

CHAPTER 5 SMART VALVE LEAKAGE DETECTOR

5.1 Overview

This chapter proposes the portable prototype called “Smart Valve Leakage Detector (SVLD)” to detect and determine valve leakage rate. Hardware design based on microprocessor as a signal processor unit and software design are explicated. Moreover, the test performance and implementation of SVLD are also resulted from both laboratory and field tests. The SVLD is capable of detecting possible valve leakage encountered at in-situ operation. With its portability, ease of use and compactness, the proposed SVLD provides fast and low cost for valve leakage detection.

5.2 Background Problem

General AE data acquisition system is an integrated system with very high sensitivity that can be used to detect small AE signals. It can be applied to detect valve leakage when the production is running. However, the disadvantages of this system are its large size, and quantity as well as complexity of its components. Therefore, it is not convenient to use in applications where mobility is in demand. Some commercially available portable AE systems at present are costly and the leakage rate are calculated offline [40, 47, 48, 49]. Moreover, the precision of the leakage rate measurement is still rather low.

Although general AE data acquisition systems are generally more sophisticated and faster than microcontroller-based, they normally require more complicated hardware design and software development [90]. Some research works incorporated an FPGA to a general AE data acquisition system to perform preprocessing on the AE signals [36, 91]. This research work proposes a novel portable AE instrument to measure a valve leakage rate, based on microcontroller as the processing unit. Only AE_{RMS} has been proved to be the most influential characteristics associated with the leakage [33, 39]. This greatly reduces computation loads of the system and makes it possible to be implemented in a microcontroller-based system. Moreover, problems such as the *curse of dimensionality* [92], which means a greater amount of training data is required to establish a usable

estimator, is also improved. This means a smaller set of training data can be used when an appropriate prediction model is selected.

Thus, it is possible to integrate microcontroller-based embedded system with timers, memory and I/O interfaces. The microcontroller is used due to its low cost, small size and low power consumption. This makes it convenient to be used and straightforwardly carried across a measurement site.

5.3 Design of Instrument

5.3.1 Hardware Details and Design

A general AE measurement system normally consists of AE sensor, couplant, signal amplification, filtering device, data acquisition and signal analyzer separately, leading to inconvenience for field uses. This dissertation designs a low cost portable AE instrument for measuring valve leakage based on microcontroller. A block diagram and a photograph of the instrument are shown in Figures 5.1. It consists of the following parts:

1. AE Sensor

AE sensor from PAC made of PZT material with the resonant frequency of approximately 150 kHz to convert acoustic waves to electrical signals, as shown in Figure 5.2.

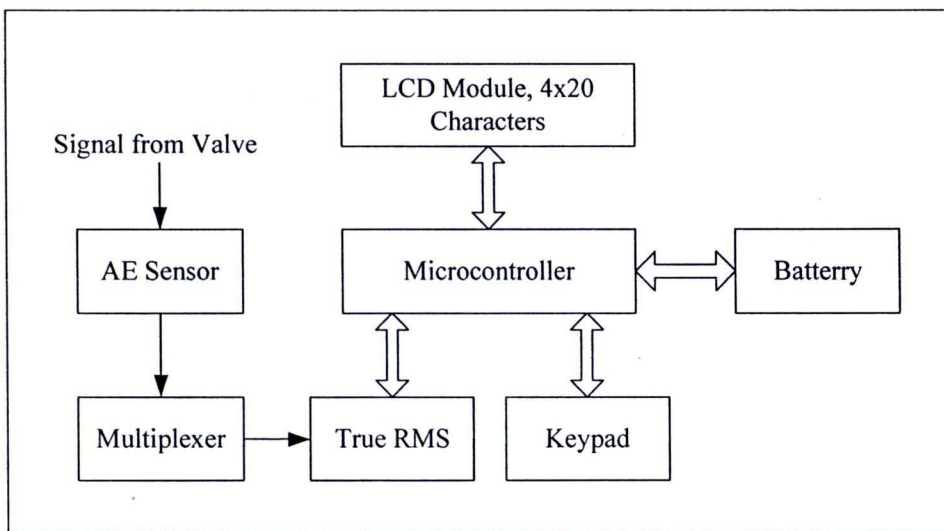


Figure 5.1 Block diagram of the system.

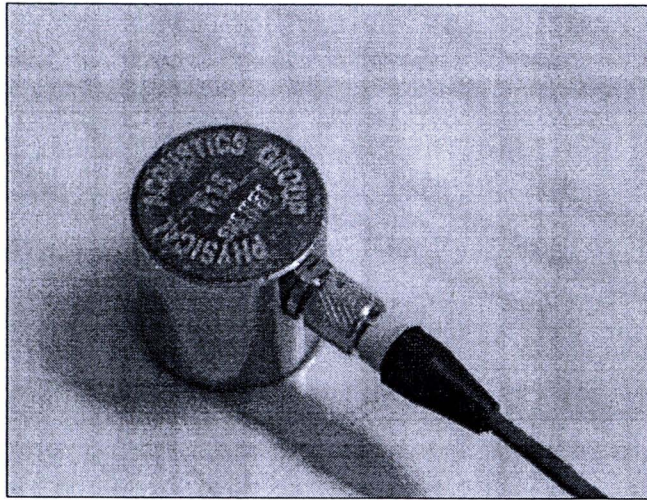


Figure 5.2 AE sensor (R15 type) from Physical Acoustic Corporation: (PAC).

2. Preamplifier Circuit

The output voltage of an AE sensor is usually very small (in millivolt or less), a preamplifier is therefore needed to enlarge the signal before it feeds into other signal processing circuits. The designed preamplifier circuit is shown in Figure 5.3.

3. Filter Circuit

Filter is often employed to reject unwanted signals (noise). In this dissertation, the designed filter circuit is a band-pass type with cutoff frequencies of 100 kHz and 300 kHz, as shown in Figure 5.4. The filter allows passing frequency components within a range of 100 kHz to 300 kHz and rejects (attenuates) frequency components outside the range.

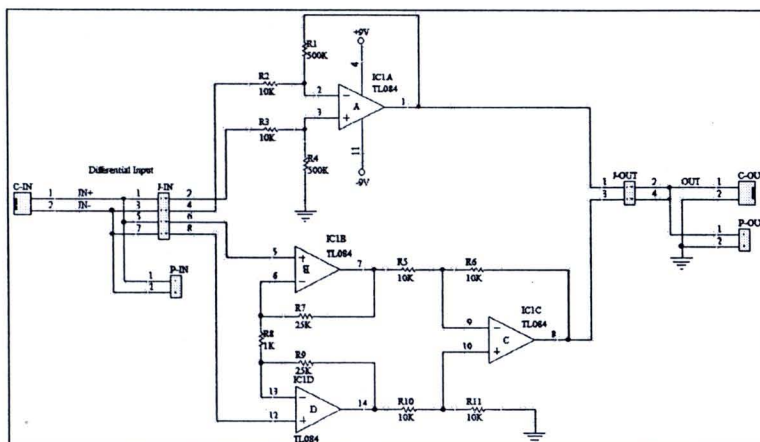


Figure 5.3 Designed preamplifier circuit.

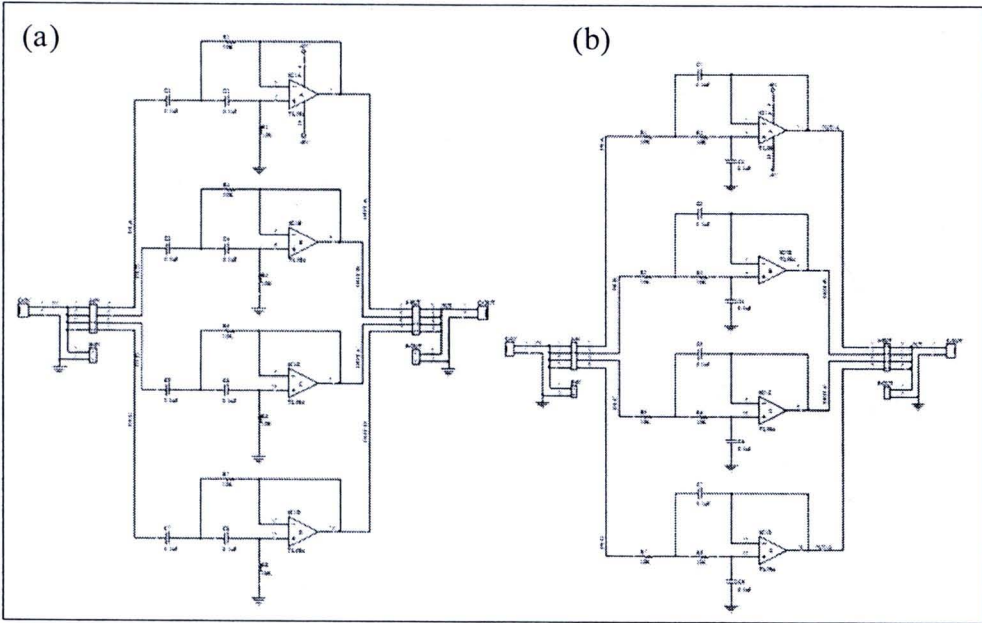


Figure 5.4 Designed filter circuit (a) low-pass filter and (b) high-pass filter.

4. Multiplexer Circuit

Multiplexer circuit is functioning as a selector to adjust the signal gain so that appropriate AE signal levels are input to the microcontroller to avoid any amplitude saturation problem, as shown in Figure 5.5.

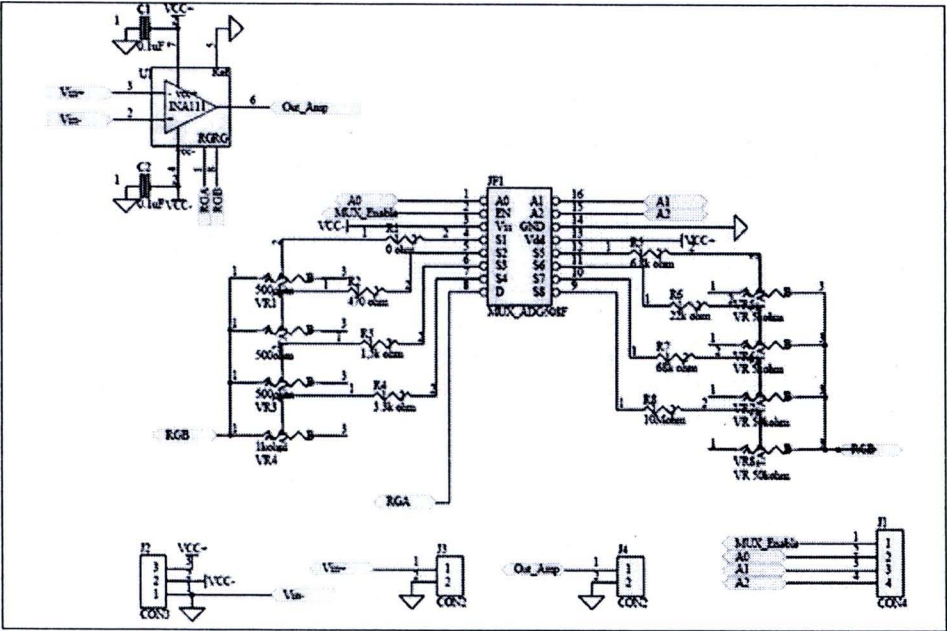


Figure 5.5 Designed multiplexer circuit.

5. True RMS

The circuit is used to convert a continuous electrical signal to a Root-Mean-Square (RMS) value, i.e. AE_{RMS} , as displayed in Figure 5.6.

6. Keypad

The keypad for user interfacing is used for entering the value of input variables. The 'up' and 'down' arrow keys are for changing the input variables and 'left' and 'right' keys for changing the units, as illustrated in Figure 5.7.

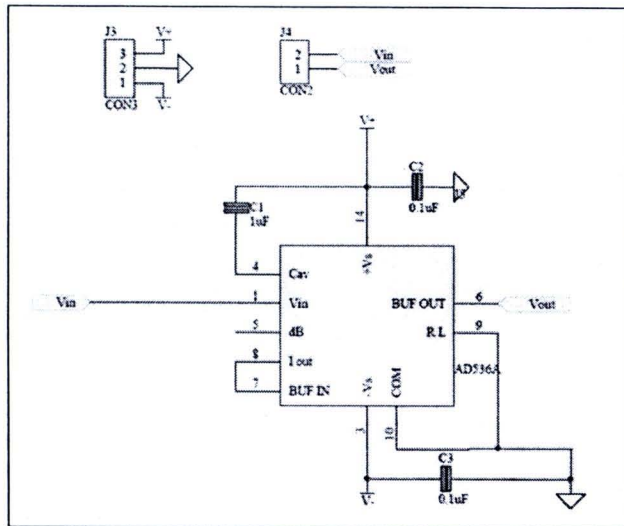


Figure 5.6 Designed true RMS circuit.

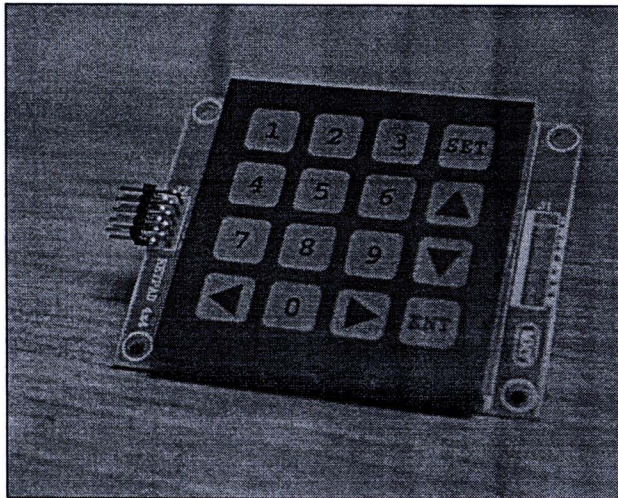


Figure 5.7 Keypad used for designed instrument.

7. Liquid Crystal Display (LCD)

Liquid Crystal Display is used for displaying result and operation status, as shown in Figure 5.8.

8. Battery or DC terminal

Battery or DC terminal is used as the main power source of the system.

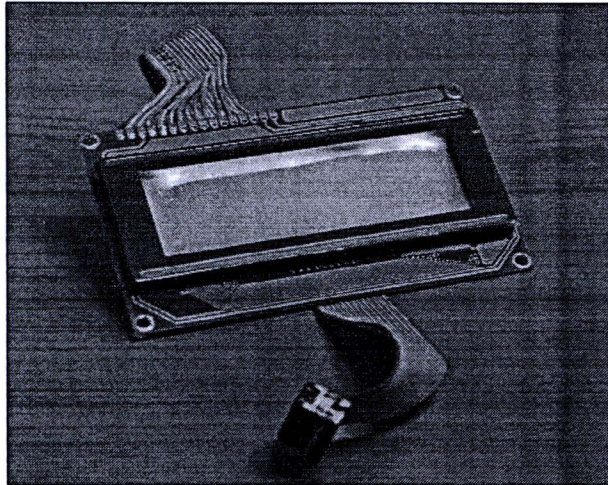


Figure 5.8 Liquid Crystal Display (LCD) used for designed instrument.

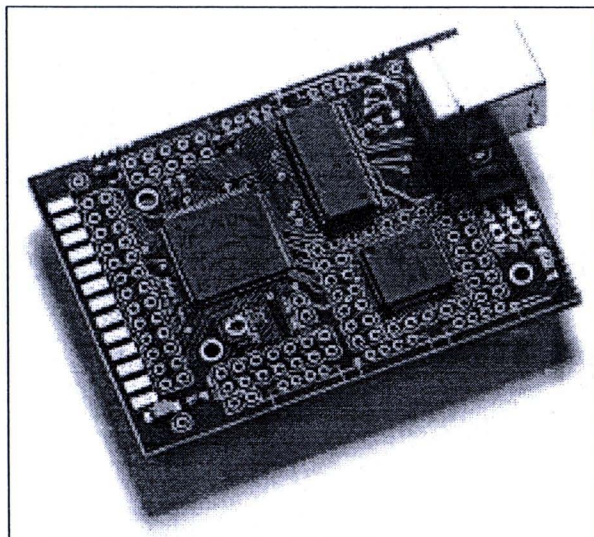


Figure 5.9 Microcontroller (ARM7) used as a signal processing unit of designed instrument.

9. Microcontroller

An ARM7 (microcontroller), as shown in Figure 5.9, is used to control the multiplexer circuit to get AE_{RMS} from the true RMS circuit via its ADC, to obtain input values of variables from user through keypad, to calculate the leakage rate from Equation 3.33, and finally to display the results via LCD.

5.3.2 Software Design and Implementation

The Software was developed in C language for initializing the display LCD and ports, as well as for calculating leakage rate according to Equation 3.33. Before using the instrument, the background interference (BGN) from the plant must be determined by mounting the AE sensor to a part of the production line, with no leakage. The AE systems converts a primary background interference signal to AE_{RMS} , usually in mV range, and store the BGN value in the memory of the microcontroller.

The value of the input variables such as the size of valve (D), the inlet pressure level (P_1), the temperature (T_1) and the gas constant (R) must be entered to the system before the leakage rate calculation. This version of design allows only air as the gas and therefore the value of R is a constant.

In measuring process, the instrument waits for the signal from the valve passing through the AE sensor and the true RMS circuit converts an analog AE signal to the AE parameter i.e. AE_{RMS} (mV). The microcontroller then compares AE_{RMS} with the previously recognized BGN and if it is found to be greater than BGN, there is a leakage. The microcontroller then computes the leakage rate according to Equation 3.33 and displays the obtained result on the LCD. The flowchart of the above tasks is given in Figure 5.10.

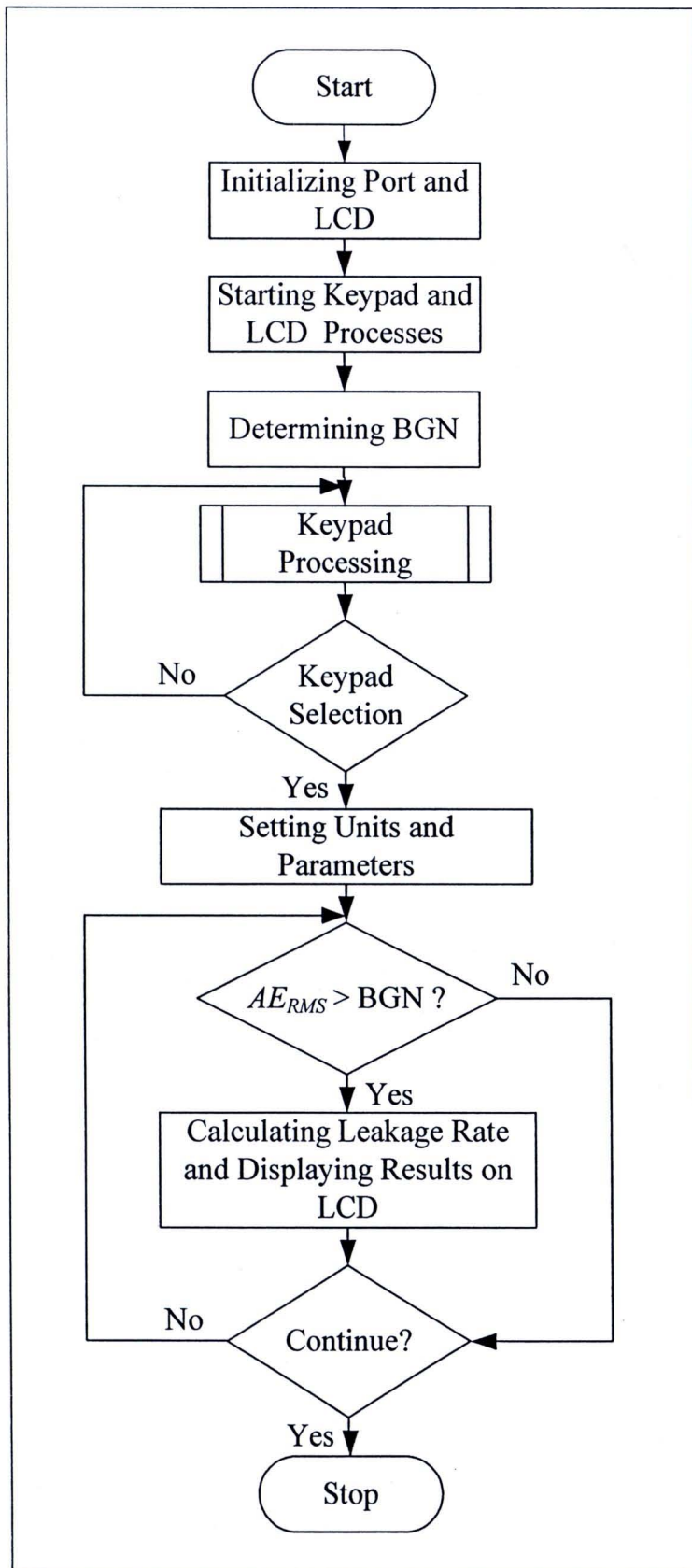


Figure 5.10 Flow chart of the software.

5.4 Proposed Smart Valve Leakage Detector (SVLD)

A photograph of the designed circuits and the Smart Valve Leakage Detector (SVLD) are shown in Figures 5.11 and 5.12, respectively. The instrument receives power from either four (2400 mAh) PP3 batteries or a standard 15 V_{dc} ac/dc adapter. Because the measurement period is as short as a few seconds, this prototype is almost always in power-safe mode for longer operation time. By using the batteries, this instrument gives operation time of 4 hours continuously before the batteries are needed to be replaced. Its dimension and weight are: 185 mm x 80 mm x 22 mm and 1.5 kg. (including the battery)

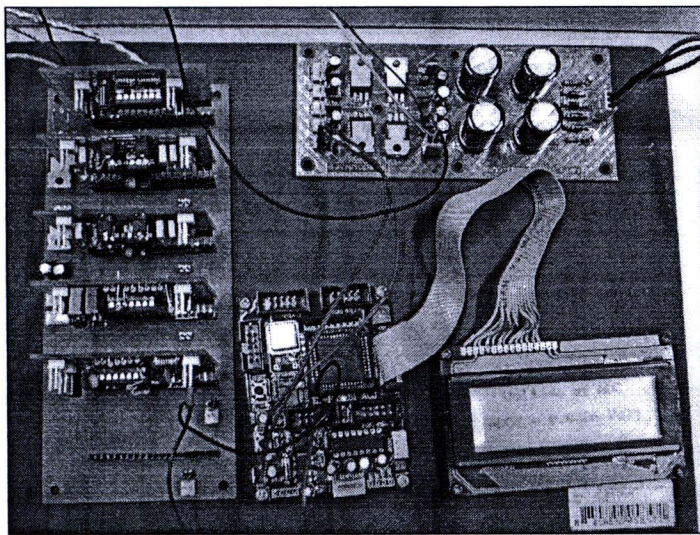


Figure 5.11 The designed circuits consisted in Smart Valve Leakage Detector (SVLD).

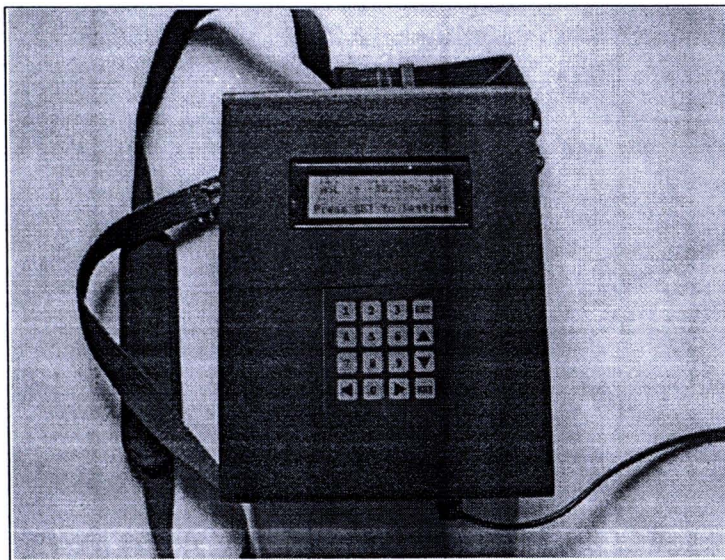
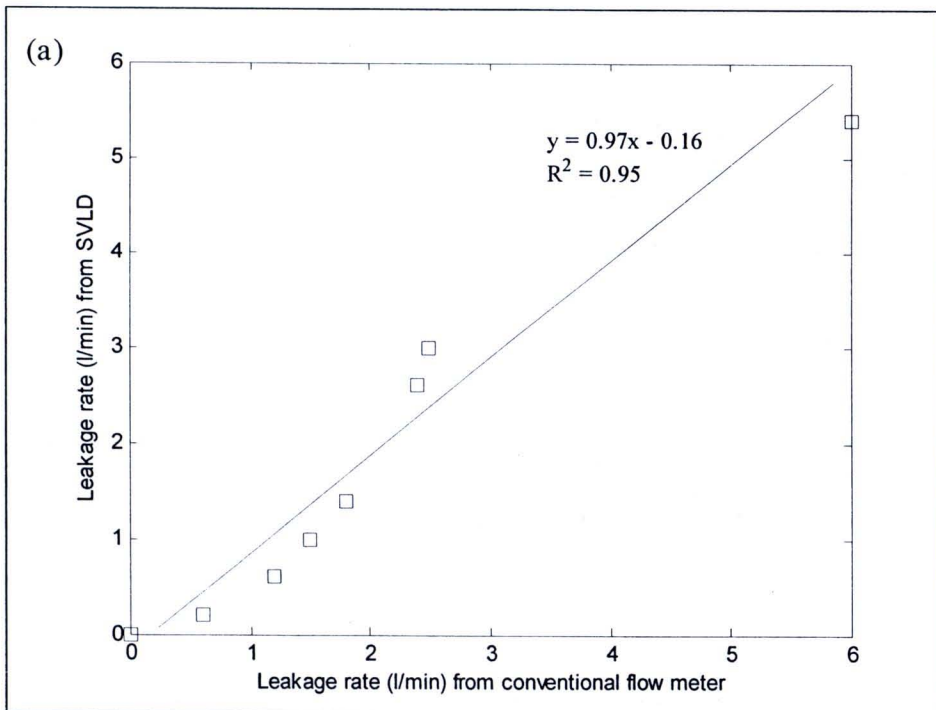


Figure 5.12 Photograph of the instrument.

5.5 Test System Performance

5.5.1 Result of Calibration Curve

Accuracy of SVLD was determined by a system calibration. In the calibration, an inline flow meter was used as the reference meter. Leakage rate obtained from the SVLD was compared with that from the flow meter. Resolutions of the meter and the SVLD are 0.1 l/min and 0.2 l/min, respectively. The experiment was conducted using valve size 25.4 mm at inlet pressure levels 100 kPa and 300 kPa at various leakage rates. Figures 5.13(a) and 5.13(b) show the calibration curves at the inlet pressures levels of 100 kPa and 300 kPa, respectively. It can be seen that output of the instrument has a linear relationship to the conventional inline flow meter reading. The R^2 of the curves are 0.95 and 0.97, respectively. The overall accuracy is approximately $\pm 11.0\%$ full scale. The measurement results obtained from this proposed and the conventional instruments show a good correlation over the range suggesting that instrument is capable for measuring the leakage rate.



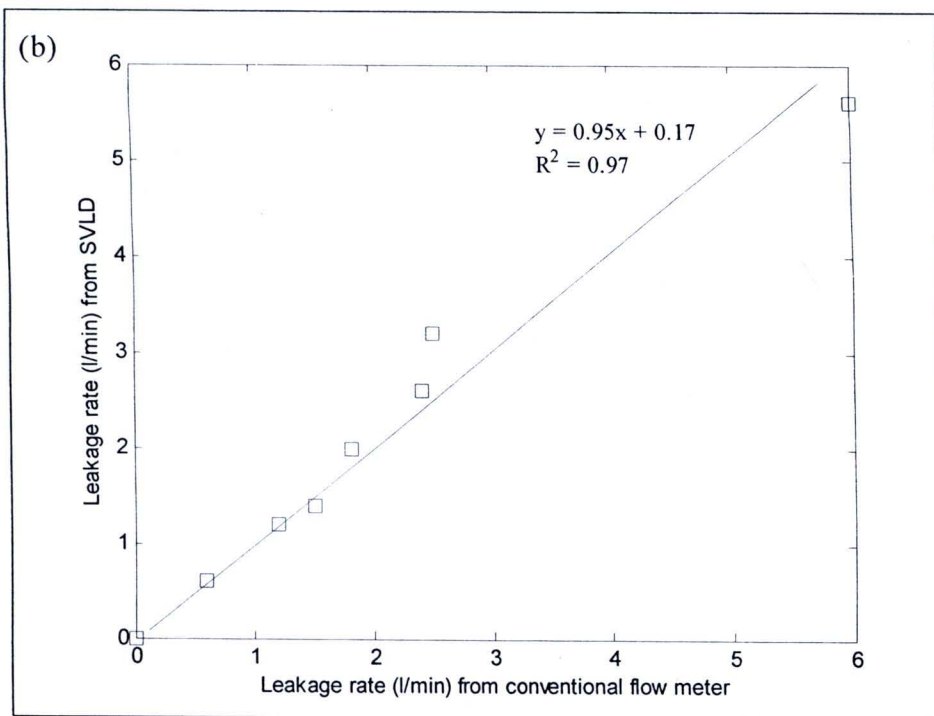


Figure 5.13 Correlation of leakage rate obtained by SVLD and by conventional flow meter at (a) inlet pressure level 100 kPa and (b) at inlet pressure levels 300 kPa.

5.5.2 Result of Accuracy and Error

The accuracy of the instrument is evaluated from differences between the leakage rates obtained by the portable instrument and the corresponding flow rates of fluid leaked through the valve read from a flow meter. The accuracy as determined by this method is approximately $\pm 11.1\%$ full scale.

An example of error of measurement for the instrument on a 25.4 mm ball valve at the inlet pressure level of 300 kPa is shown in Table 5.1.

5.5.3 Result of Sensitivity and Repeatability

The sensitivity of the portable instrument is presented in form of mV/l/min, This value is calculated from the average of 5 graphs (5 runs of the experiment). The tests were performed using a 50.8 mm ball valve at the inlet pressure level of 100 kPa. The relation between AE_{RMS} and the leakage rate are presented in Table 5.2. The sensitivity

of this instrument is 8.4 mV/(l/min) (or 60 dB_{AE} V/(m/s)) whereas sensitivity of AE sensor (R15 model) is 69 dB_{AE} V/(m/s).

Repeatability of the instrument was performed under the same condition, method and environment. Repeated measurements were carried out in a short period. The repeatability is the mean value of R^2 obtained from a curve fitting of the graph, showing the relation between AE_{RMS} and leakage rate of a 50.8 mm ball valve at the inlet pressure level of 100 kPa. The results of R^2 obtained from the experiments, shown in Table 5.2, have a mean value of 0.93.

Table 5.1 Error of measurement of this proposed instrument.

Actual leakage rate (l/min)	Calculated leakage rate (l/min)	Error (%)
1.5	1.4	6.7 %
1.8	2.0	11.1 %
2.4	2.6	8.3 %
6.0	5.6	6.7 %

Table 5.2 Slopes and R^2 from the relation of AE_{RMS} / Leakage rate of the portable instrument.

Run No.	Slope (mV/(l/min))	R^2
1	8.9	0.97
2	8.1	0.92
3	8.3	0.90
4	8.2	0.95
5	8.6	0.93
Average	8.4	0.93



5.6 SVLD Implementation

The efficiency of Smart Valve Leakage Detector (SVLD) was proved in the previous section. Then, the implementation of SVLD at in-process valve is presented in this section. In field test, the instrument returns a volumetric flow rate of the leakage within 3 seconds after mounting AE sensor to an under-test valve. Before performing measurement, the valve needs to be fully shut off temporarily. Couplant must be applied to the AE sensor before mounting to the valve. The appropriate position for mounting the AE sensor is around the valve flange area or on a flat surface of valve in the downstream side. The instrument is easy to use, convenient and only requires a short measuring time. The prediction of leakage rate of in-process valve can be done by SVLD as expressed in Figure 5.14.

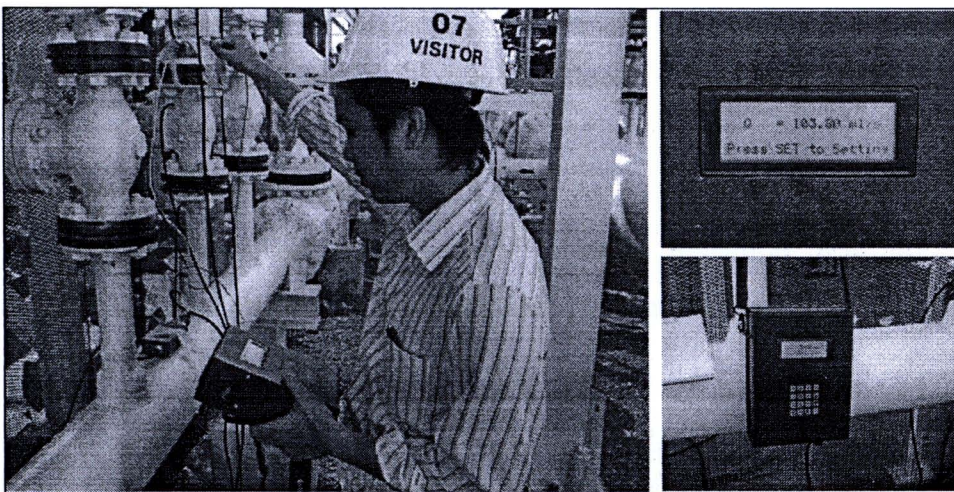


Figure 5.14 Implementation of SVLD in field test.

CHAPTER 6 CONCLUSIONS AND RECOMMENTATIONS

6.1 Overview

This research work focused on the measurement of leakage rate of valve in fluid transportation systems using acoustic emission method. Consequently, the dissertation aims to study the characteristics of AE signals, to extract the AE parameter correlating with leakage rate, to create a theoretical model for predicting the leakage rate, and to produce a portable instrument to measure the rate.

In the beginning of this chapter, a summary of the work done in this dissertation is presented in Section 6.2, in which the main findings are highlighted. Secondly, main contributions to knowledge in this study are summarized in Section 6.3. Finally, recommendation and future work of this dissertation will be suggested in Section 6.4.

6.2 Summary of the Work Done

The hypothesis of this dissertation, declared in the introduction, was proved. The objectives have been successfully accomplished by completing a sequence of steps, which can be summarized below.

1. *“To apply AE measurement technology and study of the AE signal characteristics on valve leakage application.”*

Firstly, the acoustic emission (AE) technique was used to detect a pseudo sound generated in a valve leakage application. The characteristics of measured AE signals were investigated by various signal processing techniques as addressed in Section 3.5.3. The result showed that the characteristics of AE signals were analyzed by time domain, magnitude domain and frequency domain analysis. In time analysis, it was obvious that the AE signal characteristics generated by valve leakage were continuously random signals. In magnitude analysis, it was clear that the AE signal characteristics were stationary random signal. This means that the detected AE signals were produced from a time-invariant process. In other words, the mean value was close to zero and variance was not significantly changing with time when the time passes. Moreover, the statistical property, RMS value extracted from the AE signal in magnitude analysis provided was

valuable in the derivation of the theoretical relationship and model. Finally, in the frequency domain analysis, it was found that the AE signal characteristics from compressed air rose between the operating frequency range over 100 kHz to 300 kHz. The frequency of leakage expressed significant peak amplitude around frequency of 150 kHz. This suggested that the resonant type of AE sensor from PAC, model (R15), having a resonant response center on 150 kHz, were mainly chosen to detect the AE signals generated by valve leakage with sufficient sensitivity

2. *“To determine the relationship between the AE parameter and the process variables concerning with the rate of valve leakage.”*

Firstly, the relationship between extracted AE parameter (AE_{RMS}) and the fluid variables dealing with the rate of valve leakage were presented in Section 3.5.4. From experiment, it was found that the fluid variables such as inlet pressure levels, valve sizes, and leakage rate were related to AE signals and the extracted AE parameter. It was shown that the AE_{RMS} increased with the increment of inlet pressure level. On the other hand, the AE_{RMS} decreased when the valve size increased at various leakage rates. Moreover, the theoretical relationship between sound power (P_s) and AE signal power (AE_{RMS}^2), presented in Equation 3.1; $AE_{RMS}^2 = f(P_s)$, derived by proposed assumption, presented in Equation 3.18; $AE_{RMS}^2 = f\left(\frac{c_0 P_1 Q^8}{RT_1 \alpha^5 D^{14}}\right)$, was also proved in Section 3.4. It was confirmed that the sound power has a strong non-linear relationship with the AE signal power, as shown in Section 3.5.5. In other words, the AE_{RMS}^2 was directly related to the P_s derived by Lighthill's equation in gas valve leakage application.

3. *“To investigate a theoretical model which utilized to predict the rate of in-process valve leakage.”*

Referring Equation 3.18, the theoretical relationship relating the in-process valve leakage rate was derived to theoretical model as presented in Equation 3.33 in Section

3.6.4; $Q_1 = 0.31e^{2 \times 10^{-5} \left[\frac{\alpha^5 AE_{RMS}^2 D^{14} RT_1}{P_1} \right]^{\frac{1}{8}}}$. It was presented that the leakage rate (Q_1) is an exponential function of various process variables. The result could be extended to produce a portable instrument for measuring valve leakage rate.

4. *“To produce a prototype, portable instrument called Smart Valve Leakage Detector (SVLD).”*

The prototype based on microcontroller, a portable instrument called “Smart Valve Leakage Detector (SVLD)”, was designed and implemented as described in Chapter 5. It is the 2nd generation of prototype in this current research. The system performances were tested in laboratory (Section 5.5). The accuracy of this prototype is approximately ± 11.1 % full scale. The sensitivity of this instrument is 8.4 mV/l/min. Moreover, the implementation of SVLD was also accomplished in a field test.

6.3 Contributions to Knowledge

The contributions drawn from the current research can be listed below.

Firstly, the theoretical model was derived to understand a physical relationship of various variables concerned with valve leakage rate by using AE method. Furthermore, the model leads to smaller set of training data required, which is a problem of previous empirical model.

Secondly, for the comparison method of AE spectra, we conduct experiments to explore the consistency ratios in frequency range of 100 kHz to 300 kHz. This implies that the range, like a transfer function, can be utilized to transfer or compare information between AE sensors. This is particularly useful because the information, obtained from one sensor, can be converted into another. Additionally, the concept can be used for applying the relative calibration by air jet. The advantage of implementing the relative system calibration method is to reduce the number of experiments required to determine the theoretical model when the installed AE sensor is changed.

Thirdly, Since the spectrum density function or AE spectra of both AE system show sufficient constancy of frequency response ratios in certain range of 100 kHz to 300 kHz, Parseval' s theorem can be used to convert AE signal power (AE_{RMS}^2) value or to convert the energy rate of this range from time to frequency domain. The equation is

$$\text{given by } AE_{RMS}^2 = \sum_{k=0}^{N-1} P[k]\Delta F .$$

Finally, the portable instrument, SVLD, used to measure the valve leakage rate is implemented and applied in field test. The contribution of this dissertation may lead to develop the detection by using one of NDT techniques to petrochemical process plants in Thailand. In real applications, it is immediately possible to know a condition of valve (leaking or not leaking). The quantitative measurement not only helps to plan for priority fixing heavily damaged valves among thousands in the plants but also helps to save the cost of resulting system shutdown.

6.4 Recommendations and Future Work

In this current dissertation, the theoretical model was performed with artificial leakage from incomplete closure of ball valve as defined in Chapter 1. This is due to the actual leakage is hard to control the leakage rate at various experimental conditions. However, the simulation leakage is significantly different from the actual valve leakage. Thus, it would be interesting to apply the modeling technique described in the dissertation to real leakage. In order to model the real valve leakage, a question arises: how is effect of shape and orientation of leakage on it? However, it is interesting to see the ways to prove that the effects of artificial and actual leakage are not significantly different.

Apart from leakage simulation, the theoretical model was derived from assumption based on Lighthill's theory that is not valid for any interaction of the fluid with nearby hard surfaces of valve. This is complicated to solve quantitatively, and it seems that the model approaching in this dissertation is good enough to practice in both laboratory and field tests. Lighthill's theory with Curle's extension should be considered to regard the interactions of the sound emitted from the valves.