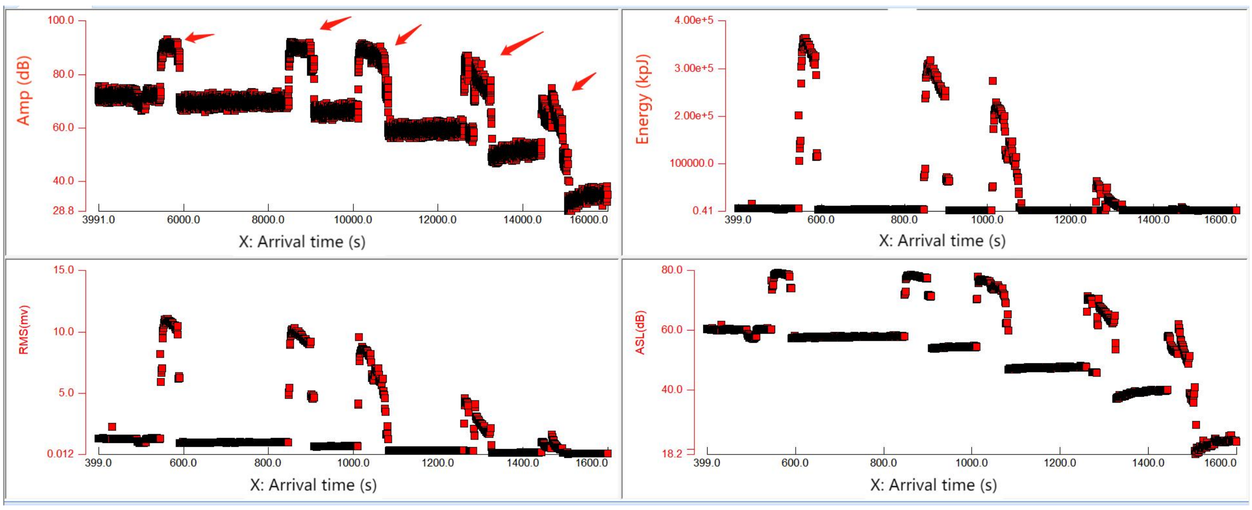


Fig. 7: Continuous waveform in time domain (same valve openings but different pressures)

After filtering processes, the following graphs were obtained:

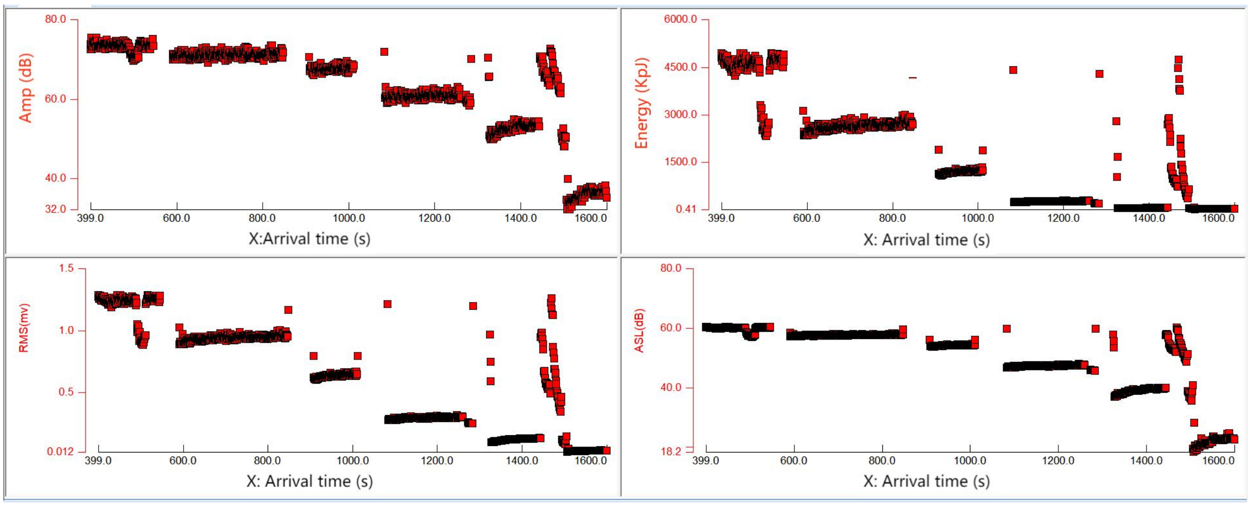


Fig. 8: Continuous waveform in time domain (same valve openings but different pressures) after filtering

The tank pressure, leakage rate and acoustic emission parameters at each stage are shown in the following table:

Table 3: Different leakage rates and AE characteristic parameters under same valve openings but different pressure

No.	Tank pressure (MPa)	Leakage rate (L/h)	Amplitude (dB)	Energy(KpJ)	RMS(mV)	ASL(dB）
1	0.42	286	72-75	4300-4800	1.2-1.3	60-61
2	0.31	227	69-72	2300-2700	0.85-0.95	56-58
3	0.21	168	65-68	900-1100	0.58-0.62	53-54
4	0.1	110	58-63	0.3-250	0.28-0.33	46-47
5	0.05	71	50-55	0.01-40	0.09-0.12	37-40
6	0.02	38	33-38	0.001-1	0.01-0.05	19-25
7	0.02	0	28-30	0-1	0.007-0.023	14-25

The above data were drawn as follows: X axis (leakage rate) -Y axis (acoustic emission parameters) coordinate scatter diagram:

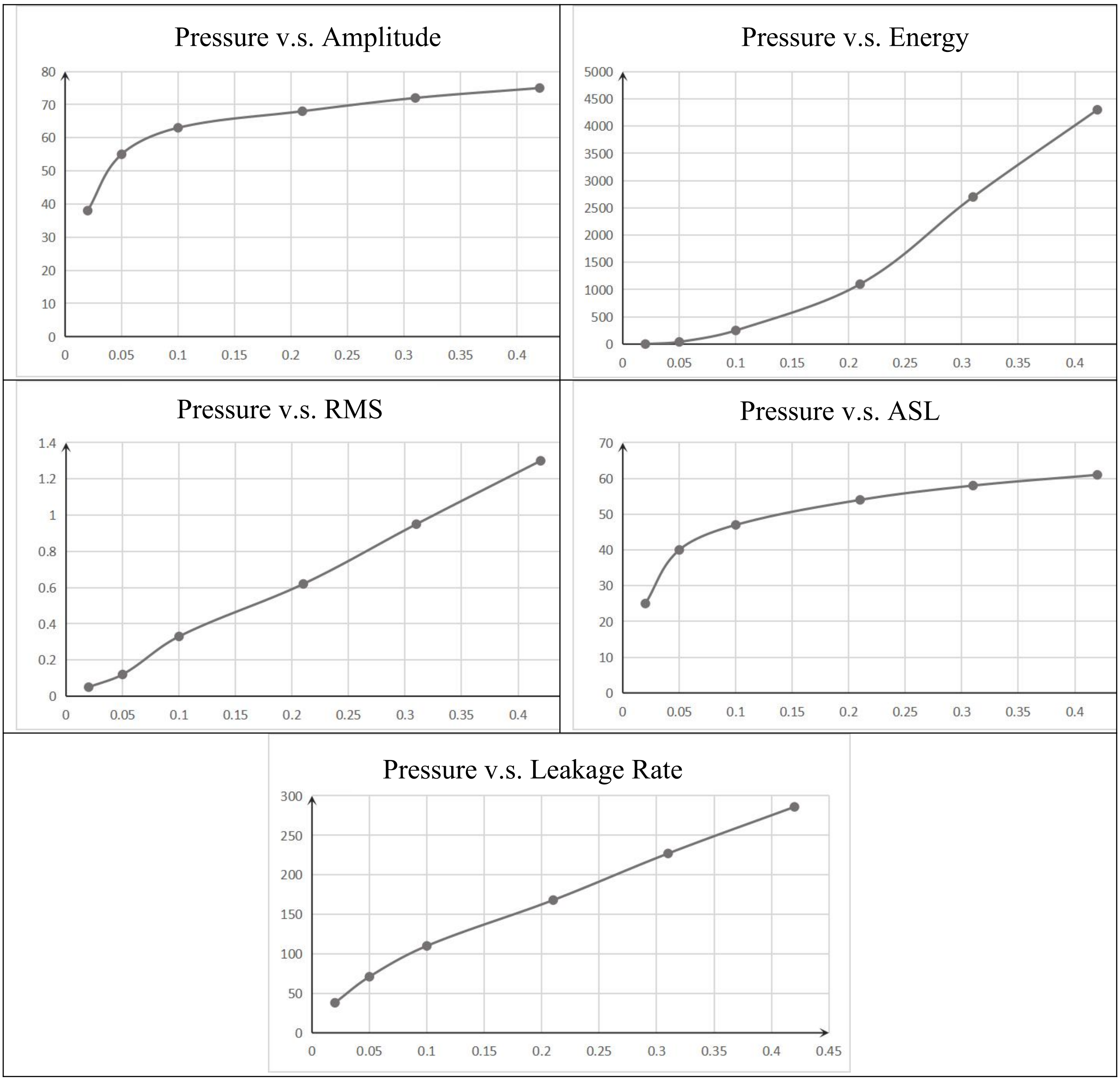


Fig. 9: Correlation graphs of different pressures and AE characteristic parameters

3.1.3. Tank wall plug: The relationship between different leakage openings and acoustic emission parameters under the same pressure difference

The tank was filled with 0.1 MPa air pressure. The test object was the plug on the outer wall of the container. By rotating the plug at different angles, the gas was seeped from the plug gap. The approximate leakage situation could be known through air bubbles (when collecting signals, the bubbles on the plug would be wiped dry to eliminate the interference signals generated by bubble rupture). The sensor was positioned at 1 meter away from the plug. This experiment was a qualitative experiment of leakage. Rotating the plug at a small angle made the gas leak slightly, or a little larger amount. They would be compared with when there was no leakage, as shown in the figures below.

Fig. 10: Plug and when it leaked slightly

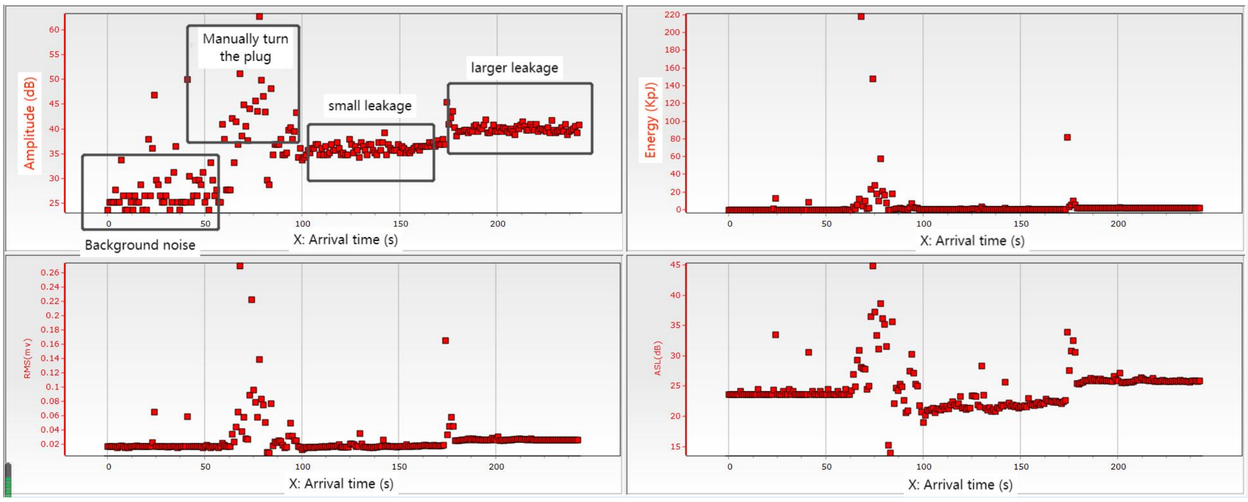


Fig. 11: Plug leakage experiment whole process correlation graphs

3.1.4. Summary of the experiment

1) The leakage was located near the valve spool. The closer the sensor was to the spool, the stronger the leakage signal was. So the best installation position of the sensor was near the spool;

2) Low frequency sensors (15-70khz) could be used for gas leakage signals;

3) Under the same pressure, the larger the leakage rate was, the larger the acoustic emission parameters (amplitude, energy, RMS, ASL) were. The amplitude and ASL increased rapidly in the front segment and slowly in the back segment, while the energy and RMS increased slowly in the front segment and quickly in the back segment.

4) Under the same leakage aperture: pressure was basically proportional to the leakage rate; Pressure was basically proportional to RMS. The relationship between pressure and amplitude: with the increase of pressure, the amplitude increased rapidly at first, then became slowly; The relationship between pressure and energy: with the increase of pressure, energy rose slowly at first, then rapidly; The relationship between pressure and ASL: with the increase of pressure, the amplitude increased rapidly at first, then slowly;

5) Energy, RMS and ASL could all be used as the criterion of leakage quantification, and ASL was the best.

6) Plug (pipeline leakage) qualitative judgment of leakage acoustic emission characteristics were obvious. Even 1 meter away from the leak source, it could still distinguish a very small leakage signal (the foam bubbles determined that the leakage was very small. The foam bubbles needed to be wiped dry during measurement);

7) Medium, pressure difference, leakage aperture size, sensor installation position and other factors directly affected the acoustic emission characteristics of valves and pipelines, which need to be calibrated on site. Once calibrated, they will be used for life.

4. Online water pipe quantitative leakage demonstration experimental system

4.1. System Introduction

As shown in the figure below, the faucet and water pipe were used to generate leaks, and the sensor was installed next to the faucet. The RAEM1 acoustic emission remote system from Qingcheng AE Institute was applied. The collector body was a small aluminum alloy shell cylinder. It was an intelligent IoT AE system integrating AE signal acquisition, analysis, storage with communications networking. It adopted the Linux system which was a long-term stable operation including watch-dog function and it was suitable for unattended monitoring for a long time. The collector collected signals and automatically determined whether there was leakage and the amount of leakage, and then transmitted them to the cloud server through 4G. Users could log in to the cloud server to view real-time and historical parameters, or set alarm push to mobile phones.

The collector was set: sampling frequency: 1000kHz; the EET: 30ms; HDT 300us; HLT 1000us; threshold 30dB; Sensor resonant frequency 35kHz and frequency range 15khz-70khz.

The schematic diagram and equipment layout were shown below:

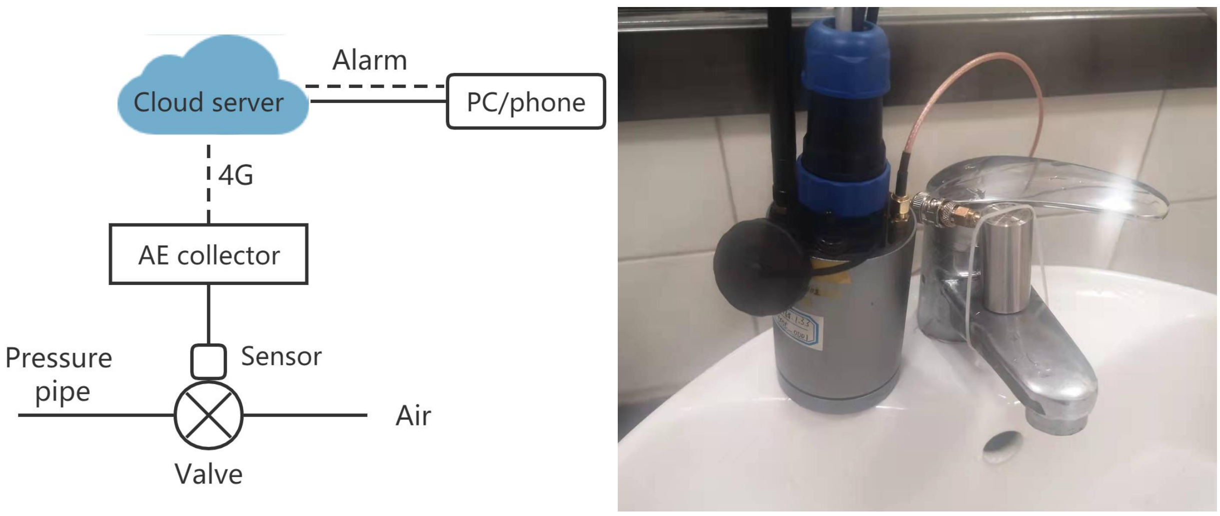


Fig. 12: Online water pipe quantitative leakage experiment system

4.2. Experiment calibration

Opened the faucet at different angles and connected the leaked fluid with a measuring cup. The relationship between the leakage rate and ASL was shown in the following table:

Table 4: Faucet leakage rate calibration

No.	Leakage rate (L/H)	ASL (dB)
1	0	32
2	8.5	38
3	18	47.8
4	29.5	53.2

Plot the scatter diagram as shown below:

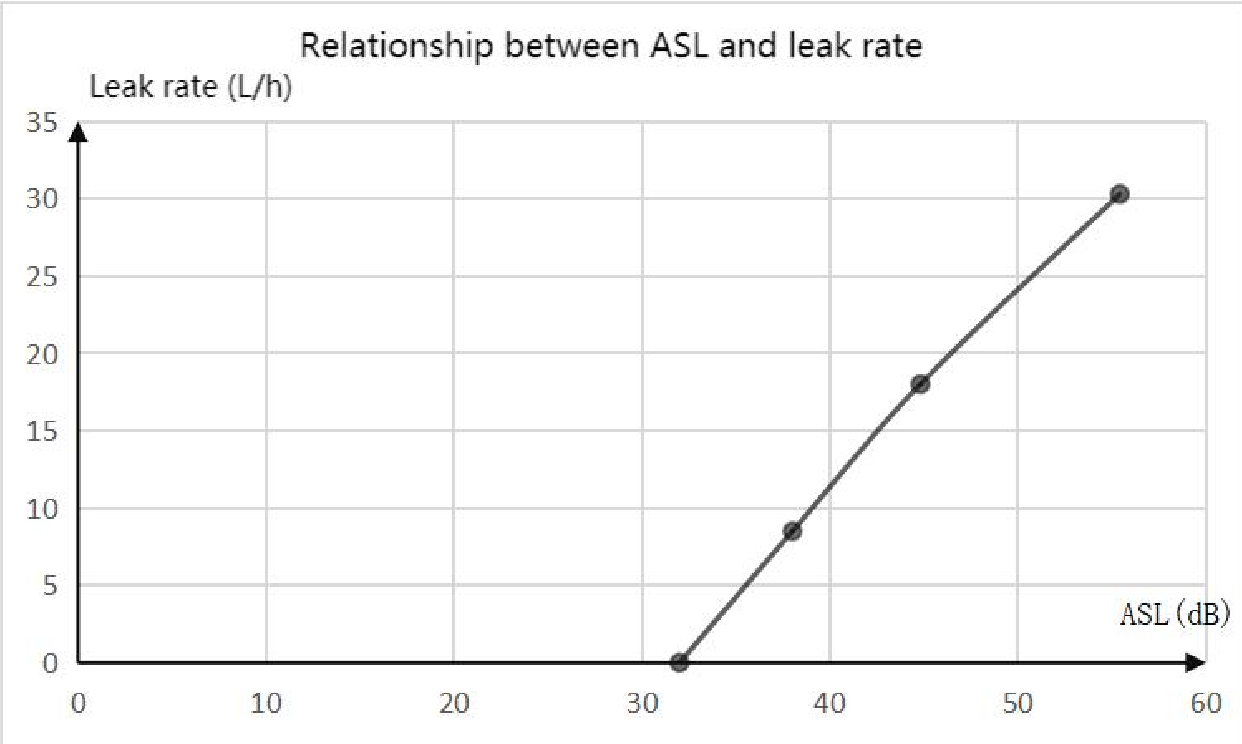


Fig. 13: Correlation graph of faucet leakage rate and ASL

According to the figure above, ASL and leakage amount basically have a straight slope. Let the leakage amount be:

$$L = k \times ASL + b$$

No. 2 and No. 3 data were k =1.4 and b = -44.7. Therefore, the relationship between leakage amount and ASL is

$$L = 1.4 \times ASL - 44.7$$

When the above formula was set to the collector, the collector could calculate the leakage amount and transmitted the leakage parameters to the cloud platform through 4G to achieve quantitative online leakage monitoring.

4.3. On-line quantitative leak monitoring

Logged in to the cloud server to view real-time data. Below was the open cloud server for long-term online monitoring where the readers could access to view data at any time. (url: https://signin.aliyun.com/login.htm#/main; Account: qc@1269046717299274.onaliyun.com; Password: qc123456). As shown in the figure below, it could be clearly seen the time when the leakage occurred and the corresponding leakage rate.

Fig. 14: Cloud server historic leakage amount

The appropriate alarms were set. The setting rules of this demonstration were as follows: 1L/H≤ leakage ≤10L/H output level 2 alarm; 10L/H≤ leakage ≤20L/H output level 3 alarm; 20L/H≤ leakage ≤30L/H output level 4 alarm; 30L/H≤ leakage ≤10L/H output level 5 alarm. For example, the setting of level 3 was as shown below.

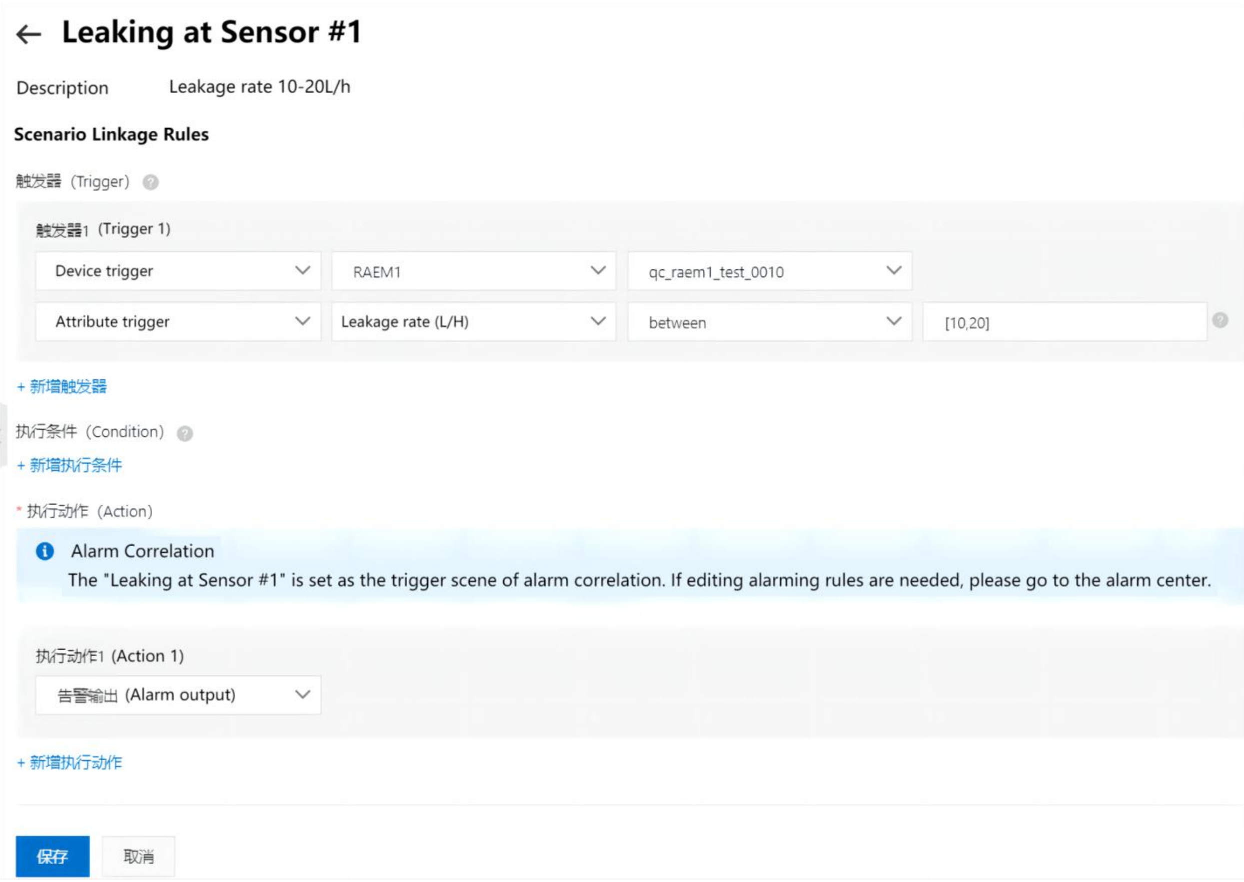


Fig. 15: Set proper alarm

When the alarm condition was reached, the system pushed the alarm information to the mobile phone. You could also log in the server through the mobile phone/computer to view and process the historical alarm information, as shown in the picture below.

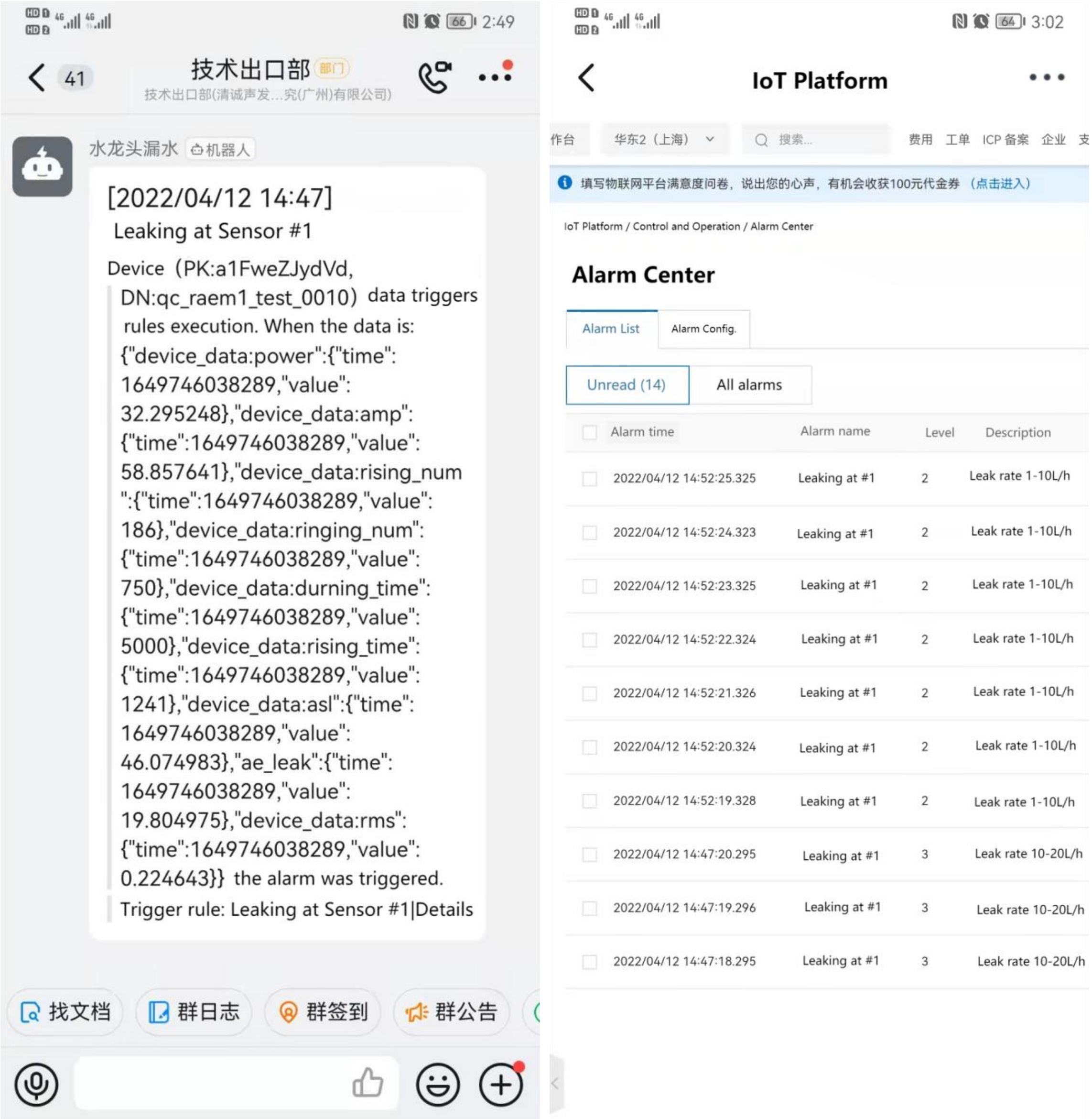


Fig. 16: Alarms on the phone or cloud server

5. Conclusions

The AE equipment of the Internet of Things can automatically control data collection, data analysis and automatic alarm pushing through embedded software and hardware to achieve long-term unmanned quantitative leak monitoring. Through automatic data processing, massive acoustic emission data can be converted into simple and understandable leakage levels, which can eliminate the trouble that traditional acoustic emission technology relies on professionals to analyse acoustic emission data, so that users who do not understand acoustic emission can quickly get started. Moreover, the data processing is centralized in the collector, and only a small amount of data is output/uploaded, which can effectively reduce the requirements of data communication speed and equipment cost. Its advantages of long-term stable operation, automatic alarm, quantitative monitoring and low equipment/operation cost are of great significance to industrial applications.

6. References

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