CHAPTER 1 INTRODUCTION

1.1 Overview

This chapter presents a motivation and a background problem of valve leakage, conducted to study in this dissertation. Generally, literature review concerning with valve leakage detection using nondestructive testing (NDT) method, especially based on acoustic emission (AE), is presented. Understanding the valve leakage, this chapter gives a description of valve and a definition of valve leakage. Objectives and scopes of the dissertation are included in this chapter.

1.2 Motivation

1.2.1 Valve Leakage Problem

The leakage problem is dreadfully significant for refineries, petrochemical plants, and power generation plants [1, 2, 3, 4]. In fluid transmission network, there are many sources of fugitive emissions from leaking components such as valves, flanges, pumps, and other connectors. However, valve leakage is critical source of losses in their plants [2].

Figure 1.1 presents that the valves are major sources for fugitive emissions [2]. Valve leakage problem can cause not only explosion and fire but also other serious threats from fluid degradation owing to fluid mixing [3]. In addition, fluid losses lead to increase in production cost as a result of fluid contamination and lowering the efficiency of the instrument and system. Terry et al. [4] reported that valve leakages were costing over $100,000 per year of production loss in British Petroleum (BP).

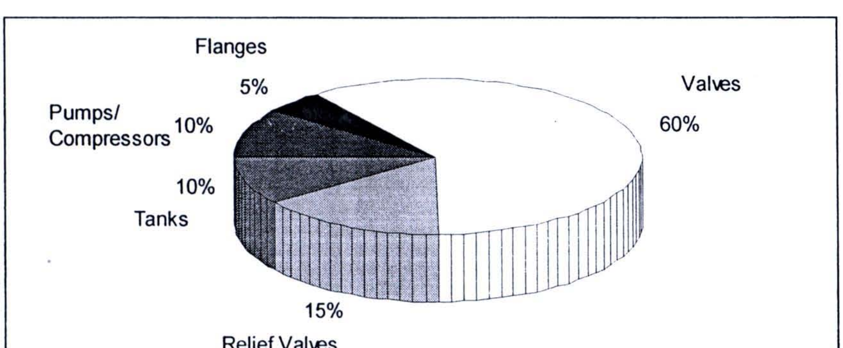

Figure 1.1 Sources of fugitive emissions by equipment type [2].

In general, most plants have planned to calendar scheduling of maintenance. Hydrostatic and pneumatic test are usually applied to valves. However, the test systems can monitor the performance of valves when the process plants are off-line or shutdown completely [5]. It can cause a great amount of cost resulting from maintenance parts, manpower, and equipment downtime. In actual fact, the leaking valves may occur and are not clearly visible before their planed service date to maintain. Bypass technique for hydrostatic and pneumatic test is utilized to considerate this problem [4], but the techniques still require a partial shutdown. In case of this, it may still lead to a waste cost for maintenance. For this reason, a technique to detect the valve leakage that may possibly accomplish on in-process or *in-situ* [6, 7, 16] is worthy for considerable reduction in down-time and its associated costs.

1.2.2 *In-situ* Valve Leakage Detection

In *in-situ* or in-process valve leakage, there are possibilities to have both internal and external leakages through valves. For external valve leakage case, it can be examined by screening techniques such soap bubble, visibility and hearing. Fortunately, these techniques are low-cost, fast and easy to screen the leakage of an *in-situ* valve [8]. For internal valve leakage case, it is obviously complex to detect leakage by using these techniques. Therefore, the motivation of this dissertation is to consider a nondestructive testing (NDT) technique, which can be used to detect internal leakage through the *in-situ* valve.

NDT technique consists of several sound or vibration methods, that are possibly developed to detect the internal leakage of in-process valve, for example: vibration analysis, ultrasonic detection, and acoustic emission [9,10]. The feasibility studies of each method to solve the in-situ valve leakage problem are summarized below.

1. Vibration Analysis

Vibration analysis, which usually covers the frequency range from 0 to 20 kHz, has been for years, the key to condition-orientation maintenance of rotating machines [11]. Nowadays, the vibration analysis method has one main deficiency when the detection of internal valve leakage is considered [12]. This is due to its inability to determine precisely the leakage rate through the valve. Even though, many researches [12, 13, 14, 15, 16] concluded that this analysis produced reliable results and provided that the background noise is kept under control. Otherwise, the frequency component, produced due to the internal valve leakage, may be covered by the mechanical noise-environment. However, there are many sources of vibration in an industry so that the background noise is hard to be considered it constant. In real application, therefore, the detection in an industry is complicated in distinguishing mechanical vibration sources from the internal valve leakage given by vibration analysis.

2. Ultrasonic Detection

Vibrations which exceed 20 kHz are not audible and for this reason they are called *ultrasonic* [17]. This method frequently detects structure born and airborne ultrasonic-signals of valve leakage in the frequency range of 20 kHz to 100 kHz. In the past, there have been a great number of studies related to any leakage in an industry. At the present time, developed ultrasound detectors have been equipped with a hand-held ultrasonic probe or scanner [8]. The detectors typically provide frequency tuning capability so that the probe can be tuned to a specific leakage sound in a noisy environment. Hence, pinpoint leakage sounds are detected by listening for an increment of sound intensity through headphones. However, the ultrasonic detectors can measure qualitatively and are also sensitive to noisy environment in an industry [18, 19].

3. Acoustic Emission

Acoustic emission (AE) is a noninvasive method of NDT technique. In the last three decades, AE has been increasingly applied to detect an internal leakage of a valve, and it was widely used *in-situ* in oil, gas, chemical and petrochemical industries, nuclear power plants, fossil fuel power plants, and petroleum plants [20, 21]. This is because of its variety of applications, for example: integrity diagnosis of valve, condition of valve monitoring and leakage rate prediction [20, 22, 23, 24]. Furthermore, AE valve leakage detection provides more reliable in industrial applications in comparison with the ultrasonic detection and the vibration analysis methods. This is owing to the high level of background noise that is usually present in an industrial environment. The background noise produces considerable interference with the leak-related frequency components. AE method is on the other hand, regularly operates at frequency range of

100 kHz to 1MHz that are well beyond the frequency range of the mechanical vibration noise and electrical noise [25, 26].

As a consequence of the reasons given about *in-situ* valve and noisy environment in Sections 1.2.1 and 1.2.2, this dissertation focuses on development of AE method applied to the internal valve leakage in on-line operation. The research concerned with this dissertation is reviewed in Section 1.3.

1.3 Literature Review

The internal valve leakage in on-line operation can be classified as AE problem which involves two major areas of study (i) condition monitoring and (ii) leakage rate prediction.

1.3.1 Condition Monitoring

1. AE in Check Valve Application

In condition monitoring based on AE detection, it is usually attempted to detect undesirable failure of check valve. The check valve is one of the typical components which have been extensively used in the safety systems of nuclear power plants [27]. The components have basically been attributed to severe degradation of internal parts of check valve such as hinge pins, arms, disks, and disk nut pins resulting from the instability of check valve disks under flow oscillations or vibrations of system pipe which may induce these components wear [23].

Most evaluations have focused on determining the capability of AE method to provide diagnostic information of on-off condition, degradation components, and failure mode of check valve [27, 28]. The AE measurement system can detect the wave and identify the changes of the characteristics of a failed check valve from the changes of acoustic wave, since the backward flows or unintended reverse flows through the failed check valve changes the characteristics of the acoustic wave.

2. Background Research of Condition Monitoring

The research of Joon-hyune Lee, et al [29] in 2004 presented that the characteristics of AE signals responses of internal parts of check valve due to artificial worn disk were analyzed by extracting effective AE parameters. The disk was worn by round cutting (disk wear) of 1.0, 2.0, 3.0 mm and water as the process fluid was varied. Its pressure was changed to 0, 300, 600 and 900 kPa in the experiment. They found that the AE_{RMS} parameters detected from disk wear increased as the pressure in the same leakage size and also increased according to the leakage size. Moreover, they presented that the relationship between AE_{RMS} parameters and leak flow rates are linear. The analyses of the results suggested that AE signals depended on leakage rate.

The different types of failure modes of check valve such as disk wear and foreign object have been studied extensively by Joon-hyune Lee, et al [30, 31] in 2005 and 2006 respectively. Disk wear failure means that a disk was artificially worn by round cutting to produce some flaw in the surface. Foreign object means artificial leakage when a disk was not fully closed by inserted weld rods between disk and housing of a check valve. They performed the analysis of power spectral density and artificial neural network in order to identify the characteristics of failure in a check valve.

In the experimental set-up, simulating disk wear and test pressure were the same as the setting in previous research. In addition, various sized weld rods of 0.5, 1.0, 1.2, 1.5, and 2.4 mm were assumed as foreign objects.

The results showed that the AE signals of 150 kHz of AE sensor were greater than that of 60 kHz and 1.2 MHz. Hence, the signals of 150 kHz were very sensitive to the leakage. In addition, it was found that the frequency spectrum profiles of the check valve leakage did not depend on the leakage rate and the pressure, but that they were strongly depended on the types of the failure mode. The peak frequencies in all of the disk wear failures were about 150 kHz and 225 kHz and those in all the foreign object failures were about 100 kHz and 150 kHz. The characteristics of different failure modes in check valve were significantly distinguished by power spectral density in frequency domain analysis. In the time domain analysis, they presented that the AE signal levels had a dependency to the sizes of each failure mode of the check valves. In order to estimate the failure size, the main diagnosis algorithm using artificial neural network had input nodes with AE amplitude, AE_{RMS}, pressure, and two characteristic peak frequencies. However, some estimation error existed that the algorithm could estimate an averaged 3.26% error between the estimate and actual size for disk wear failure and an averaged 6.06% error between the estimate and actual size for foreign object failure.

1.3.2 Leakage Rate Prediction

1. Process Variables Influenced on AE

In case of study on common fluid types, there were both compressible fluid such as air and gases and incompressible fluid, for instance, water and oil. Pollock [26] inferred that ASTM recommended practice for minimum AE leakage detection quoted about 1.0 ml/s for liquid and 10.0 ml/s for gas. This implies that the leakage of liquid is more sensitive to that of gas.

In case of study on inlet pressure level and valve size, it was found that the AE signal level increased with higher inlet pressure levels [32] and decreased with large valve sizes [33,34]. Several research works studied the effects of AE parameters on valve and fluid variables such as inlet pressure level, types of gas and valve size [35, 36]. It was found that only AE_{RMS} had a good correlation with those variables; whereas others AE parameters were reported to have insignificant influence.

In case of study on valve shape, geometry of valve and valve type was partly a factor influencing the propagation of high frequency wave into different paths which caused the analysis of AE signal depending on results from the experiment of each valve type. Previously, the AE was studied qualitatively on check valves to find the characteristics of the AE signal in both time (e.g. RMS value) and frequency domains (e.g. frequency spectrum of AE signals) that were related to the on-off condition and the degradation of valve leakage [27, 28, 29]. Another research studied leakage in safety and relief valves by measuring the signal from leakage of sub-cooled water and saturated stream through the valves [32]. The RMS value of the signal in the frequency domain was found varying according to the mass flow rate in log scale and the correlation equation between both variables was also established. In addition, it was also found that low leakage rates ranging from 1.1 ml/s to 5 ml/s could also be detected by AE. For the detection of leakage in gate valves, the study on the response of AE sensor towards the least leakage signal was performed and found that the AE signal was sensitive to the leakage signal for leakage rate below 3.3 ml/s at inlet pressure level of 113 kPa [25].

For ball valves, leakage detection has been studied in many research works due to its utilitarian role in industries [16, 37, 38]. The research of Dickey, et al [35] presented the correlation between AE signal and leakage of air, steam, water, and oil from valve leakage at various inlet pressure levels and leakage rates via a 50.8 mm ball valve. Shack [39] studied the correlation between the ratio of AE_{RMS} against leakage rate and jet velocity with the use of ball valve sizes 101.6 mm (4 inches) and 152.4 mm (6 inches), and artificial leakage from orifice plates of 1.6, 0.4 and 0.3 mm diameters. It was found that the ratio strongly depended on the jet velocity.

2. Experimental Model

Many researches have been completed to investigate and estimate leakage rate through acoustic emission [32, 33, 34, 35]. Multiple regression fitting models for multi-independent variables (such as inlet pressure level, leakage rate, etc.) were developed in quantitative models. Dickey, et al [35] in 1978 was the first who determined the feasibility of acoustic signatures of various leakage rates using AE method. The research found that a peak amplitude of the AE signal in frequency domain occurred at certain frequencies when leakage rate changed. Moreover, these peak amplitudes and leakage rates from 3.3 to 5.0 ml/s at fixed valve size of various fluid types were linearly correlated in log scale.

During the 1980s, the license for the VPAC database and equation for valves leakage rate prediction were distributed by the Physical Acoustics Corporation [3, 40]. This database was compiled from British Petroleum and other companies. Using these data, the rate of leakage (Q; l/min) may be estimated from the signal of the average AE signal level (ASL; dB), the valve type, valve size (S; inch), and inlet pressure level (P; bar) [41]. The equation was given by

$$\begin{aligned}\log_{10}(Q_i) = 0.168 &+ 0.0453 \times (ASL) \\ &- 0.286 \times \log_{10}(P) \\ &+ 0.936 \times \log_{10}(S) \\ &+ 0.568 \quad (\textit{add only for gate valve}) \\ &- 0.269 \quad (\textit{substract only for ball valve})\end{aligned} \tag{1.1}$$

In order to calculate the leakage rate using the Equation 1.1, it needs to measure AE data (ASL) only with VPAC instrument. Additionally, user must pay an associated royalty fee to determine the leakage rate. As a consequence, a theoretical model of fluid variables to provide the valve leakage rate prediction was worthy to develop for AE implementation.

Recently, an extended application to predict the leakage rate using AE was presented by Chen, et al [42] in 2007. This research analyzed the characteristic of AE signals generated by internal leakage in a water hydraulic cylinder. Experiments were designed, including the simulation of the internal leakage across the leakage hole of piston seal, which had 0.39 mm radius. They presented that the relationship between AE_{RMS} (V) value and the internal leakage rate Q_i (l/min) was obtained using least squares method, given by

$$Q_i = 7.86 AE_{RMS} + 0.14 . \tag{1.2}$$

3. Theoretical Model

The production of sound by turbulence gas flow has been extensively studied following Lighthill's pioneering work on the jet engine noise [43, 44, 45]. The classic theory has been developed in considerable details and has been applied successfully to a number of industrial problems [46]. This body of knowledge is helpful also in the study of acoustic emission from valve leakage.

Only research of Shack, et al. in 1980 [39] investigated the theoretical relationship relating with Lighthill's theory. The research showed the difference between the effects of the subsonic and supersonic turbulent jets created by orifices. Depending on the size of the leakage, as well as on the pressure and the velocities involved. The sound emitted is often in the ultrasonic range of frequencies. The transition from subsonic to supersonic brings about a considerable change in the relationship between the flow-rate through a leak and the sound generated. It is stated that in a subsonic jet, the power of the sound is proportional to the seventh power of the velocity at the throat of the leakage. In a supersonic jet, however, the power of the sound is proportional to the mass flow-rate through the leakage.

4. Development of AE Instrument

In November 1973, the Acoustic Valve Leak Detector (AVLD) was developed by The David W. Taylor Naval Ship R&D Center (DTNSRDC). The AVLD, a passive and portable instrument, listens for the ultrasonic acoustic emissions characteristic of the internal valve leakage [47, 48]. This designed to detect leaks through large seawater ball valve at low pressures. It has since been adapted to use with other fluids and vales. The AVLD monitors leakage associated acoustic energy in the frequency range of 10 kHz to 100 kHz. The detector permits the operator to observe the acoustic energy density as an analog meter reading or to listen to it on headphone. The audio output is derived from the ultrasonic frequency oscillator and amplifying the resulting beat frequency for the headphone. The detector unit is in a small case about 18 cm high by 23 cm wide by 25 cm long. The entire instrument, with all accessories stored in the case cover, weighs less than 7 kg. Power is supplied by rechargeable 6-volt batteries which will operate the unit continuously for 8 hour charge. The sensor of AVLD was attached temporarily to the valve. Then, the amplitude of the audio signal on the headphone was also displayed on the analog acoustic amplitude meter located on the front panel.

VPAC^{TM}, a portable instrument, of Physical Acoustics Cooperation (PAC): Model 5131 was produced to estimate through-valve leakage. The measurements based on acoustic emission acquire the average AE signal level together with data on valve size, type, and differential pressure in order to predict valve leakage rate. Developed for use in refineries, chemical plants and offshore platforms by British Petroleum (BP), VPAC is sold under license exclusively by Physical Acoustics Limited. This technology package is primarily used for estimating gas losses [3, 40, 49].

1.4 Description of Valve and Definition of Valve Leakage

1.4.1 Ball Valve

Ball valves have been widely used in various industries and have an economic means of providing control with tight shut-off for many fluids [13, 14, 16, 38]. Ball valve consists of a body which has a house for rotated ball. The ball is machined spherically and drilled directly through it. The ball is located in the body by two sealing rings [50]. Rotation of the ball through 90 degrees to open and close the valve allows fluid directly through the orifice. In the closed position, the blank sides of the ball block the inlet and the outlet for preventing any flow. The structure of ball valve is shown in Figure 1.2.

1.4.2 Valve Leakage

Artificial leakages from incomplete closure of ball valve are provided to simulate the leakage. The word "valve leakage" used through this dissertation means the passing of fluid through valve body internally when valves are incompletely closed or partially open, as shown in Figure 1.3(b) [51]. The other leakage such as external leakage (fluid through valve body to atmosphere), worn seat, and loose stem package are not considered in this dissertation.

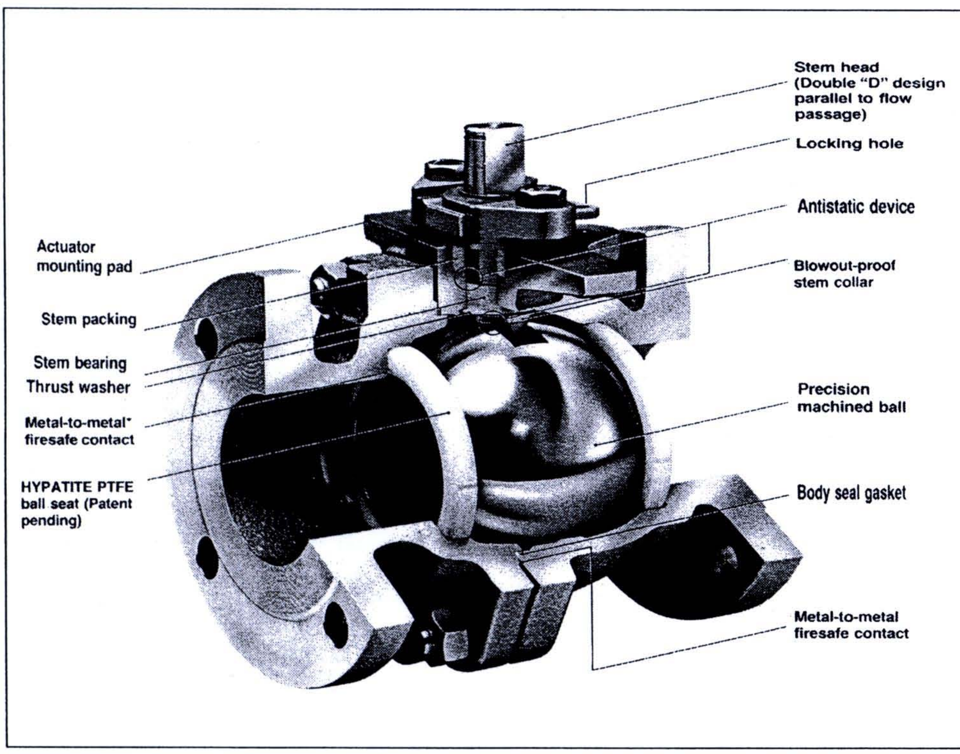

Figure 1.2 Ball valve structures [50].

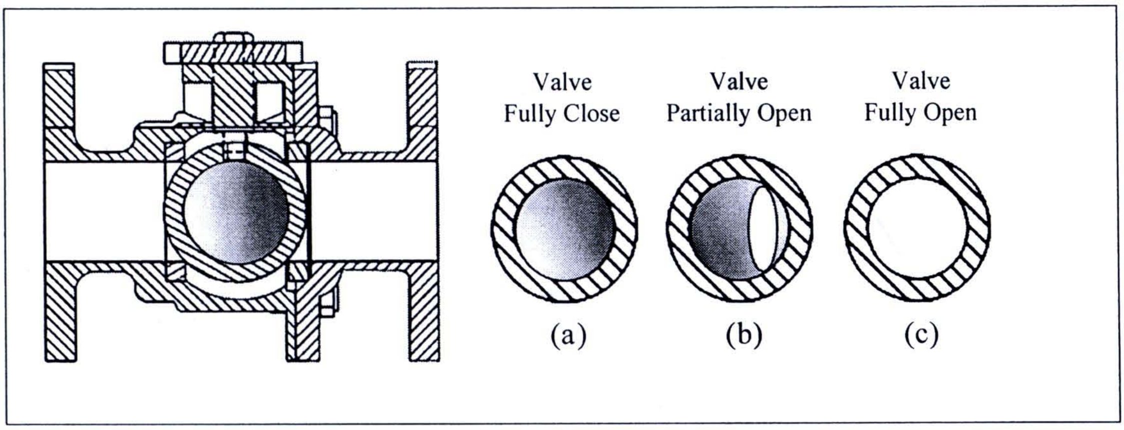

Figure 1.3 Ball valve at different stages of rotation (a) fully open (b) partially open, and (c) fully close [51].

1.5 Objectives of Dissertation

The primary hypothesis of this investigation is:

"The acoustic emission signals detected from in-process valve leakage indicate a high correlation with its leakage rate. To quantitative measurement, the acoustic emission parameter can be used to predict the rate of the valve leakage theoretically"

The goal of this dissertation is to understand the leakage signal, model and predict the valve leakage rate using NDT technique called "acoustic emission (AE)". There are four major objectives in this dissertation:

1. To apply AE measurement technology and study of the AE signal characteristics on valve leakage application,
2 To determine the relationship between the AE parameter and the process variables concerning with the rate of valve leakage,
3. To investigate a theoretical model which utilized to predict the rate of in-process valve leakage, and
4. To produce a prototype, portable instrument, this is called "Smart Valve Leakage Detector (SVLD)".

1.6 Assumptions and Scopes of Dissertation

The main concern of this dissertation is to characterize the AE signal conducted to the creation of theoretical model to predict valve leakage rate. The scopes of the current dissertation are defined as follow:

1. The assumptions of the investigations are that the fluid-sound source concerned with this dissertation is aerodynamic sound, a turbulence jet, and that the AE signal power (AE_{RMS}^2) is a function of the sound power (P_S) based on Lighthill's theory.
2. Compressible fluid provided to take the experiment was air as an alternative to gas due to its ease to use and safety reason.
3. The valve type selected as the test subjects in the experiment was ball valve since it is widely used in industries.
4. Ball valve made of cast iron material was utilized in this dissertation.
5. Different sizes of soft-valve-seat ball valves of 25.4, 50.8, and 76.2 mm inside diameter were employed as the valve leakage.
6. Air flow generated by an air compressor was used to generate the inlet pressure levels between 100 kPa to 500 kPa.
7. The leakage rate for test ranged from 0 to 100 ml/s or 0 to 6 l/min.
8. The experiment set-up in laboratory test was operated at the room temperature.

1.7 Organization of Dissertation

This dissertation includes six chapters as follow:

CHAPTER 1, INTRODUCTION, addresses the problem of valve. Description of valve components and definition of valve leakage are presented. The literature review underlying concepts of the proposed nondestructive evaluation method using acoustic emission are presented. In addition, this chapter also presents the objectives and scopes of the dissertation.

CHAPTER 2, THEORETICAL BACKGROUND, describes fundamental theory of sound and acoustic emission. There are subjects; fundamentals of sound sources, pressure- recovery process of valve, sound sources from valve leakage, and sound power based on Lighthill's theory. Additionally, the phenomena of acoustic emission, acoustic emission measurement system, and AE signal analysis techniques are also considered in this chapter.

CHAPTER 3, THORETICAL MODEL, presents the assumptions to develop the theoretical relationship and model for predicting valve leakage rate using AE method. To achieve the objective, the theoretical or physical model, based on Lighthill's theory concerning with sound power of turbulent jet (P_s) and related to AE signal power (AE_{RMS}^2), is derived in this chapter. The experiment was also set to study the characteristic of AE signal generated by valve leakage and to verify the proposed relationship.

CHAPTER 4, COMPARISION METHOD OF AE SPECTRA, presents the proposed comparison method to transfer AE information between different AE systems. Linear system responses of two different AE sensors were proved by the ratios of both frequency response functions. The validation of the proposed method was established experimentally. Finally, relationship of AE powers extracted by both time and frequency domain was derived using Parseval's theorem.

CHAPTER 5, SMART VAVE LEAKAGE DETECTOR, Smart Valve Leakage Detector, (SVLD) to detect and determinate valve leakage rate is designed and presented in this chapter. For validation the proposed instrument, the efficiency of SVLD and its implementation at in-process vale are proved both laboratory and field study.

CHAPTER 6, CONCLUSIONS AND RECOMMENDATIONS, contains conclusions, recommendation and contributions of this work employed from this dissertation.