

## CHAPTER 5 INTERNAL VALVE LEAKAGE RATE MEASUREMENT

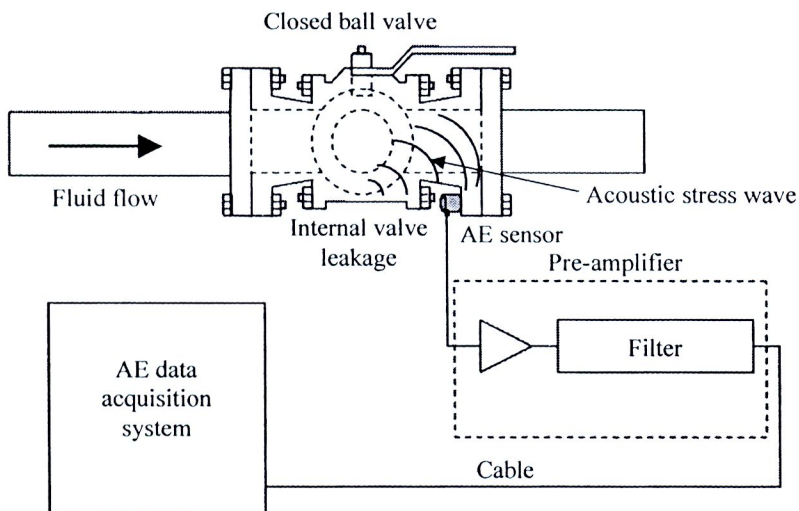
This chapter presents the experiment procedures, results and discussions of the internal valve leakage rate measurement in the laboratory and in the field work. The home-built AE sensor made from chapter 4 is applied to the internal valve leakage rate measurement system. A system calibration is applied, using an air jet as the artificial AE source. A method for transferring information between different AE sensors is also proposed. The detail is shown follow.

### 5.1 Introduction of Internal Valve Leakage Rate Measurement

The better information on fluid leakage for internal valves used in the petrochemical industry is needed for optimising maintenance plans and reducing expenditures. AE is one convenient method that can be used to measure leakage rate. The surface acoustic waves generated from the fluid turbulence are converted to an AE signal that is then used to predict leakage rate. In this section, the internal valve leakage rate measurement using AE is studied. The details of AE testing system in internal valve leakage rate measurement are described as follow.

#### 5.1.1 System for Internal Valve Leakage Rate Measurement Using AE

For valve leakage, high frequency components of the AE signal emitted from the leakage are attributed from turbulence flow of fluid inside the valve passing the valve seat (McIntire, 1987). The diagram is shown in figure 5.1.



**Figure 5.1** System of AE testing for internal valve leakage rate measurement

This is because the movement directions of fluid particles are in a disorderly manner and there are changing of momentums from one part of the fluid to another. As a consequence, constant crashing of particles at high velocities generates high frequency components of the continuous acoustic wave. The signal normally has its frequencies ranging from 100 kHz to 1MHz (Pollock and Hsu, 1982).

For a continuous AE signal in time and frequency domains, the most frequently used AE parameter is the average energy of the AE ( $AE_{rms}$ ), which is the root-mean-square value of the AE signal. Since AE activity is attributed to the rapid release of energy in the material, the energy content of the AE signal is directly related to this energy release.

The relationship between  $AE_{rms}$  and valve leakage rate is selected as the subject to be transferred to another system. As shown in the previous research (Kaewwaewnoi et al., 2005; Kaewwaewnoi et al., 2007; Kaewwaewnoi et al., 2010),  $AE_{rms}$  exhibited a relationship with valve leakage rate. An experiment was conducted using three sizes of ball valve of diameter 25.4, 50.8 and 76.2 mm and inlet pressure between 100-500 kPa. The experiment resulted in the relationship shown as.

$$\log(Q_{AE}) = 1.782 \log(AE_{rms}) - 0.543 \log(P_{AE}) + 0.320 \log(S_{AE}) - 3.550 \quad (5.1)$$

where  $Q_{AE}$  is the leakage rate in ml/sec,  $P_{AE}$  is the inlet pressure in  $10^{-2}$  kPa (bars), and  $S_{AE}$  is the valve size in 1/25.4 mm (inches).

The relationship between leakage rate and average energy of AE signal ( $AE_{rms}$ ) is used to predict leakage rate and was determined both by an empirical regression and a theoretical model. The equation is based on a reference AE sensor, which has a frequency response that can differ significantly compared to other AE sensors. As a consequence, changing an AE sensor can produce a large prediction error when using these leakage rate equations. Therefore a time-consuming calibration process must be performed to acquire the correct parameters for the leakage rate equations. However, when a part of the AE system was changed, equation 5.1 is not transferable.

### 5.1.2 Character of AE Source and Wave Propagation

The AE signals received from sensors are elastic energy waveforms generated from intrinsic sources (turbulence flow of fluid) and propagated through valve body and couplant into AE sensors.

From aperture effect subsection (see subsection 3.1.3), if the sensor is in the near vicinity of AE source and multiple reflections of the AE signals occur within the specimen, a diffuse wave field is produced. For this application the aperture of the sensor is of no significance due to the diffuse wave field.

## 5.2 Experimental Producers of Internal Valve Leakage Rate Measurement

The experiment producers are divided into six subsection: i) using the air jet to calibrate the sensitivity of AE sensors and AE spectra ii) using the AE sensors to measure the internal valve leakage rate (artificial air leakage) to find out AE spectra iii) comparison of AE spectra between air jet and leakage iv) computation of the transfer function between AE sensors v) applying the transfer function to measure the internal valve leakage rate (air) in the laboratory and vi) applying the transfer function to measure the internal valve leakage rate (natural gas) in the field work. The detail of each subsection is explained as follow.

### 5.2.1 Using the Air Jet to Calibrate AE Sensors and AE Spectra

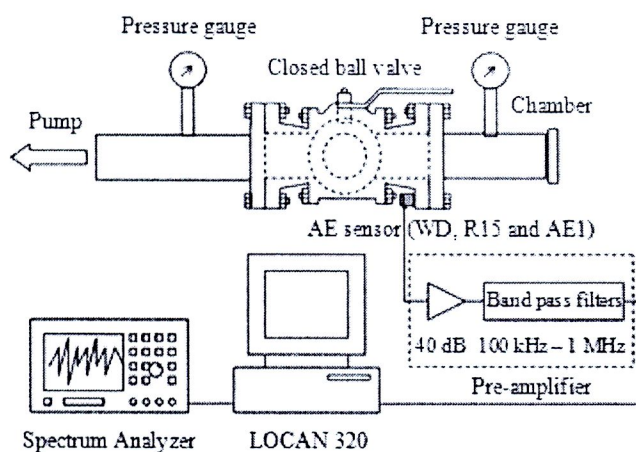
For the air jet, the air supply system that drove the air jet calibration rig is shown in the block diagram of figure 4.3. A nozzle with a 0.5 mm diameter bore is placed normal to the 25.4 mm internal ball valve side at a fixed distance of 5 mm. The air pressure is varied from 300 to 500 kPa in increments of 50 kPa.

The AE sensors are mounted in the same vicinity, near the downstream side of the valve, as illustrated in figure 5.2. The three AE sensors are the wide band (WD) sensor, the resonant (R15) sensor from PAC (Physical Acoustics Corporation), and a third sensor we call AE1. The application of appropriate couplant is one of the most important factors in applying an AE measurement. A couplant of the same type is applied using a standard procedure.

The signals are amplified by 40 dB using pre-amplifiers fitted with a 100 kHz – 1 MHz band-pass filter. Output signals from the pre-amplifier are fed into the amplifier and analyser, a LOCAN 320, set at a gain of 20 dB, and recorded by a real-time signal analyser HP 89410A (with a sampling rate of 10 MHz). The spectrum in the frequency span from 0 to 1 MHz is recorded using 401 sample points and is averaged over 500 samples.

### 5.2.2 Measurement of the Internal Valve Leakage Rate and AE Spectra

The experiments are designed to investigate the transferability of the relationship obtained from a system using one type of AE sensor to another. Variation in operating conditions including leakage rate, size of valve, and inlet pressure is also examined. The test system is set up as illustrated in figure 5.2. To compare the ratio and find the correlation between the AE spectra of the artificial AE air jet and the valve leakage rate, the WD, R15, and AE1 sensors are mounted in the same place, near downstream side of the valve. The AE sensor mounting and signal setup are the same as used in the air jet calibration (subsection 5.2.1).



**Figure 5.2** A diagram of the experimental set-up

An air compressor is used to generate the system pressure, which is then kept steady by a regulator. The valve leakage rate is determined from the differential pressure of a

known volume chamber. A high-precision pressure gauge with resolution of 5 kPa is used for monitoring the chamber's pressure. In these experiments, artificial leaks from incomplete closure of ball valve are used to simulate the leakage. The tests are conducted by varying leakage rate for on a 25.4 mm ball valve at inlet pressure from 300 to 500 kPa in three valve leakage rate of 100, 130 and 160 ml/sec, respectively.

### 5.2.3 Comparison of AE Spectra between Air Jet and Artificial Leakage

In this study, a constant frequency response ratio in the form of the RMS spectrum is presented to make information transferable between systems using different AE values (see section 4.2 and 3.6.4: calibration system and transferable system, respectively). This ratio can be defined as

$$AE_{rms} = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} V^2(t) dt} = \sqrt{\frac{1}{N} \sum_{n=1}^N V^2(n)} \quad (5.2)$$

where  $V$  is the voltage signal from the AE sensor,  $t$  is the initial time,  $T$  the integration time of the signal, and  $N$  the number of discrete AE data samples within the interval  $T$ .

For comparison of the AE spectra between air jet and valve leak rate, an  $n$ -point RMS discrete AE spectrum can be thought of as a vector  $u'$  defining a point in the  $n$ -dimensional vector space. By analogy with vectors in the three-dimensional space, the length squared of  $u'$  is the inner product of  $u'$  with itself. Thus, the length of  $u'$  can be computed from

$$|u'| = \sqrt{u' \cdot u'} = \sqrt{\sum_{k=1}^n u_k^2} \quad (5.3)$$

where  $|u'|$  is the length of an  $n$ -point RMS discrete spectrum, and  $u_k$  is a point in an  $n$ -dimension vector space.

This length  $|u'|$  gives the overall  $AE_{rms}$  of the AE signal. The vector  $u'$  can be normalised by dividing its elements by the length of the vector. Thus a normalised vector, denoted by  $\bar{u}$ , can be computed from

$$\bar{u} = u' / |u'| \quad (5.4)$$

Given two normalised vectors,  $\bar{u}$  and  $\bar{v}$ , in the  $n$ -dimensional space, the included angle  $\theta$  between them is related to the inner product of  $\bar{u}$  and  $\bar{v}$  as

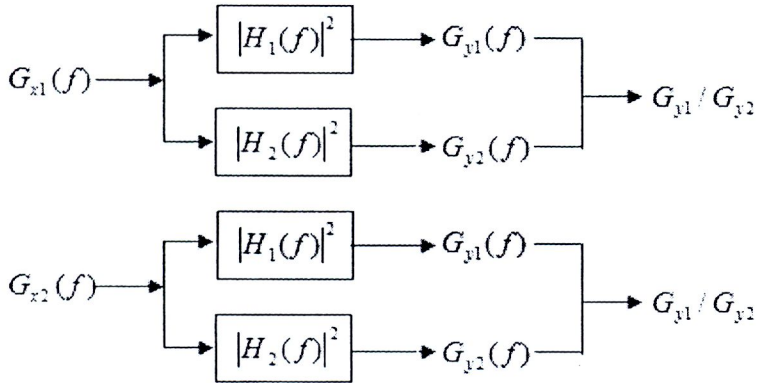
$$\cos \theta = \bar{u} \cdot \bar{v} \quad (5.5)$$

where  $\cos \theta$  is called the similarity coefficient. When the similarity coefficient is one, the two unit vectors  $\bar{u}$  and  $\bar{v}$  point are in the same direction, which means that the two corresponding spectra have the same shape differing by a scale-factor. When the similarity coefficient is zero, the two vectors  $\bar{u}$  and  $\bar{v}$  are orthogonal to each other,

which suggests that the two corresponding spectra have nothing in common, or maximum dissimilarity.

#### 5.2.4 Computation of the Transfer Function between Sensors

In the transferable system (subsection 3.6.4), the output signals from air jet ( $G_{x1}(f)$ ) and leak ( $G_{x2}(f)$ ) of the AE1 and WD sensors are represented by  $G_{y1}(f)$  and  $G_{y2}(f)$  respectively. In each result, the curve of the ratio  $G_{y1}(f)/G_{y2}(f)$  is computed and is shown in figure 5.3.



**Figure 5.3** Computation of the ratio curve

Then the average of all ratios is computed. Thereafter, the ratio is compared, and a correlation is found between the AE spectra of the artificial AE air jet and the valve leakage rate.

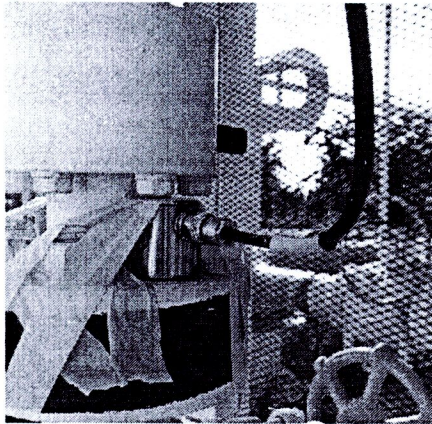
#### 5.2.5 Applying the Transfer Function to Detect the Internal Valve Leakage Rate in the Laboratory

In this study, artificial leaks from the incomplete closure of a ball valve are used to simulate a leak. The tests are conducted by varying the leakage rate for a 25.4 mm ball valve at inlet pressure from 300 to 500 kPa at three valve leakage rates of 100, 130 and 160 ml/sec, respectively. The AE sensor mounting and signal set up are the same as is used in the air jet calibration (subsection 4.3.1). After that, the  $AE_{rms}$  obtained from the AE1 sensor is calculated and converted to a valve leakage rate using equation 5.1.

#### 5.2.6 Applying the Transfer Function to Detect the Internal Valve Leakage Rate in the Field Work

To validate that the transfer function and measurement system can be used in the field, a test is performed in an actual petrochemical plant (see figure 5.4). The fluid is natural gas and the valve is a 38.1 mm ball valve. Owing to the restrictions posed by field testing in an actual working plant, the tested valve is not shut down for a long duration. The test is conducted for only one fixed simulated leakage rate of 55 ml/sec. The inlet pressure is varied from 100 to 1400 kPa. The AE sensor type AE1 is mounted at the down stream side of the valve. The AE spectrum is recorded with the same equipment

and conditions used in the laboratory. After that, the  $AE_{rms}$  obtained from AE1 sensor is calculated and converted to a valve leakage rate.



**Figure 5.4** Measurement the internal valve leakage rate in the field work

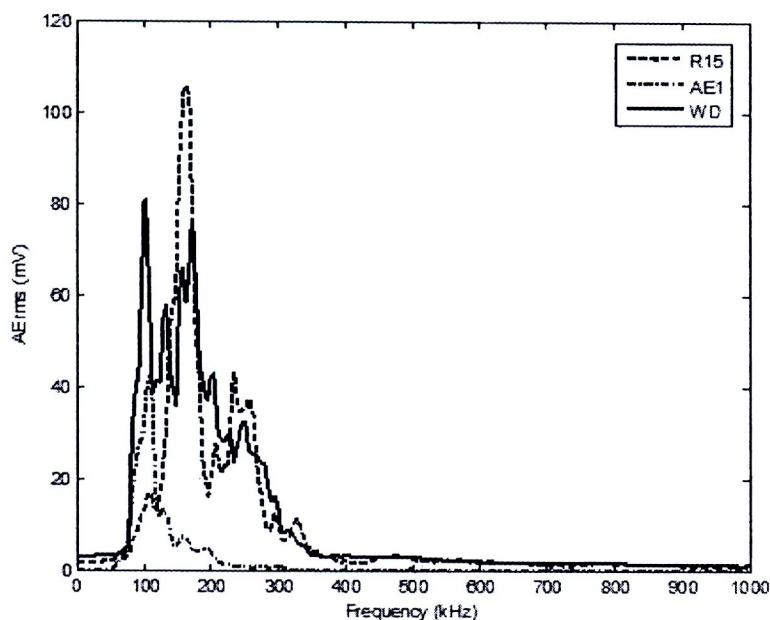
### **5.3 Experimental Results of Internal Valve Leakage Rate Measurement**

The objective of this experiment is to study a relative calibration and the transferable method for transferring the AE data between AE sensors and AE measurement systems. The AE sensors are calibrated by air jet, internal ball valve side at a fixed distance of 5 mm, to find out the sensitivity of AE sensors and the AE spectra of air jet. Then, the internal valve leakage rate is measured using these AE sensors to find out the AE spectra of internal valve leakage. Finally, the transfer function is calculated and applied to internal valve leakage rate measurement in the laboratory and field work. The results are described as follows.

#### **5.3.1 The Sensitivity of AE Sensors and the AE Spectra of Air Jet**

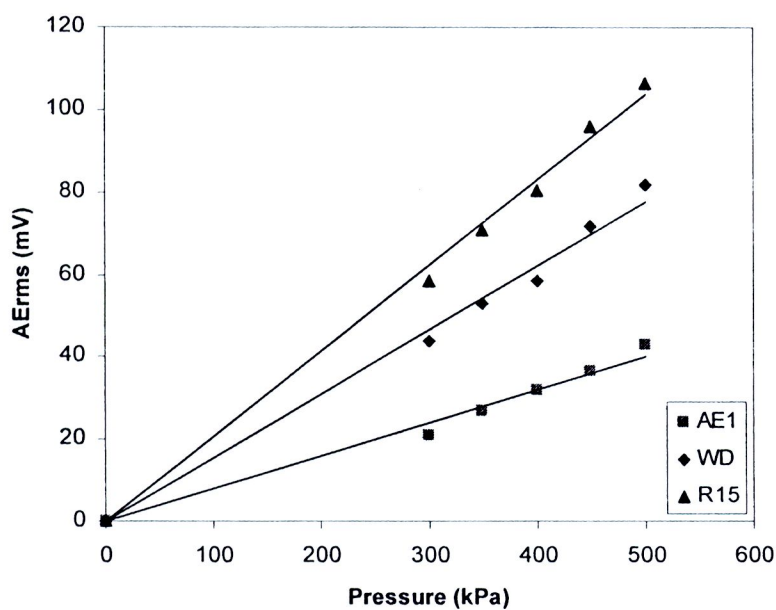
##### **1. The Sensitivity of AE Sensors**

The AE1 sensor is calibrated by an air jet with WD and R15 sensors. Since the  $AE_{rms}$  spectra of each sensor at the pressure level between 300 and 500 kPa have a similar shape, their amplitude is increased as air jet pressure increased. The typical  $AE_{rms}$  spectra of the air jet at 500 kPa pressure obtained from the three sensors are shown in figure 5.5.



**Figure 5.5**  $AE_{rms}$  spectra of air jet at 500 kPa pressure for each sensor

The calibration results from the WD, R15 and AE1 sensors are plotted in figure 5.6. It can be seen that the  $AE_{rms}$  and air pressure are linearly related, and the gradients for the R15, WD and AE1 sensors are 0.20, 0.15 and 0.08 mV/kPa. The  $R^2$  are 0.99, 0.98 and 0.98, respectively. These values represent the sensitivity of the three sensors.



**Figure 5.6** The relation between  $AE_{rms}$  and air jet pressure for each sensor

From the calibrated result using the air jet at approximately 100 kHz, the frequency response of the AE1 sensor and the  $AE_{rms}$  increases linearly with air pressure, which is the same as the WD and R15 sensors. However, the sensitivity (mV/kPa) of the AE1 sensor is lower than the WD and R15 sensors. This lower sensitivity is not significant because the AE1 sensor can be applied to valve leakage rate measurement. This method will be explained in the next subsection.

## 2. The AE Spectra of Air Jet

The objective of this subsection is to study a relative calibration and the transferable method for transferring the AE data between home-built AE sensors (AE1 sensor) and commercial one (WD sensor). The air jet calibration results of AE spectra from internal ball valve side are shown in figure 5.5.

Since the AE spectra from air jet calibration of each sensor at the pressure level between 300 and 500 kPa have five shapes, the degree of likeness (the similarity coefficient) of each shape and each sensor are calculated. The degree of likeness of AE1 and WD sensor are shown in table 5.1 and 5.2, respectively.

**Table 5.1** The degree of likeness of AE1 sensor

1	0.9912	0.9906	0.9933	0.9956
0.9912	1	0.9980	0.9961	0.9951
0.9906	0.9980	1	0.9985	0.9969
0.9933	0.9961	0.9985	1	0.9983
0.9956	0.9951	0.9969	0.9983	1

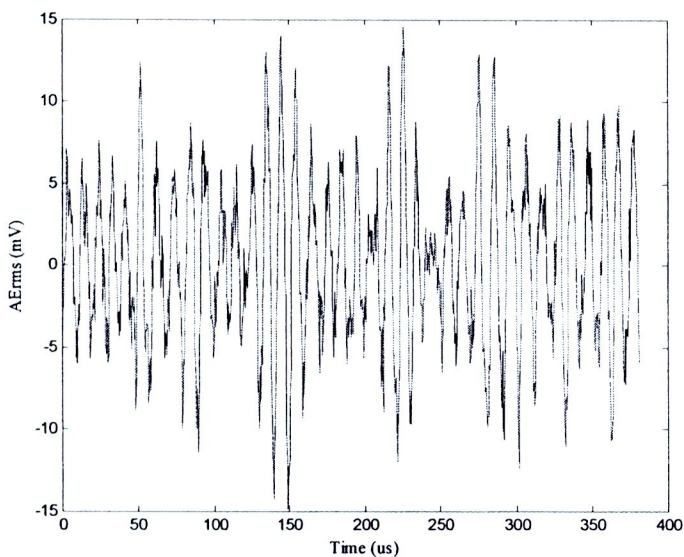
**Table 5.2** The degree of likeness of WD sensor

1	0.9871	0.9873	0.9879	0.9817
0.9871	1	0.9962	0.9893	0.9776
0.9873	0.9962	1	0.9922	0.9826
0.9879	0.9893	0.9922	1	0.9962
0.9817	0.9776	0.9826	0.9962	1

In table 5.1 and 5.2, the rows and the columns represent the progressive pressure values of 300, 350, 400, 450 and 500 kPa. It is shown that the AE spectra of AE1 sensor and WD sensor are very similar to each other within this range of pressure as the coefficients are all very close to 1.

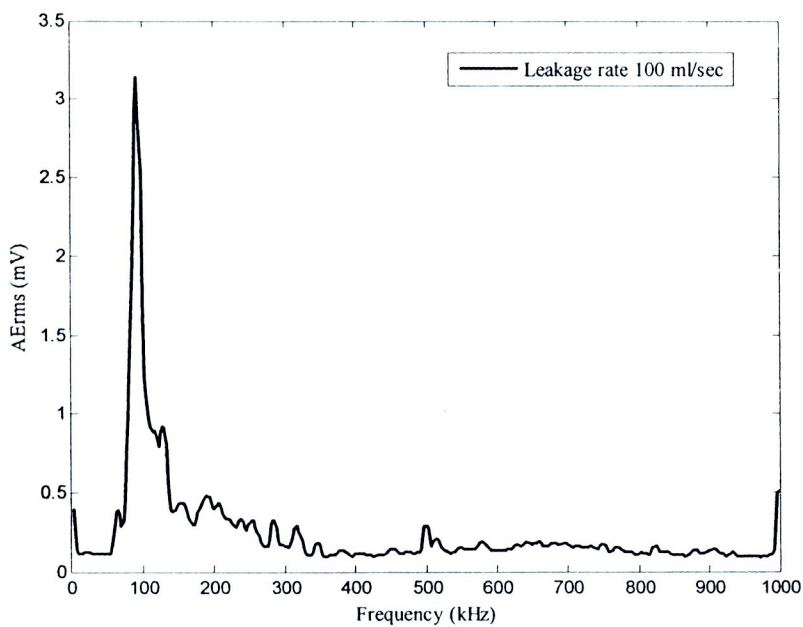
### 5.3.2 The AE Spectra of Internal Valve Leakage

In this study, artificial leaks from the incomplete closure of a ball valve are used to simulate a leak. The tests are conducted by varying the leakage rate for a 25.4 mm ball valve at inlet pressure from 300 to 500 kPa at three valve leakage rates of 100, 130 and 160 ml/sec, respectively. The AE signals from internal valve leakage are continuous signal. The character of AE signal in term of time domain is shown in figure 5.7.

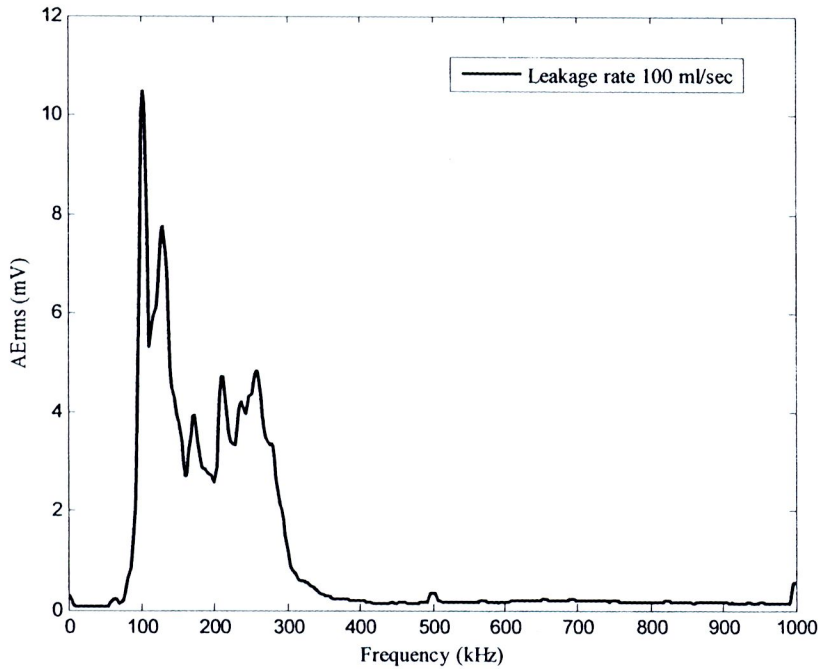


**Figure 5.7** Time domain of AE1 (pressure 300 kPa, leakage rate 100 ml/sec)

The AE spectra from internal ball valve leakage are shown in figure 5.8 (AE1 sensor) and figure 5.9 (WD sensor). The frequency response of the AE1 and WD sensor is about 100 kHz also (comparison with air jet calibration).



**Figure 5.8** The AE spectra from internal ball valve leakage of AE1 sensor (pressure 300 kPa, leakage rate 100 ml/sec)

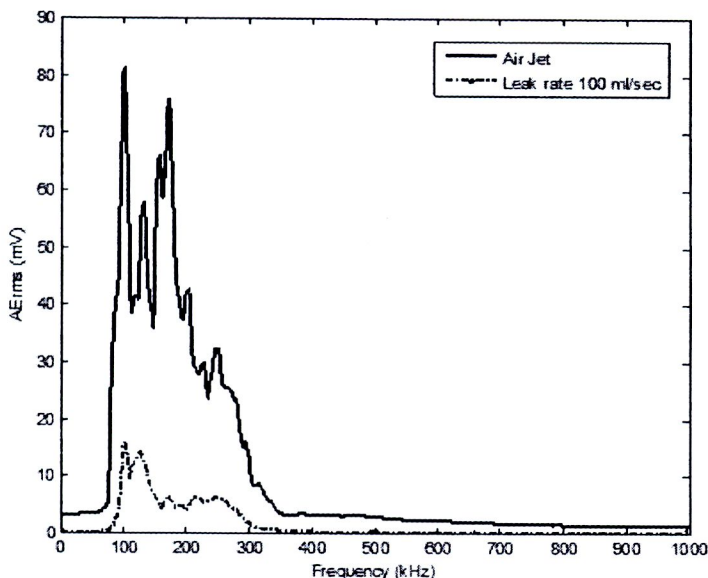


**Figure 5.9** The AE spectra from internal ball valve leakage of WD sensor (pressure 300 kPa, leakage rate 100 ml/sec)

### 5.3.3 Comparison of the AE Spectra between Air Jet and Artificial Leakage

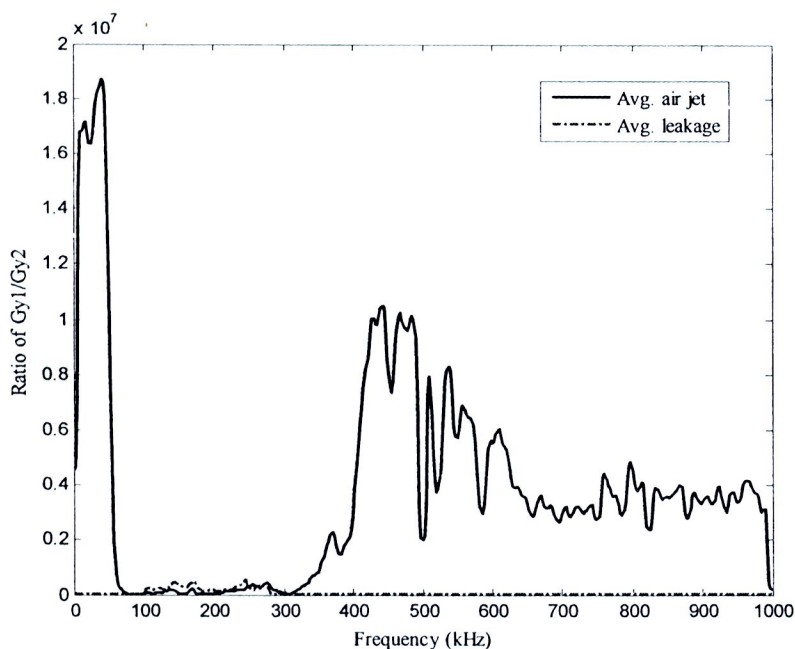
In this study, the different sensitivities of the three AE sensors are selected. The WD sensor is selected as the reference sensor because the sensitivity is between AE1 and R15 sensor.

AE spectra received from both the air jet and fluid leakage for all three sensors are recorded and compared. For each sensor, both sources provide similar spectra for all pressures. The amplitude of the spectra increases with pressure or leakage rate. An example of  $AE_{rms}$  spectra obtained from the air jet and the fluid leakage for 100 ml/sec and 500 kPa pressure is shown in figure 5.10.

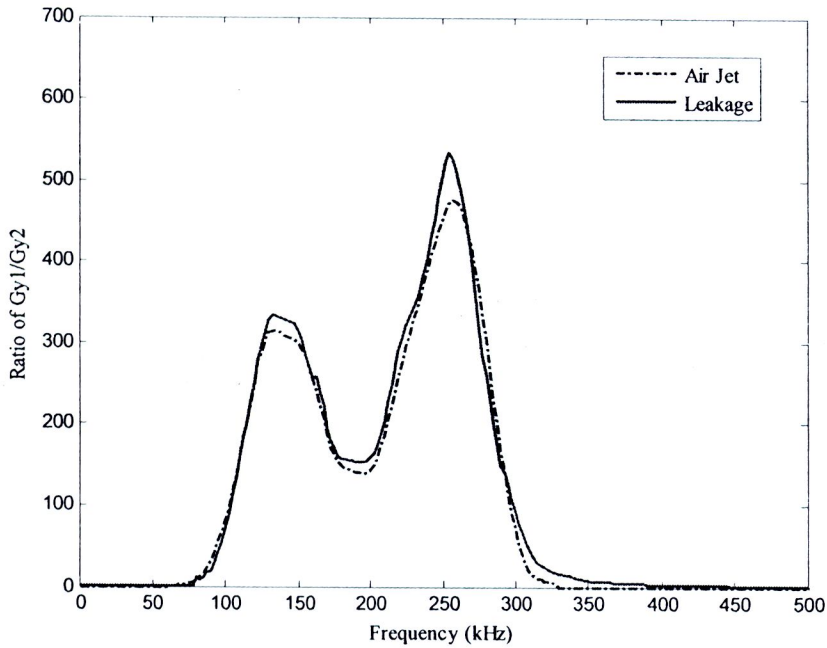


**Figure 5.10**  $AE_{rms}$  spectra of air jet and fluid leakage for 500 kPa pressure

The air jet is varied from 300 to 500 kPa in the increment of 50 kPa. Three replicates are performed for each pressure level. The average ratios between  $G_{y1}/G_{y2}$  (AE1/WD) from both the air jet and fluid leakage spectra are shown in figure 5.11. The ratio of the air jet and the fluid leak between two AE sensors are similar in shape. Principally, the ratios between frequency spectra are constant in the range of 100 – 300 kHz (figure 5.12). Consequently this ratio can be used to transfer data between the different sensors.



**Figure 5.11** The average ratio of  $G_{y1}/G_{y2}$  (AE1/WD) for a case with air pressure from 300 to 500 kPa and leakage rate from 100-160 ml/sec



**Figure 5.12** The average ratios of  $G_{y1}/G_{y2}$  (AE1/WD) constant in the range of 100 – 300 kPa

The similarity coefficient is computed using equation 5.5. The similarity coefficient between air jet calibration and average leakage (average for leakage rate 100,130, and 160 ml/sec for each inlet pressure) in each condition is illustrated in table 5.3.

**Table 5.3** Similarity coefficient of the curve of the ratio between air jet and average leakage

Valve sizes (mm)	Pressure (kPa)	Similarity coefficient
25.4	300	0.80
	350	0.80
	450	0.78
	500	0.79

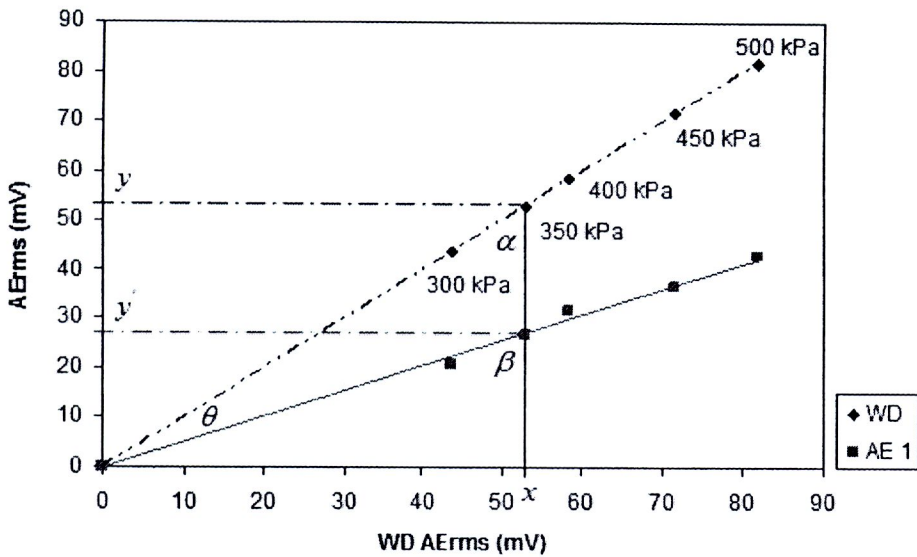
### 5.3.4 The Transfer Function between Sensors

Figure 5.13 shows the relationship between  $AE_{rms}$  from the WD and AE1 sensors. In this case, the WD sensor is used as the reference because the sensitivity of the WD sensor is higher than the AE1 sensor. The  $AE_{rms}$  from one sensor (AE1) can be converted to the  $AE_{rms}$  for another sensor (WD) with equation 5.6. The difference of value used to convert the data can be computed by equation 5.7.

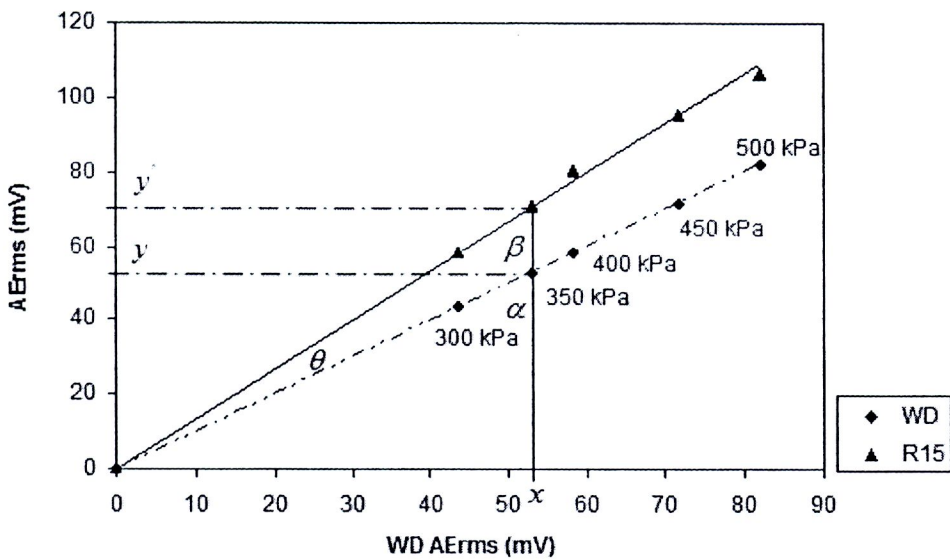
$$y' = y \pm \frac{x \sin \theta}{\sin \beta \sin \alpha} \quad (5.6)$$

$$\Delta y = y - y' \quad (5.7)$$

where  $y$  is the  $AE_{rms}$  from reference AE sensor (WD) and  $y'$  is the  $AE_{rms}$  from other AE sensor (AE1 and R15).



**Figure 5.13** The relationship between the  $AE_{rms}$  of the reference AE sensor and the lower sensitivity sensor



**Figure 5.14** The relationship between the  $AE_{rms}$  of the reference AE sensor and the higher sensitivity sensor

Figure 5.14 shows the relation between  $AE_{rms}$  from sensor R15 and reference sensor (WD). In this case, the sensitivity of R15 is higher than WD, thus the different in  $AE_{rms}$  value computed by equation 5.6 is negative.

From the previous research, the relationship of fluid leakage and  $AE_{rms}$  from the WD sensor used as the reference sensor is determined by equation 5.1. In other words, this equation is used to convert  $AE_{rms}$  to a fluid leakage rate when using reference sensor WD. For other AE sensors besides a WD sensor, the value of  $\Delta y$  carried out from equation 5.7 is used as compensating factor by equation 5.1 and given by

$$\log(Q_{AE}) = 1.782 \log(AE_{rms} + \Delta y) - 0.543 \log(P_{AE}) + 0.320 \log(S_{AE}) - 3.550 \quad (5.8)$$

Then, data from different sensors can be transferred.

Before this relationship is available, whenever any AE sensor is changed the equation 5.1 would need to be re-established. This calibration process is time consuming. Using the new method of data transfer described above, only the ratios of  $AE_{rms}$  between the new sensor and reference sensor are needed, therefore reducing the time required. This method is called relative system calibration using an air jet as the artificial source.

### 5.3.5 The Transfer Function to Detect the Internal Valve Leakage Rate in the Laboratory

To validate the data transfer of the system calibration, the leakage rate based on the WD sensor is calculated by equation 5.1. In addition, the leakage rate measured by AE1 and R15 are computed by equation 5.8. The prediction errors are then compared with the actual leakage rate measured by a standard flow meter. The prediction error is presented in table 5.4. The error is low in most cases (below than 5%) and acceptable for the rest. The maximum error is 9.17%.

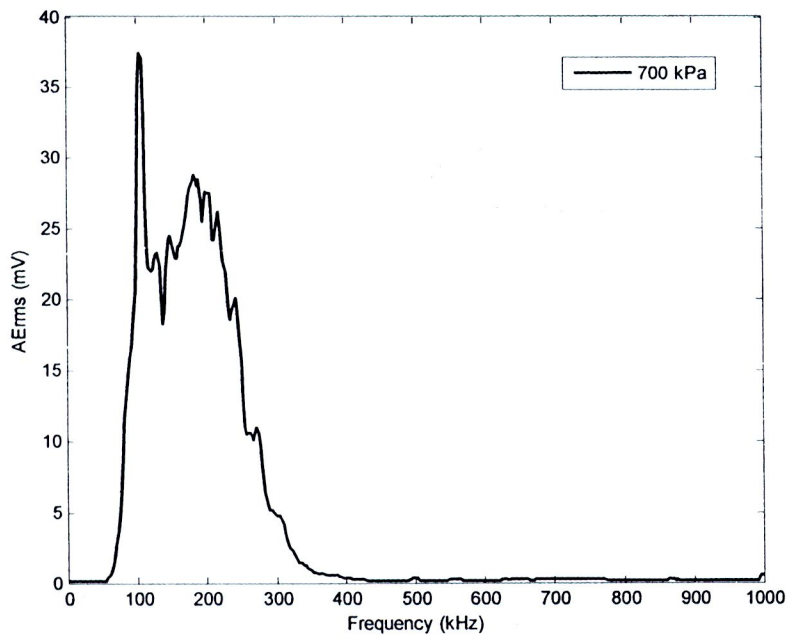
**Table 5.4** Error of laboratory leakage rate measurement when using transfer method

Pressure (kPa)	Actual leakage rate (ml/sec)	Calculated leakage rate (ml/sec)			Prediction error (%)		
		WD	AE1	R15	WD	AE1	R15
300	100	94.72	101.47	97.36	5.28	1.47	2.64
	130	131.44	128.15	129.63	1.11	1.42	0.28
	160	154.89	153.39	163.97	3.19	4.13	2.48
350	100	92.29	104.22	99.35	7.71	4.22	0.65
	130	128.70	133.34	135.65	1.01	2.57	4.34
	160	164.33	155.66	169.16	2.70	2.71	5.72
450	100	102.58	108.43	104.59	2.58	8.43	4.59
	130	134.67	135.76	140.55	3.59	4.43	8.11
	160	158.35	163.45	170.94	1.03	2.16	6.83
500	100	104.92	109.17	106.25	4.92	9.17	6.25
	130	125.23	135.16	140.83	3.67	3.97	8.33
	160	168.87	162.47	172.35	5.54	1.54	7.72

### 5.3.6 The Transfer Function to Detect the Internal Valve Leakage Rate in the Field Work

The frequency spectrum of the natural gas field measurement is shown in figure 5.15. The frequency spectrum is similar to the frequency spectrum of air leakage in the laboratory (figure 5.10). The similarity coefficient of frequency spectrum between natural gas (leakage rate 55 ml/sec, inlet pressure 700 kPa) and air leakage (leakage rate 100 ml/sec, inlet pressure 500 kPa) is computed by equation 5.5. The similarity

coefficient between natural gas and air leakage is 0.91. For this reason, the ratio or transfer method can be used in the field work.



**Figure 5.15** Frequency spectrum of natural gas leakage at 700 kPa pressure

We must ensure that the equation 5.8 established in the laboratory can be used in field given that the pressures are higher in the laboratory. Table 5.5 illustrates the calculated leakage rate carried out from equation 5.8. The prediction errors at pressures above the laboratory level, (at 700 and 1400 kPa) are low.

**Table 5.5** Error for natural gas leakage rate measurement when using transfer method from our AE sensor (AE1)

Pressure (kPa)	Actual leakage rate (ml/sec)	Calculated leakage rate (ml/sec)	Error (%)
100	55	51.10	7.09
350		52.49	4.57
700		56.53	2.78
1400		54.66	0.62

#### 5.4 Summary

In this chapter, a relative calibration method for an internal valve leakage rate measurement system using AE method was presented. An air jet was selected to calibrate because it provides a frequency spectrum similar to the AE spectrum obtained from the valve leak, especially in the frequency range of 100-300 kHz. Three AE sensors mounted on a valve were used to validate the system calibration. Ratios between the average energy ( $AE_{rms}$ ) were obtained from each pair of sensors, and these ratios were used to transfer the leakage  $AE_{rms}$  value. Subsequently, its performance to predict the leakage rate in the laboratory and in the field was tested. From the results,

the error is less than 5% in almost cases. The home-built AE sensor can be used to measure the internal valve leakage rate in the laboratory and in the field work. However, the sensitivity of the home-built AE sensor is lower than the commercial AE sensors. This lower sensitivity is not significant because the home-built AE sensor can be applied to valve leakage rate measurement. The benefit of this study is to reduce the recalibration time when a part of measurement system is changed.