Gas Pipeline Leak Detection Using Differential Pressure Analysis Method

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved by,

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD IZWAN BIN MOHD SANI

ABSTRACT

With the increase usage of pipeline in industrial process, especially within the gas transmission and distribution systems, it has become very crucial to develop the reliable method for predicting gas release and dispersion in the pipeline due to many reasons such a safety, security and economic reasons, ecological reasons and etc. The predicting should have fast and accurate detection of the leaks.The primary objective of this project is to design a leak detection system in order to test the method and gather experimental data with using method of pressure analysis to detect, as early as possible, the exact location and magnitude of such faults with minimal instrumentation and should have fast and accurate detection of the leaks. The system will combine the use of instrumentation that normally available in the pipeline such as Differential Pressure (DP) Transmitter and orifice. The DP transmitter will indicate the pressure different between inlet and outlet flow which is before and after the leak location. The fluid used is the instrumentation air and the leaks are controlled with variable operating condition. This project will combine all the skill from Instrumentation, Control System and Fluid Mechanics.

ACKNOLEDGEMENT

First and foremost, the author would be very grateful to God the Almighty for His mercy as he gave me strength to complete the final year project throughout the year. The author would like to express my gratitude to all those who gave him the possibility to complete this Final Year Project. The author want to thank the Universiti Teknologi PETRONAS for giving him opportunity to commence this Final Year Project in the first instance, to do the necessary research work and to use Laboratory.

The author is deeply indebted to my FYP supervisor, Ir. Idris Bin Ismail whose help, stimulating suggestions and encouragement helped him in all the time of research for and writing of this Final Year Project. Thanks also to his colleagues who supported him in research work especially obliged to Mr Zhafif Zamros for all his assistance on the development of this project, both on the technical part and documentation.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Analysis of data from previous research paper entitle *Ensemble Dual Recursive Learning Algorithms for Identifying Custom Tanks Flow* by Afifi Akib, indicates that, possibility of predicting the mass flow rate of a leakage pipe using on-line system identification technique with different types of tank that are available in process industries. The Simulation studies for a pipe leakage problems show the feasibility and effectiveness of the proposed methods. This had been one of the main reasons to validate the finding by using the real test rig and controlled leak situation.

In this paper various pipeline leak detection methodologies are reviewed. These include biological, hardware-based and software-based methods. Each method has its advantages and disadvantages. To compare the performance of these methods, seven key attributes are defined: ***leak sensitivity, location estimate capability, operational change, availability, false alarm rate, maintenance requirement*** and ***cost.***

Pipeline leak detection systems (LDS) are also beneficial because they can enhance productivity and system reliability thanks to reduced downtime and reduced inspection time. Leak Detection Systems are therefore an important aspect of pipeline technology.

1.2 Problem statement

In many industries, there are serious safety concerns related to the use of flammable gases in both indoor and outdoor environments. Any accidental release of gas that might occur through damaged pipes or leakage at the storage tank imply risk which must be controlled. In such cases, the prediction of release flow-rate and time of duration of emergency is very crucial. A recent survey of 185 accidents involving natural gas showed that, of the total, 131 were caused during transportation, either by road, railway, ship or pipeline. The analysis of these data clearly shows the relatively high frequency of accidents in pipes: 127 of them occurred in piping systems. [3]

The most frequent causes of the accidents were mechanical failure, impact failure, human error and external events. Amongst the accidents arising from impact failure (39 cases), the most frequent specific cause was excavating machinery (21 accidents), followed by vehicles (5 cases) and heavy objects (5 cases). Other specific causes due to external events were ground subsidence (4 cases) and sabotage/vandalism (4 cases).Therefore, it is very important to develop reliable method of analyses of flammable gas release and dispersion [3]

1.3 Objective and Scopes of study

1.3.1 Objective

a) *To design leak detection test rig.*

Test rigs need to be build to test the laboratory so that the leak can be tested with various leak condition. The design of the test rig is based on the simulated situation in the previous research paper.

b) *To Select flow measurement system*

Flow can be calculated by various methods. There are many instruments that can be used to measure the flow, but in this project a suitable instrument based on the available budget and also the range of sensitivity are needed.

c) *To validate the finding from previous research paper*

Based on the previous finding, there are mathematical modelling has been used to done the simulation. By using the gathered data taken from the test rig experiments, both data can be compared thus validating the previous finding.

1.3.2 Scope of study

There are two part of this project. The first part involves the design and development of the test rig to gather data of the leaks. The test rig need to have capability to simulate leak based on wanted condition. A control mechanism is needed. Therefore, it is necessary to have a broad knowledge in instrumentation and control. The second part of the project is to analyse all the data gather from the experiment and convert it to suitable data for validating purposes. A strong knowledge of fluid mechanics and leak detection method are much needed to perform the task. Experience during industrial internship at site and plant would be very helpful to understand the project and relate it to the experimental setting in the laboratory.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of Leak Detection Methods

Methods used to detect product leaks along a pipeline can be divided into two categories, externally based (direct) or internally based (inferential). Externally based methods detect leaking product outside the pipeline and include traditional procedures such as right-of-way inspection by line patrols, as well as technologies like hydrocarbon sensing via fibre optic or dielectric cables. Internally based methods, also known as computational pipeline monitoring (CPM), use instruments to monitor internal pipeline parameters (i.e., pressure, flow, temperature, etc.), which are inputs for inferring a product release by manual or electronic computation [1]

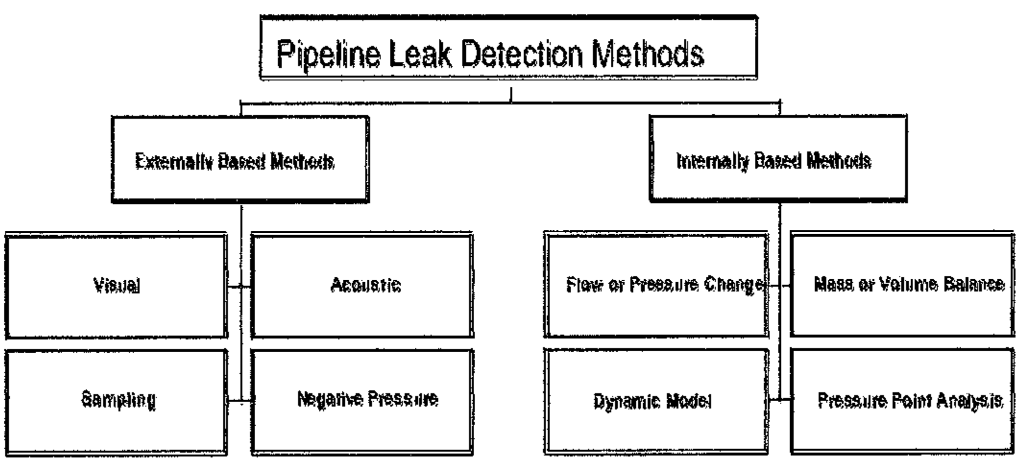


Figure 2 : Leak Detection Method

The method of leak detection selected for a pipeline is dependent on a variety of factors including *pipeline characteristics, product characteristics, instrumentation, communications capabilities,* and *economics* [3]. Pipeline systems vary widely in their physical characteristics and operational functions, and no one external or internal method is universally applicable or possesses all the features and functionality required for perfect leak detection performance. However, the chosen system should include as many desirable leak detection utilities as possible such as:

- Possesses accurate product release alarming
- Possesses high sensitivity to product release
- Identifies leak location
- Identifies leak rate
- Configurable to a complex pipeline network
- Offers efficient field and control centre support

2.2 Internal Leak Detection Systems

2.2.1 Volume Balance

The author has chosen the Volume Balance method for his model. This decision is base on the cost and feasibility criteria. The volume balance method of leak detection, also known as line balance, compensated volume balance, or mass balance, is based on measuring the discrepancy between the incoming (receipt) and outgoing (delivery) product volumes of a particular pipeline segment [7]. During a unit time interval, the volume of product that enters a pipe may not be equal to the measured volume exiting the pipe.

This relationship is stated below:

$$Q_l = Q_{in} - Q_{out} \quad (1)$$

where,

Q_l = Flow rate of the leak
Q_{in} = Inflow
Q_{out} = Outflow

2.2.2 Pressure Analysis

The Pressure Analysis method of leak detection is based on the analysis of pipeline pressure variations. When product breaches the pipeline wall there is a sudden drop in pressure at the location of the leak followed by rapid line depressurization a few milliseconds later. Pressure monitoring devices measure the rate of change of pressure or the mass flow at different sections of the pipeline. If the rate of change of pressure or the mass flow at two locations in the pipe differs significantly, it could indicate a potential leak. [5]

2.3 Instrumentation

Instrumentation includes the flow meters, pressure transducers, sensors, and cables situated along the pipeline (externally or internally) which measure parameters such as line pressure, temperature, flow, product characteristics, and the presence of hydrocarbons. Because the effectiveness of any pipeline LDS is limited primarily by the sensitivity and accuracy of the installed instrumentation, it is critical to select the best performing setup for a given operating scenario. In this project, we use orifice differential pressure and manometer to measure the differential pressure.

2.3.1 Orifice

2.3.1.1 Orifice Plate

The orifice plate is commonly used in clean liquid, gas, and steam service. It is available for all pipe sizes, and the pressure drop it requires is free, it is very cost-effective for measuring flows in larger pipes (over 6" diameter). The orifice plate is also approved by many standards organizations for the custody transfer of liquids and gases. [11] An orifice plate is a very simple device installed in a straight run of pipe. The orifice plate contains a hole smaller than the pipe diameter. The flow constricts experiences a pressure drop, and then the differential pressure can be related to a flow.

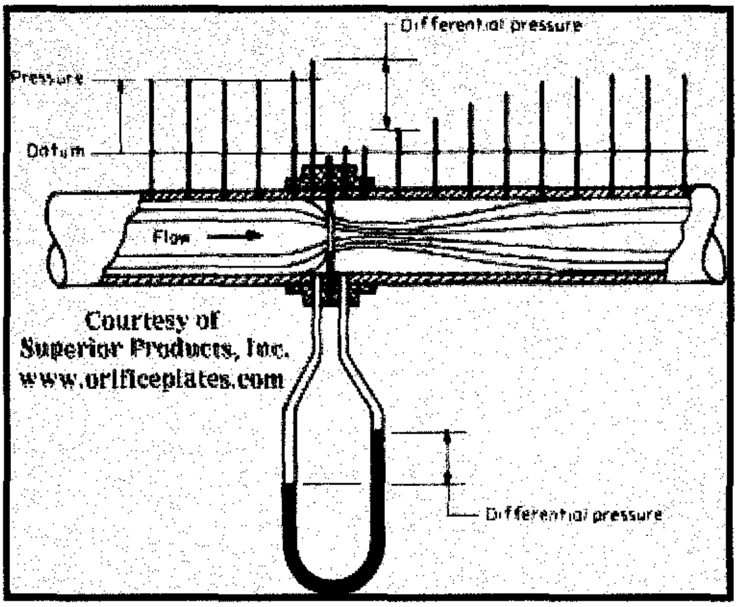


Figure 3 : Orifice Plate Flow Profile

The material use to made orifice plate normally is the stainless steel, but it also can be made of many other materials. The normal thickness of the plate used is in the range of 1/8” to 1/2” based on the function of the line size, the process temperature, the pressure, and the differential pressure. The conventional orifice is a thin circular plate into the pipeline between the two flanges.

2.3.1.2 Orifice Plate Types

There are three major types of orifice, which is concentric, eccentric and segmental. The differences allowed orifice to be use on different condition based on the type and flow of the fluid. The commonly used concentric orifice plate (Figure 3A) has a sharp (square-edged) concentric bore that provides an almost pure line contact between the plate and the fluid, with negligible friction drag at the boundary.

Eccentric (Figure 3B) bored plates are plates with the Orifice off-centre, or eccentric, as opposed to concentric. The bore of the eccentric Orifice normally is inscribed in a circle with is 98% of the pipe diameter, so that solids or slurries may pass through, Eccentric Orifice plates are used in many industries including heavy and light chemicals, steel, paper, atomic and petrochemicals.

Segmental bore Orifice (Figure 3C) plates are provided for measurements where solids are entrained in a gas or liquid flow stream. The circular portion of the bore is inscribed within a circle which is normally 98% of the pipe diameter. The segmental opening may be placed either at the top or bottom of the pipe. Industries using these bores include sewage treatment, steel, chemical, water conditioning, paper, and petrochemical.

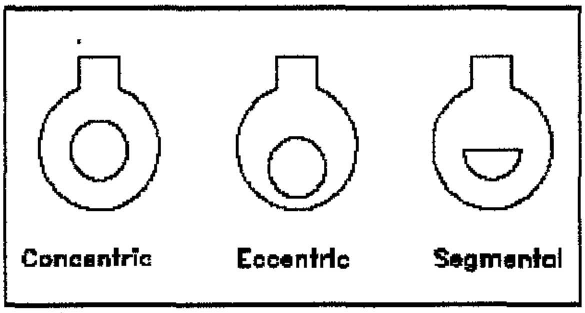


Figure 4 : Orifice Plate Types

2.3.1.3 Orifice Pressure Tap

When the flow area changes abruptly flow area downstream is not necessarily be the same as the pipe flow area due to vena contracta effect. This effect is brought about by an ability of a fluid to expand immediately upon encountering an area expansion as a result of the inertia of each fluid particle. This forms a central core flow bounded by regions of slower moving recirculation eddies, but the pressure sensed with pipe wall taps located within the vena contracta region will correspond to the higher moving velocity within the vena contracta of unknown area.

Pressure Tap Types

a) Flange Type

Both upstream and downstream are located at a distance of 25mm from the Orifice plate. This method is applicable to smaller pipes.

b) Corner Tap

Tapping for differential pressure is made at immediately upstream and downstream positions of the orifice. This system is used primarily for small pipes. (Smaller 2")

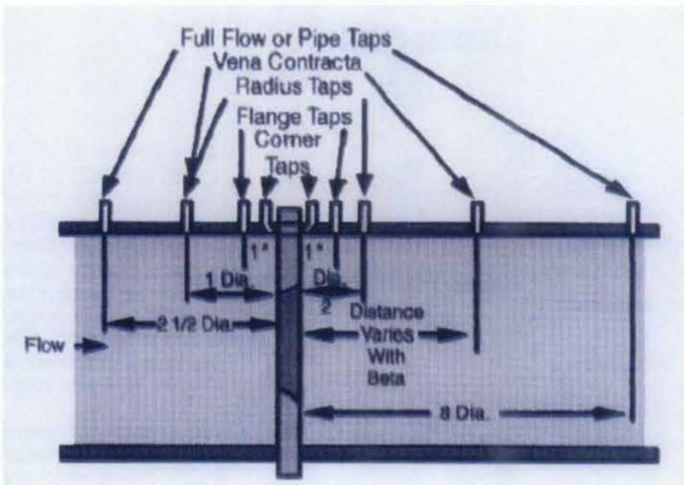


Figure 5 : Pressure Tap Location

2.3.1.4 Orifice Meter

An orifice meter is a conduit and a restriction to create a pressure drop. An hour glass is a form of orifice. A thin sharp edged orifice can be used as the flow restriction. As the fluid approaches the orifice the pressure increases slightly and then drops suddenly as the orifice is passed. It continues to drop until the "vena contracta" is reached and then gradually increases until at approximately 5 to 8 diameters downstream a maximum pressure point is reached that will be lower than the pressure upstream of the orifice. The decrease in pressure as the fluid passes thru the orifice is a result of the increased velocity of the gas passing thru the reduced area of the orifice.

When the velocity decreases as the fluid leaves the orifice the pressure increases and tends to return to its original level. All of the pressure loss is not recovered because of friction and turbulence losses in the stream. The pressure drop across the orifice increases when the rate of flow increases. When there is no flow there is no differential. The differential pressure is proportional to the square of the velocity, it therefore follows that if all other factors remain constant, then the differential is proportional to the square of the rate of flow. [6]

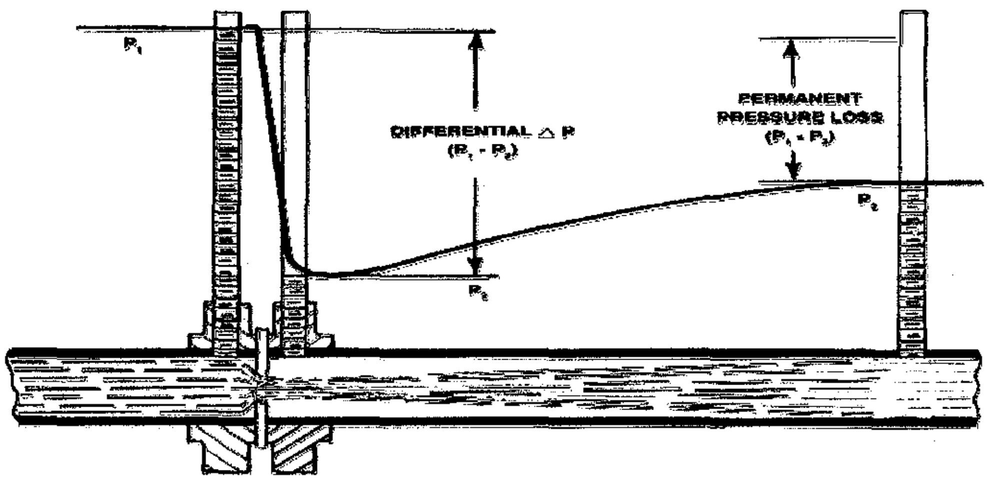


Figure 6 : Typical Orifice Flow Pattern

2.3.1.5 Orifice Pressure Drop and Flow Rate Calculation

Orifice plate pressure drop calculator is used for flow rate measuring in pipe systems. With orifice plate, pressure drop is created. Based on the magnitude of pressure drop, flow rate can be calculated. It is practical for larger tube diameters and for dirty fluid where other methods are impractical. Pressure drop through the orifice because of velocity increase can be calculated as follows:

$$\frac{2(p_1-p_2)}{\rho} = \frac{16Q^2}{\pi^2}\left(\frac{1}{D_2^4} - \frac{1}{D_1^4}\right) \quad (2)$$

Where:
Q - Volumetric flow rate (m^2/s)
D - diameter of pipeline (mm)
p – Pressure (Pa)
ρ – density of the fluid in kilograms per cubic metre (kg/m^3)

Flow rate can be determined as:

$$Q = CEAY\sqrt{\frac{2(\Delta p)}{\rho}} \quad (3)$$

Where:

C = orifice flow coefficient, $\frac{0.65}{\sqrt{1-(\beta)^4}}$

A =cross-sectional area of the orifice hole, $\frac{\pi D_2^2}{4}$ (m)

Y = for compressible gas < 1.0,

Reynolds Number

$$Re_D = \frac{VD}{u} = \frac{\rho VD}{\mu} \qquad (5)$$

where,

β - Diameter relation $\frac{D2}{D1}$
Re_D - Reynolds number which can be calculated as follows:
u - Kinematic viscosity
μ - dynamic viscosity

Orifice Flow coefficient can be calculated (for gases at STP):

$$C = \frac{0.65}{\sqrt{1-(\beta)^4}} \qquad (6)$$

Friction Factor (F)

The formula used to calculate the friction factor is dependent on the magnitude of the Reynolds Number. If the Reynolds Number is less than 2300, flow is laminar and the following formula is used to calculate the friction factor:

$$f = \frac{64}{\text{Re}} \qquad (7)$$

where,

F - friction factor
Re - Reynolds Number < 2300

In instances where the Reynolds Number is greater than 100,000, friction is highly dependent on the roughness of the conductor's inner surface. In these cases Colebrook's equation, which considers pipe roughness, is used to calculate the friction factor. However, due to the relatively low fluid velocities and high fluid viscosities present in hydraulic systems, Reynolds Numbers of this magnitude should not be encountered.

2.3.2 Manometer

Manometers measure a pressure difference by balancing the weight of a fluid column between the two pressures of interest. Large pressure differences are measured with heavy fluids, such as mercury (e.g. 760 mm Hg = 1 atmosphere). Small pressure differences, such as those experienced in experimental wind tunnels are measured by lighter fluids such as water (27.7 inch H_2O = 1 psi; 1 cm H_2O = 98.1 Pa).

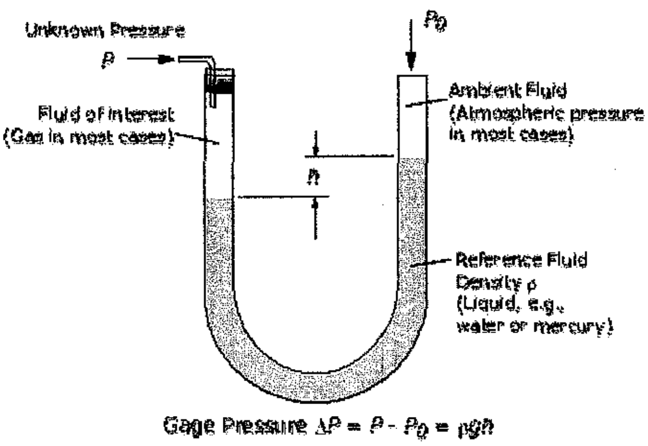


Figure 7 : Manometer Operation

If the U-tube manometer is connected to a pressurized vessel at two points the *pressure difference* between these two points can be measured.

$$
\begin{aligned}
&P = P_0 \\
&P = P_0 + \rho gha \\
&P = P_0 + \rho g(h_b - h_a) + \rho mgh \\
&P - P_0 = \Delta P = \rho g(h_b - h_a) + (\rho_m - \rho)\, gh
\end{aligned}
\tag{8}
$$

If the fluid whose pressure difference is being measured is a gas and $\rho m \gg \rho$, then the terms involving ρ can be neglected, so

$$\Delta P = \rho gh \tag{9}$$

2.3.3 Differential Pressure Transmitter

2.3.3.1 Operating Principle

Differential pressure flow meters use Bernoulli's equation to measure the flow of fluid in a pipe. Differential pressure flow meters introduce a constriction in the pipe that creates a pressure drop across the Flowmeter. When the flow increases, more pressure drop is created. Impulse piping route the upstream and downstream pressures of the Flowmeter to the transmitter that measures the differential pressure to determine the fluid flow.

Bernoulli's equation states that the pressure drop across the constriction is proportional to the square of the flow rate. Using this relationship, 10 percent of full scale flow produces only 1 percent of the full scale differential pressure. At 10 percent of full scale flow, the differential pressure flowmeter accuracy is dependent upon the transmitter being accurate over a 100:1 range of differential pressure. Differential pressure transmitter accuracy is typically degraded at low differential pressures in its range, so flowmeter accuracy can be similarly degraded. Therefore, this non-linear relationship can have a detrimental effect on the accuracy and turndown of differential pressure flow meters. Remember that of interest is the accuracy of the flow measurement system not the accuracy of the differential pressure transmitter.

Figure 8 : Differential Pressure Transmitter

2.4 Mathematical modelling

2.4.1 Model of Gas Release

A reversible and adiabatic process, complying with the gas state equation and Poisson equation. In order to account for deviation from an ideal state, a compressibility factor Z is included in the state equation. Accordingly, the state equation of real gas is given as:

Here Z is assumed to be constant over the pipe length of interest:

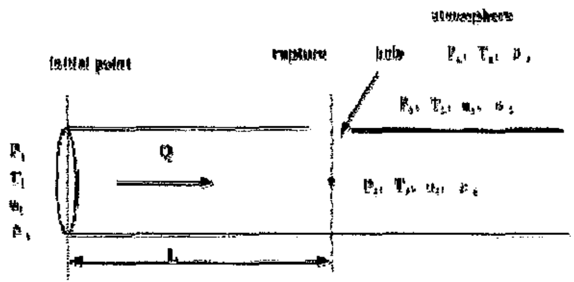


Figure 9 : Schematic Diagram of Gas Release

A schematic diagram of gas release through a hole given by Helena, Juan, Joaquin, & Josep (1998) is as shown in figure 2, indicating a hole located in the distance L from a pressure regulation valve of a pipeline, through which the release takes place. Various points are considered: Point 1, near the valve; Point 2, inside the pipeline on a level with the hole; Point 3, the release point; and a point in atmosphere. Several assumptions are given; (1) gas flows adiabatically in the pipeline and isentropically at the release point and (2) a model of a flow is considered as a one dimensional model.

In order to delineate the adiabatic flow of gas in the pipeline quantitatively, an equation can be obtain by using equations of energy and momentum:

$$\frac{k+1}{k} ln\left(\frac{P_1T_1}{P_2T_2}\right) + \frac{M}{RG^2}\left(\frac{P_2^2}{T_2} - \frac{P_1^2}{T_1}\right) + \frac{4fL_e}{D} = 0 \qquad (10)$$

where,

L_e - The equivalent length of the pipeline
f - Friction factor is a function of the roughness of the pipe (e)
Re - Reynolds number

The expression for the gas release rate (Q) can be obtained by substituting the state equation of gas, the Poisson equation and the continuity equation.

$$Q = C_o A_{or} \frac{dP}{dt} \sqrt{\left(\frac{2M}{ZRT_2} \frac{\gamma}{\gamma-1}\left[\left(\frac{P_a}{\frac{dP}{dt}}\right)^{2/\gamma} - \left(\frac{P_a}{\frac{dP}{dt}}\right)^{\frac{\gamma+1}{\gamma}}\right]\right)} \qquad (11)$$

where

C_o - Discharge coefficient
A_{or} - Area of hole
M - Molecular weight (kg/kmol)
Z - Compressibility factor
R - Gas constant (Pa $m^3Mol^{-1}K^{-1}$),
T - Temperature (K),
P_a - Atmospheric pressure (Mpa),
γ - Heat capacity ratio
$\frac{dP}{dt}$ - Change in pressure over time.

The expression of pressure throughout a pipe is given as:

$$\frac{dP}{dt} = -\frac{\gamma Q_o}{m_o} . P_o^{(3-\gamma)/2\gamma} . \frac{\left[P^{\frac{\gamma-1}{\gamma}} - P_a^{\frac{\gamma-1}{\gamma}}\right]^{1/2} . P^{\frac{\gamma-1}{\gamma}}}{\left[1 - \frac{P_a}{P_o}^{\frac{\gamma-1}{\gamma}}\right]^{1/2}} \qquad (10)$$

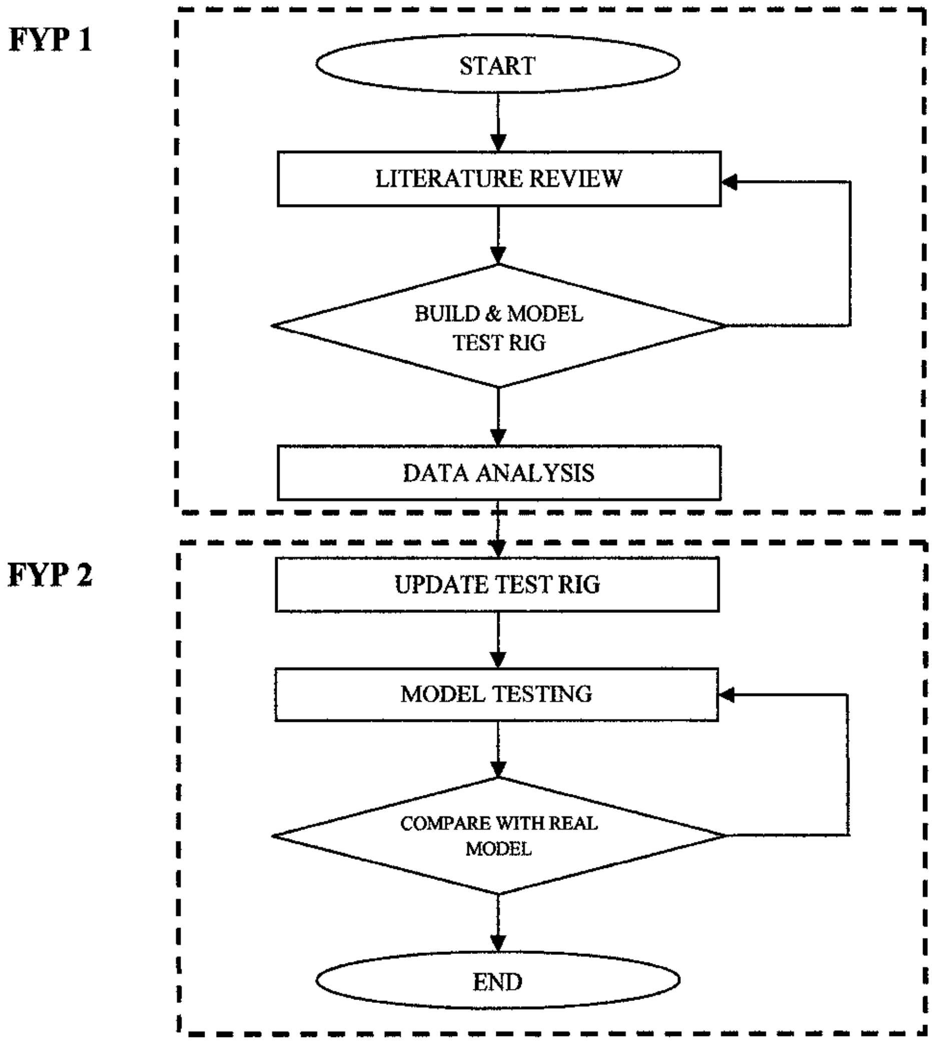
Where Q_o is the initial flow rate in the pipe (kg/s), P_a is the atmospheric pressure (MPa), P_o initial pressure (MPa) and m is the gas mass (kg). This equation cannot be solved analytically. The fourth order Runge-Kutta method can be used to get the pressure, temperature and density of a gas at any moment of subsonic flow [7].

CHAPTER 3

METHODOLOGY

3.1 Project Workflow

This project will be based on the following methodology. The methodology has been designed to fully optimise the time frame provided in order to completely carry out the planned and anticipated project works.



3.2 Research Methodology

In order to achieve the aim of the project, some researches had been done on leak detection systems that are been used from the past, present and followed by future technology to detect leak in pipeline. Journals, conference paper, books and internet website are referred. As the information is available, it is very crucial to for the author to undergo the learning process as building and modelling test need to be done by the first semester.

The next step is to select the flow measurement and experiment method. The budget available is not much so the author needs to think of the suitable instrumentation that needs to be used. After the design of test rig is completed, for the first semester, manometer is used because it suits the criteria of selection. The following step is preparing the report that need to be submitted to the Final Year Project Committee. There is also an oral presentation which will take place towards the end of the semester.

3.3 Procedure Identification

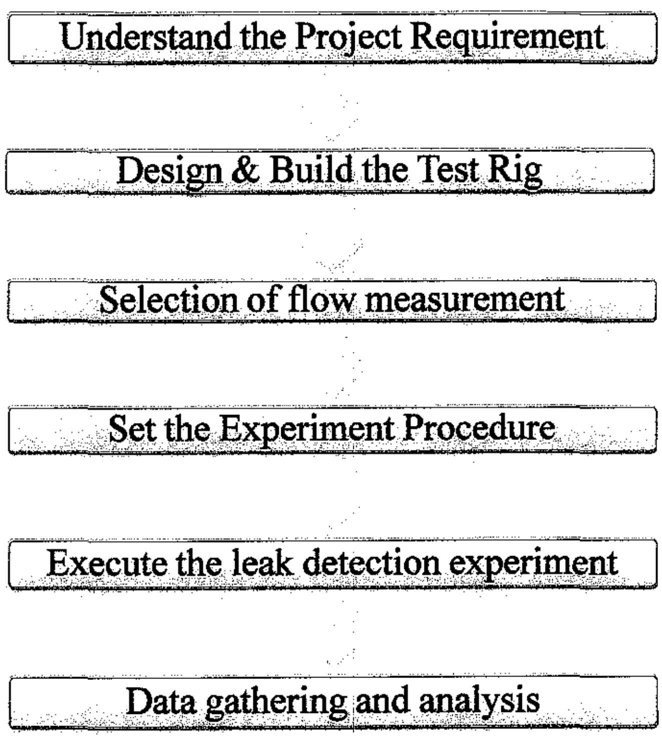


Figure 10 : Procedure Identification and Flow Diagram

3.3 Experimental Work

3.3.1 Test Rig

The test rig is build beside a pilot plant in building 23 of Universiti Teknologi PETRONAS. The connection to the test rig is an exhaust discharge that can be control by control valve. Initially, the characteristics of pressure analysis by leak occurrence in a 3 m long pipeline were analyzed during pipeline operation with and with continuous gas flow. An orifice flange is installed to create pressure drop before and after the leak placement. The leak size is varied by 4mm, 5mm, 6mm at different valve opening. The instrument used to measure differential pressure drop at the orifice is a manometer. Figure below show the experimental assembly used to simulate the occurrence of leaks in the pipeline.

In FYP2 2, the test is modified by adding the Differential Pressure transmitter and also a better flange tap so that a measurement can be done much more easily than the first model test rig. Furthermore the pipeline for leak location also has been change to 1 meter for distance factor. The leak this time is varied to 4mm, 6mm, 8mm and 10 mm. The distance of each leak also is 10cm each.

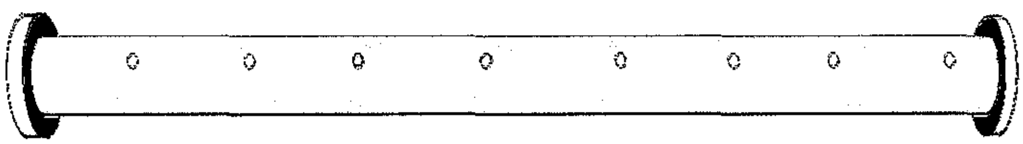


Figure 11 : Leak Testing Pipeline

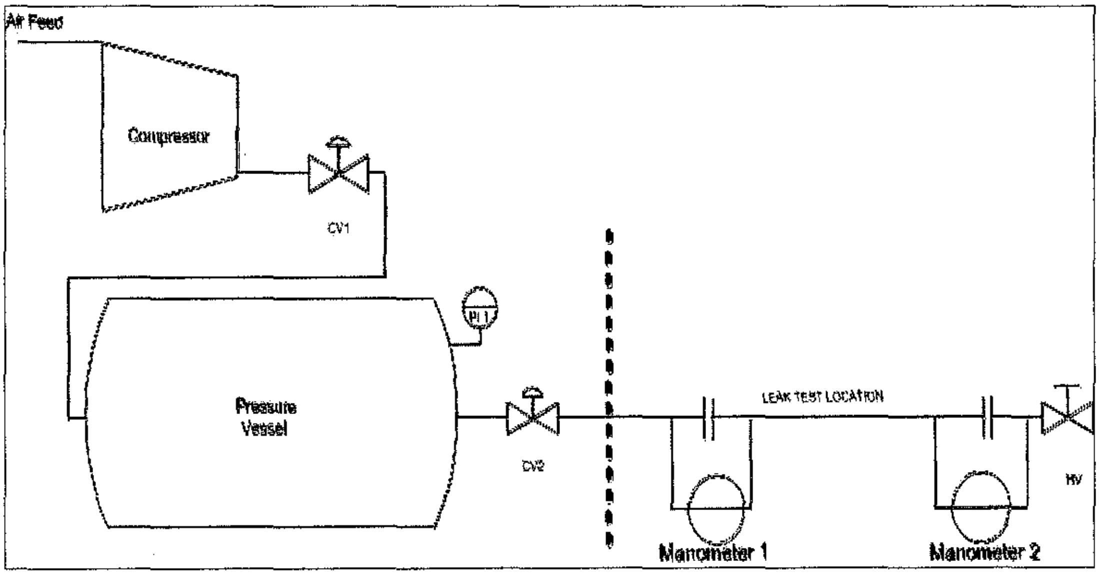


Figure 12 : Test Rig Assembly (FYP 1)

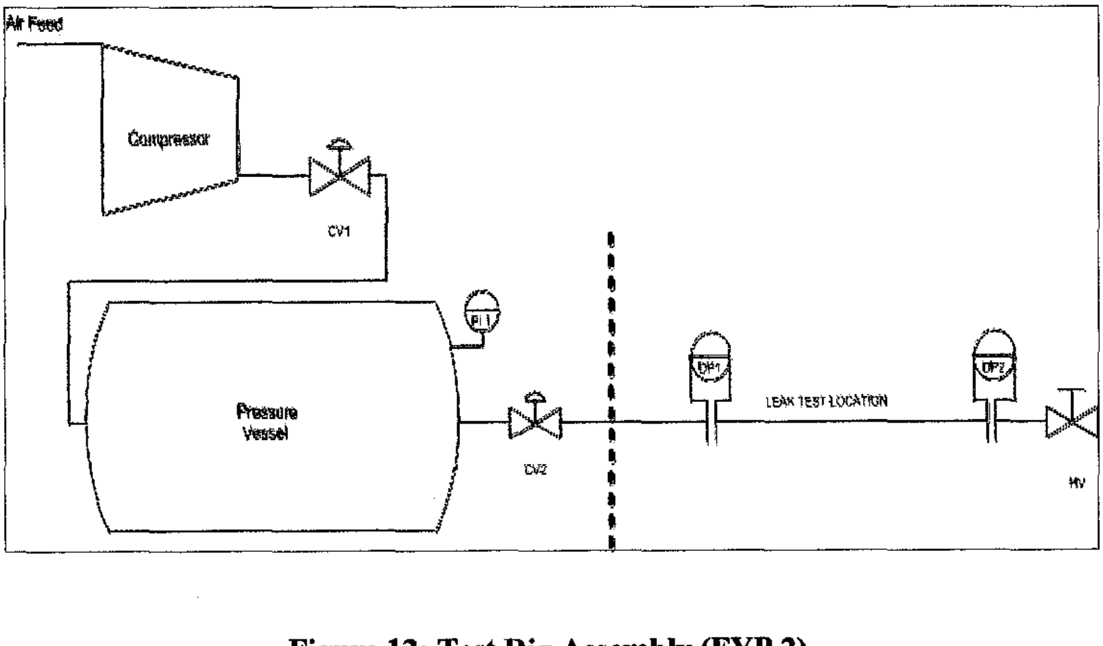


Figure 13: Test Rig Assembly (FYP 2)

3.4 Tools required

There will be some equipments and tools that will be used for this project. This project mostly involves the hardware implementation. Thus, the hardware or tools and software required are:

a. *Orifice Selection*

*(source:*http://saba.kntu.ac.ir/eecd/ecourses/instrumentation/types & Selection)

The concentric orifice plate is recommended for clean liquids, gases, and steam flows when Reynolds numbers range from 20,000 to 107 in pipes under six inches. Because the basic orifice flow equations assume that flow velocities are well below sonic, a different theoretical and computational approach is required if sonic velocities are expected. The minimum recommended Reynolds number for flow through an orifice varies with the beta ratio of the orifice and with the pipe size. In larger size pipes, the minimum Reynolds number also rises.

Flange taps have been used and concentric orifice plate selected. These plates are usually used in pipe sizes exceeding four inches in diameter, and must be carefully installed to make sure that no portion of the flange or gasket interferes with the opening. Flange taps are used with both types of plates, and are located in the quadrant opposite the opening for the eccentric orifice, in line with the maximum dam height for the segmental orifice.

Orifice Performance

Although it is a simple device, the orifice plate is, in principle, a precision instrument. Under ideal conditions, the inaccuracy of an orifice plate can be in the range of 0.75-1.5% AR. Orifice plates are, however, quite sensitive to a variety of error-inducing conditions. Precision in the bore calculations, the quality of the installation, and the condition of the plate itself determine total performance.

Installation factors include tap location and condition, condition of the process pipe, adequacy of straight pipe runs, gasket interference, misalignment of pipe and orifice bores, and lead line design. Other adverse conditions include the dulling of the sharp edge or nicks caused by corrosion or erosion, war page of the plate due to water hammer and dirt, and grease or secondary phase deposits on either orifice surface. Any of the above conditions can change the orifice discharge coefficient by as much as 10%.

b. Differential Pressure Transmitter Selection

Flowmeter selection is complicated, partly due to the number of design and technologies, but also to the great many factor that influence the choice. Here are just some of the factors to consider before selecting a flowmeter:

- Size and measuring range of the flowmeter
- Fluid compatibility
- Process accuracy requirements
- Pressure requirements
- Acceptable pressure drop
- Cleaning requirements
- Desired measurement units (such as volume, velocity or mass)
- Uni-directional or bi-directional measurement
- Fluid viscosity limitations
- Necessary approvals for use in hazardous areas, sanitary applications and so on
- Data-output requirements (i.e., 4–20 mA, relay, digital or simple display)
- Calibration and re-calibration requirements
- Maintenance issues
- Operating costs
- Connection styles (flanged, wafer, threaded, weld-on)

CHAPTER 4

RESULT AND DISCUSSION

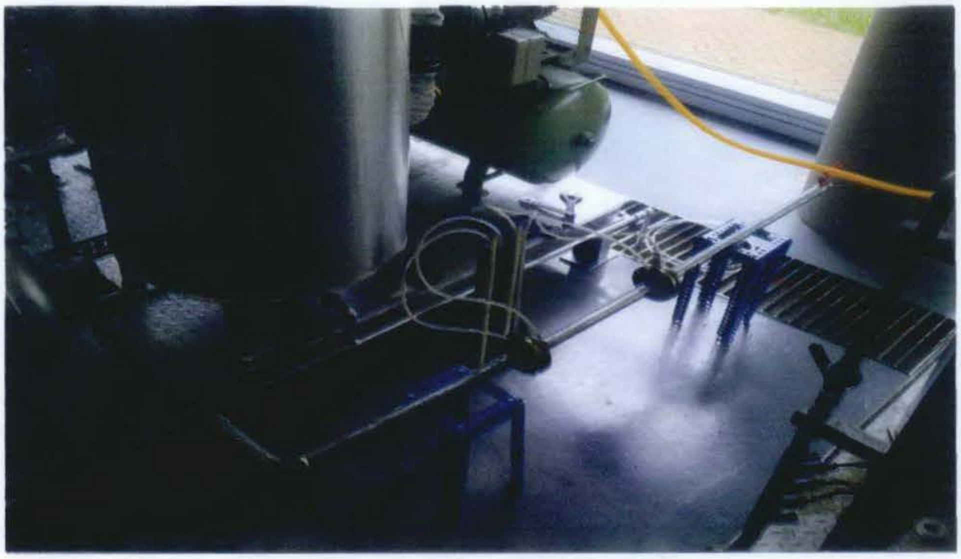
4.1 Complete Test Rig

In FYP 1, Leaks were provoked through a hole, drilled in manipulated portion of pipeline. The leak magnitude was controlled through an orifice installed in the leak line. Air was used in the experiments been provided by the compressor which feed the air line and was fed to the pipeline through a pressure vessel. Air pressure was constant at 2.0 bars. In the leakage experiments with steady state gas flow a 8.5 mm orifice was installed at the end of the pipeline to keep it pressurized. The orifice size was varied 0.5 to 0.7 bore ratio Leaks were simulated experimentally for various valve opening.

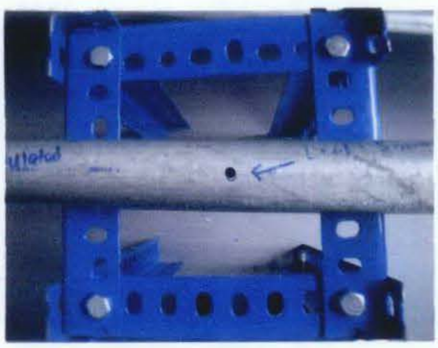
Figure 14 : Complete Test Rig

4.2 Initial Test run

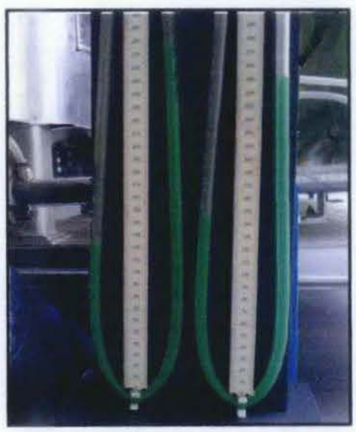
Valve Opening	: 0% - 50%
Vessel Pressure	: 2 Bar.
Leak size	: 5mm (diameter)



(a)



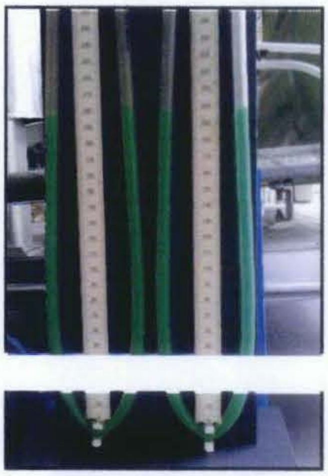
(b)



(c)

Figure 15 : a) Layout of Test Rig
b) Leak hole
c) Manometer

Table 1 : Manometer Fluid Height Difference, Before and After Leakage

Valve Opening	Manometer Measurement	Remarks
0 %		before leakage, $h = 0$ After leakage , $h = 0$
10 %		before leakage, $h = 10$ mm After leakage , $h = 8$ mm
20 %		before leakage, $h = 15$ mm After leakage , $h = 9$ mm

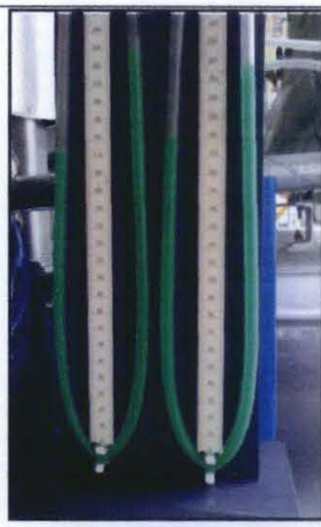
30%		before leakage, *h* = 53 mm After leakage , *h*= 36 mm
40 %		before leakage, *h* = 153 mm After leakage , *h*= 106 mm
50 %		before leakage, *h* = 277 mm After leakage , *h*= 186 mm

Table 2: Differential Pressure Calculation (manometer)

Valve Opening	Differential Pressure	
	Before leak	After Leak
0 % (no flow)	h= 0 mm = 0.0 m $\Delta P = \rho gh$ ΔP = 1000 kg/m^3 × 9.81 m/s^2 × 0 ΔP = 0	h= 0 mm = 0.0 m $\Delta P = \rho gh$ ΔP = 1000 kg/m^3 × 9.81 m/s^2 × 0 ΔP = 0

Table 3: Comparison between Pressure Drop ($\Delta P1$ -$\Delta P2$)

Valve opening	($\Delta P1$)	($\Delta P2$)	($\Delta P1$- $\Delta P2$)
0 %	0	0	0
10%	98.1 N/m^2	78.50N/m^2	19.60 N/m^2
20%	147.15 N/m^2	88.29 N/m^2	58.86 N/m^2
30%	519.93 N/m^2	353.16 N/m^2	166.77 N/m^2
40%	1500.93 N/m^2	1039.86 N/m^2	461.11 N/m^2
50%	2717.37 N/m^2	1824.66 N/m^2	892.71 N/m^2

Theoretically, if the rate of change of pressure or the mass flow at two locations in the pipe differs significantly, it could indicate a potential leak. From the table above, there is difference in the value of differential pressure before the leakage and after the leakage which means there are pressure drop. The valve opening is tested at 10 % opening to 50 % opening because at 60% opening, the pressure is out of the manometer range used. The author planned to use the higher range of manometer in future experiment.

4.3 Improved Test Rig

4.3.1 Measurement Instrument Replaced.

In FYP1 manometer was used as the instrument to measured differential pressure. The result we get is limited because at certain range, the manometer will burst the fluid out. So, an instrument with higher range is needed. With the help of lab technologist, we manage to get two set of differential transmitter for our project. The new instrument allowed the experiment to be the experiment at higher range than before.

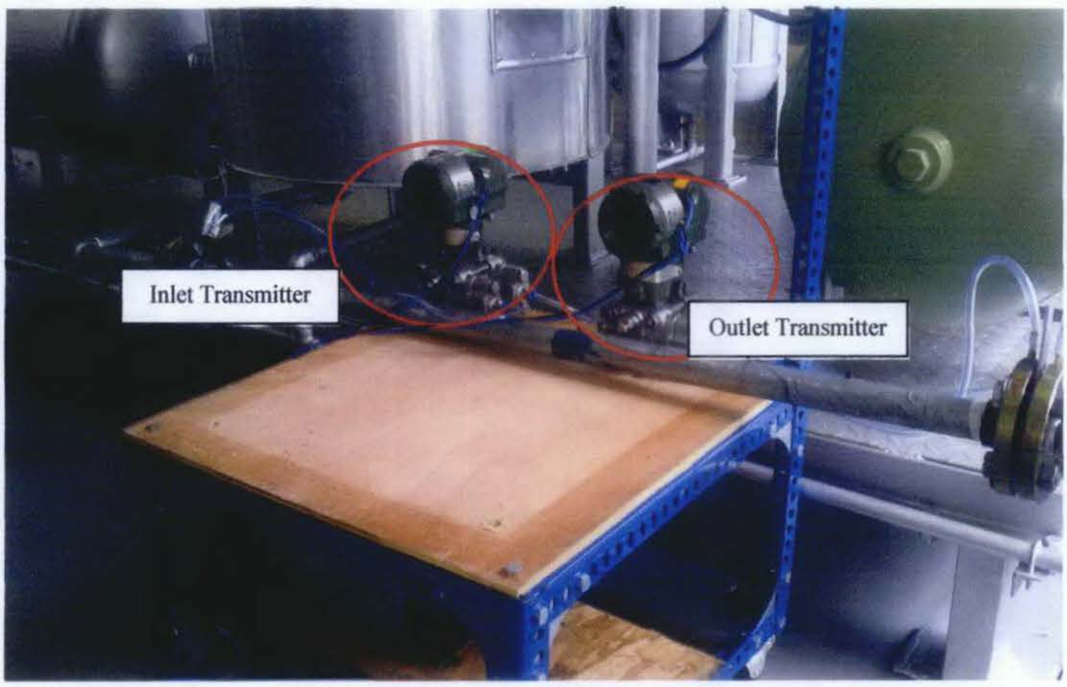


Figure 16 : Transmitter Installed at the test rig

The newly installed are the Differential transmitter from Yokogawa with range 0 kPa to 200 kPa. At first the instrument is calibrated before being use. Calibration was done at the transmitted span is adjusted so it fit our experiment. The span use is from 0 kPa to 100 kPa. The outlet transmitter is used to measure the differential pressure at orifice before the leak, while the outlet transmitter is used to measure the after leak differential pressure.

4.3.2 New Flange Pressure Tap

This design uses the flanges of adjacent pipes upstream and downstream of the orifice. According to ISO5167, the taps are positioned 25mm (1") upstream of the plate and 25mm (1") downstream in the respective pipe sections. This design facilitates replacement of the orifice plate, meaning that orifice plate of different restrictive diameter can be inserted to increase the range ability of the flow. Furthermore, this allowed the pipe changed without disturbing with the connection between the transmitter and the pipeline.

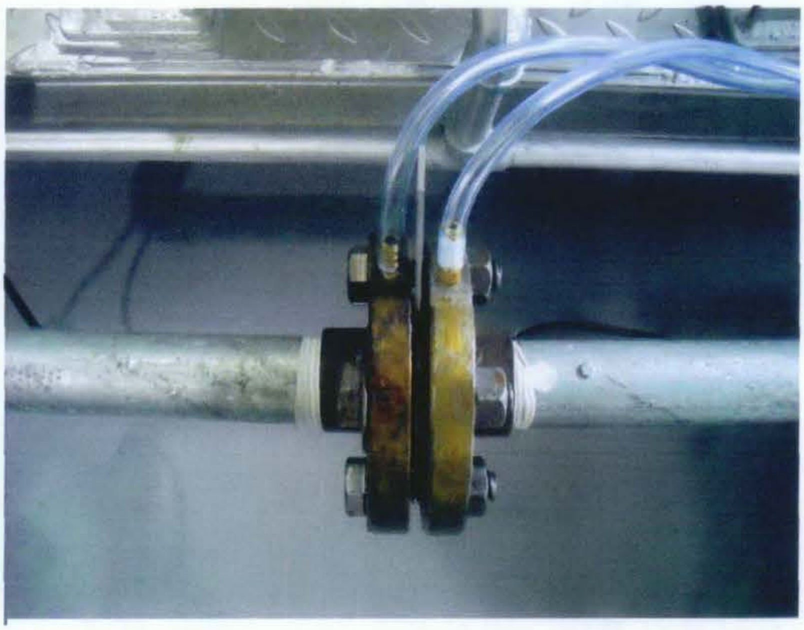
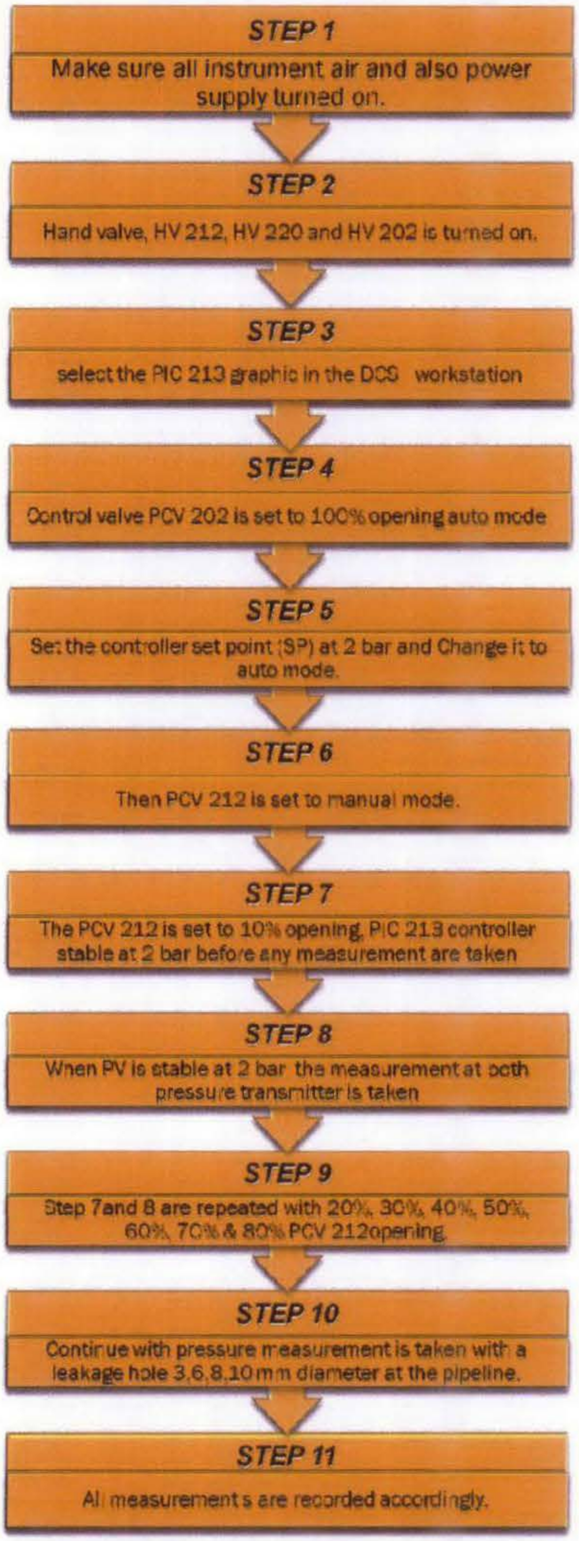


Figure 17 : New Flange Pressure Tap

4.4 Experimental Procedure

After the completion of the test rig, a proper procedure is needed to gather data from the test rig. The procedure objective is for the data taken is accurate and also stable. The procedure use is as below:



4.5 Leak Test

The first part of the experiment is to take the pressure measurement without any leakage at the pipeline.Before leak was introduced, the test rig were tested to verify all the connection are properly made. Leaking test was done by using the soap water at every connection, bolt, screws and gasket-orifice area. if there are leaking, the a bubble will form indicating that the leak was found. A further adjustment need to mend the leak. After confirmed all the leakage was cover, then the first experiment were done. The results are as below.

Pressure in vessel : 2 Bar
Temperature : Room Temperature (20 °C)

Table 5: Initial differential Pressure

Valve Opening	10%			20%		
	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2(KPA)	DP (KPA)
No Leak	0.1	0.08	0.02	0.1	0.08	0.02
Valve Opening	30%			40%		
	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2(KPA)	DP (KPA)
No Leak	0.5	0.3	0.2	1.8	1.2	0.6
Valve Opening	50%			60%		
	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2(KPA)	DP (KPA)
No Leak	3.5	2.2	1.3	8.2	5.4	2.8
Valve Opening	70%			80%		
	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2(KPA)	DP (KPA)
No Leak	29.4	21.8	7.6	40	30.4	9.6

4.6 Pipe Friction

Ideally the differential pressure should be the same at both inlet and outlet based on the theory that if there were no leak, Qin = Qout. As the table show, the different are cause by the friction factor in the pipeline. This factor is because the flow of liquid through a pipe is resisted by viscous shear stresses within the liquid and the turbulence that occurs along the internal walls of the pipe, created by the roughness of the pipe material. This resistance is usually known as pipe friction and is measured is feet or metres head of the fluid, thus the term head loss is also used to express the resistance to flow.

4.7 Differential Pressure

This is the pressure drop at the inlet and outlet represents by transmitter 1 and transmitter 2 respectively. DP is the different between pressure drop at transmitter 1 and transmitter 2.

Table 6: Transmitter Reading Based on Differential Pressure (10% - 40%)

Valve Opening	10%			20%		
Leak Distance (cm)	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2(KPA)	DP (KPA)
6	0.1	0.08	0.02	0.1	0.08	0.02
16	0.1	0.08	0.02	0.2	0.1	0.1
26	0.1	0.08	0.02	0.2	0.1	0.1
36	0.1	0.08	0.02	0.2	0.1	0.1
46	0.1	0.08	0.02	0.2	0.1	0.1
56	0.1	0.08	0.02	0.2	0.1	0.1
66	0.1	0.08	0.02	0.2	0.1	0.1
76	0.1	0.08	0.02	0.2	0.1	0.1
86	0.1	0.08	0.02	0.2	0.1	0.1
96	0.1	0.08	0.02	0.2	0.1	0.1
Valve Opening	30%			40%		
Leak Distance (cm)	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2 (KPA)	DP (KPA)
6	0.7	0.4	0.3	1.7	1.0	1.6
16	0.7	0.4	0.3	1.7	1.0	1.6
26	0.6	0.4	0.3	1.7	1.0	1.6
36	0.7	0.3	0.4	1.7	1.0	1.6
46	0.6	0.4	0.3	1.7	1.0	1.6
56	0.6	0.4	0.3	1.7	1.0	1.6
66	0.6	0.4	0.3	1.7	1.0	1.6
76	0.7	0.3	0.4	1.7	1.0	1.6
86	0.7	0.4	0.3	1.7	1.0	1.6
96	0.7	0.4	0.3	1.7	1.0	1.6

Table 7: Transmitter Reading Based on Differential Pressure (50% - 80%)

Valve Opening	50%			60%		
Leak Distance (cm)	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2(KPA)	DP (KPA)
6	3.3	2.0	1.3	7.4	4.5	2.9
16	3.3	2.0	1.3	7.4	4.5	2.9
26	3.3	2.0	1.3	7.4	4.6	2.9
36	3.3	1.8	1.5	7.4	4.8	2.6
46	2.9	2.0	0.9	7.8	4.8	3.0
56	3.3	2.0	1.3	7.8	4.8	3.0
66	3.1	2.0	1.1	7.8	5.0	2.8
76	3.1	1.8	1.3	7.8	5.0	2.8
86	3.1	2.0	1.3	8.7	5.4	3.3
96	3.1	2.0	1.3	8.7	5.4	3.3
Valve Opening	70%			80%		
Leak Distance (cm)	TX 1(KPA)	TX 2(KPA)	DP (KPA)	TX 1(KPA)	TX 2(KPA)	DP (KPA)
6	26.2	17.5	8.7	38.7	27.3	11.4
16	26.3	17.3	9.0	38.8	27.3	11.5
26	26.3	17.3	9.0	38.7	27.2	11.5
36	26.3	17.5	8.8	38.8	27.3	11.5
46	26.3	17.5	8.8	38.8	27.2	11.6
56	26.5	17.4	8.2	38.6	27.2	11.4
66	26.7	17.5	8.2	38.7	27.3	11.4
76	26.7	17.5	8.2	38.7	27.3	11.4
86	27.1	17.7	9.4	38.8	27.3	11.5
96	27.4	18.5	8.9	38.8	27.4	11.4

Valve Opening Factor

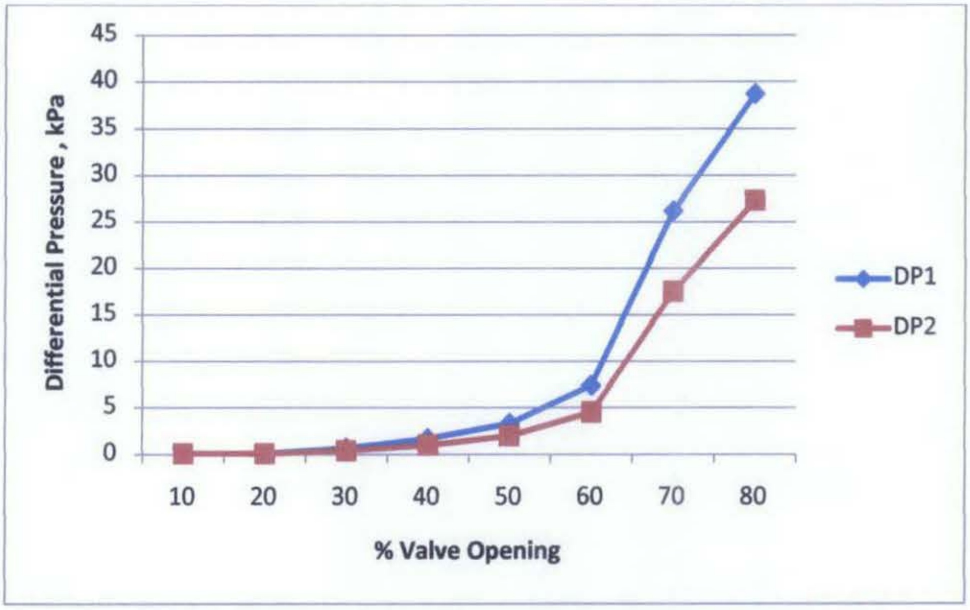


Figure 18: Differential Pressure against Valve Opening.

As the result shown, the distance factor does not affect the inlet and outlet differential pressure. This is because the holes are located very near to each other hence the result of differential pressure is almost the same. Due to the restriction of the experiment, larger distance test cannot be tested. The result showed that the higher valve opening percentage will result in higher pressure difference.

4.8 Flowrate Calculation

The equation applies only to perfectly laminar, in viscid flows. For real flows (such as water or air), viscosity and turbulence are present and act to convert kinetic flow energy into heat. To account for this effect, a **discharge coefficient** C is introduced into the above equation to marginally reduce the flowrate Q. To calculate the flow rate, the bellow formula is used:

$$Q = CEAY\sqrt{\frac{2(\Delta p)}{\rho}} \qquad (3)$$

where:

CE = orifice flow coefficient, $\frac{0.65}{\sqrt{1-(\beta)^4}} = 0.6713$

A =cross-sectional area of the orifice hole, $\frac{\pi D_2^2}{4} = 1.26676 \times 10^{-4}\ m^2$

Y = for compressible gas < 1.0, ∴ we assume = 0.98

Δp = from the table 2

ρ = 1.205 at room temperature (20°C)

The leak flow rate:

$$Q_{leak} = Q_{inlet} - Q_{outlet}$$

The data after the computations:

Table 8: Calculated Flowrate Result (10% - 40%)

Valve Opening	10%			20%		
Leak Distance (cm)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)
6	1.07E-03	1.05E-03	2.40E-04	1.07E-03	1.02E-03	3.39E-04
16	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
26	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
36	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
46	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
56	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
66	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
76	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
86	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
96	1.07E-03	1.05E-03	2.40E-04	1.52E-03	1.05E-03	1.10E-03
Valve Opening	30%			40%		
Leak Distance (cm)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)
6	2.84E-03	2.15E-03	1.86E-03	4.42E-03	3.39E-03	2.84E-03
16	2.84E-03	2.15E-03	1.86E-03	4.42E-03	3.39E-03	2.84E-03
26	2.63E-03	2.15E-03	1.52E-03	4.42E-03	3.39E-03	2.84E-03
36	2.84E-03	1.86E-03	2.15E-03	4.42E-03	3.39E-03	2.84E-03
46	2.63E-03	2.15E-03	1.52E-03	4.42E-03	3.39E-03	2.84E-03
56	2.63E-03	2.15E-03	1.52E-03	4.42E-03	3.39E-03	2.84E-03
66	2.63E-03	2.15E-03	1.52E-03	4.42E-03	3.39E-03	2.84E-03
76	2.84E-03	1.86E-03	2.15E-03	4.42E-03	3.39E-03	2.84E-03
86	2.84E-03	2.15E-03	1.86E-03	4.42E-03	3.39E-03	2.84E-03
96	2.84E-03	2.15E-03	1.86E-03	4.42E-03	3.39E-03	2.84E-03

Table 9: Calculated Flowrate Result (50%-80%)

Valve Opening	50%			60%		
Leak Distance (cm)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)
6	6.16E-03	4.80E-03	3.87E-03	9.23E-03	7.20E-03	5.78E-03
16	6.16E-03	4.80E-03	3.87E-03	9.23E-03	7.20E-03	5.78E-03
26	6.16E-03	4.80E-03	3.87E-03	9.23E-03	7.28E-03	5.68E-03
36	6.16E-03	4.55E-03	4.16E-03	9.23E-03	7.43E-03	5.47E-03
46	5.78E-03	4.80E-03	3.22E-03	9.48E-03	7.43E-03	5.88E-03
56	6.16E-03	4.80E-03	3.87E-03	9.48E-03	7.43E-03	5.88E-03
66	5.97E-03	4.80E-03	3.56E-03	9.48E-03	7.59E-03	5.68E-03
76	5.97E-03	4.55E-03	3.87E-03	9.48E-03	7.66E-03	5.58E-03
86	5.97E-03	4.80E-03	3.56E-03	1.00E-02	7.88E-03	6.16E-03
96	5.97E-03	4.80E-03	3.56E-03	1.00E-02	7.88E-03	6.16E-03
Valve Opening	70%			80%		
Leak Distance (cm)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)	Qin (m^2/s)	Qout (m^2/s)	Qleak (m^2/s)
6	1.74E-02	1.42E-02	1.00E-02	2.11E-02	1.77E-02	1.15E-02
16	1.74E-02	1.41E-02	1.02E-02	2.11E-02	1.77E-02	1.15E-02
26	1.74E-02	1.41E-02	1.02E-02	2.11E-02	1.77E-02	1.15E-02
36	1.74E-02	1.42E-02	1.01E-02	2.11E-02	1.77E-02	1.15E-02
46	1.74E-02	1.42E-02	1.01E-02	2.11E-02	1.77E-02	1.16E-02
56	1.75E-02	1.42E-02	1.02E-02	2.11E-02	1.77E-02	1.15E-02
66	1.75E-02	1.42E-02	1.03E-02	2.11E-02	1.77E-02	1.15E-02
76	1.75E-02	1.42E-02	1.03E-02	2.11E-02	1.77E-02	1.15E-02
86	1.77E-02	1.43E-02	1.04E-02	2.11E-02	1.77E-02	1.15E-02
96	1.78E-02	1.46E-02	1.01E-02	2.11E-02	1.78E-02	1.15E-02

Inlet flow rate against leak flow rate

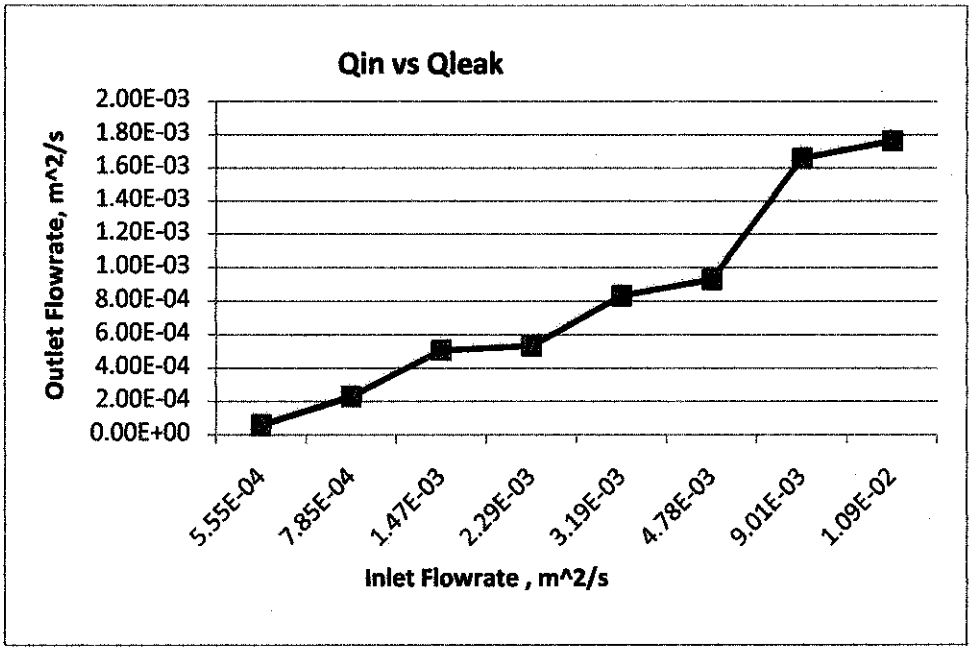


Figure 19: The Graph between Inlet Flow Rates against Leak Flow Rate

Based on the result, we can see that the inlet flow influence the leak flow rate. At higher inlet pressure, the leakage rate increase. So with this we can make use of the lowering the inlet pressure to reduce the amount of fluid flowing out due to the pressure lost in the leaks.

Distance Factor

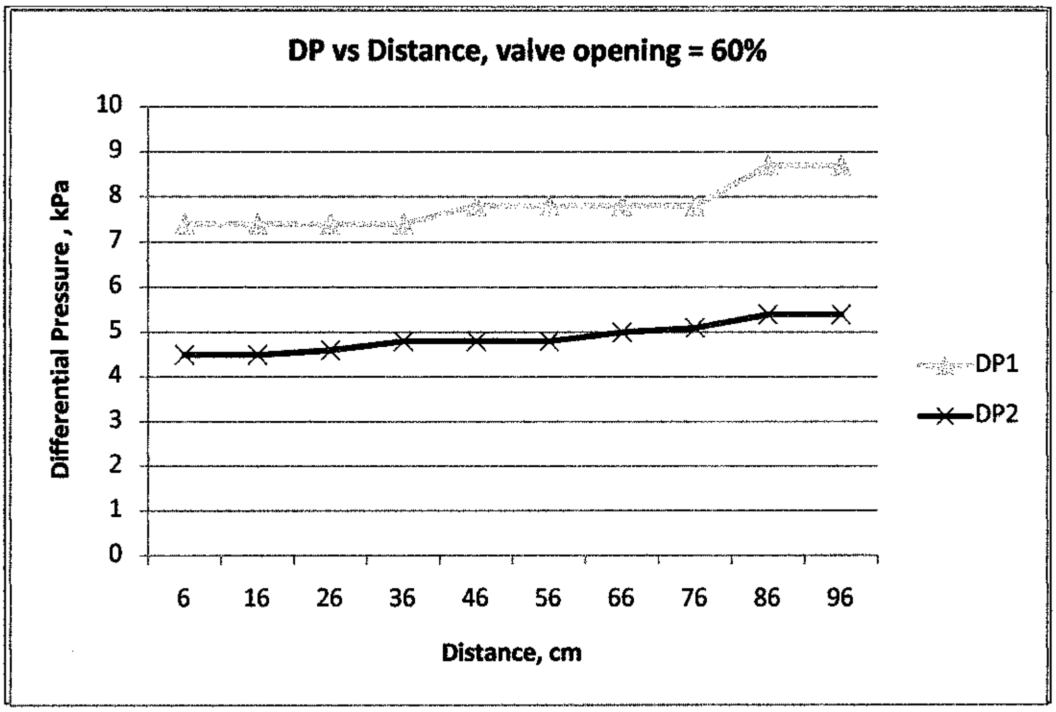


Figure 20 : Distance against Differential pressure

Distance is the important in determining the leak localization. Different placement of leak taken as 6cm, 16cm, 26cm, 36cm, 46cm, 56cm, 66cm, 76cm, 86cm, and 96cm was done in the experiment. The result of the experiment showed that the distance is very near and not very significant to influence the leak flow rate. Thus, for a longer pipeline needed to investigate this factor of leak for leak locating.

Leak Size Factor

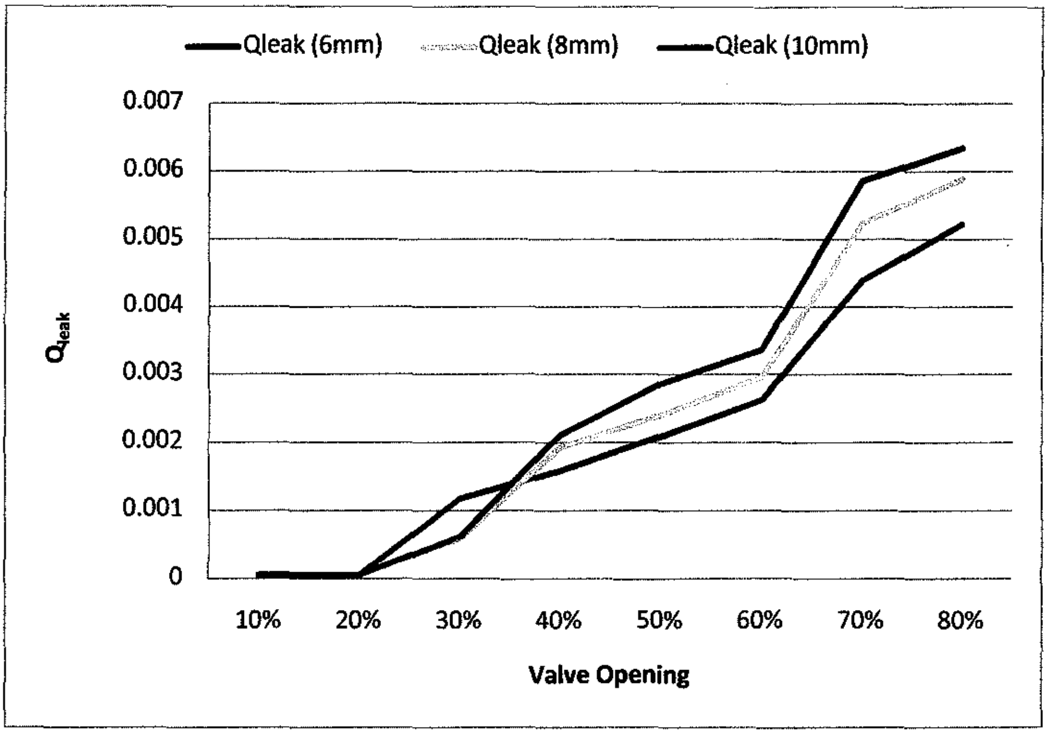


Figure 21 : Leak size factor against Valve Opening

The leak size factor plays an important role in leak flow rate result. In the beginning, valve opening 10% to 30% the effect is not very significant. Then when the valve opening increase the pressure drop also increase cause by the increase in velocity of the fluid in the pipeline. These showed that, when there is larger pressure drop in the pipeline would give probability of larger leak hole size.

Air Flow Velocity Calculation

The velocity distribution can be determined at a number of cross sections at different locations along a pipe. With the differential pressure already obtain in from the first table, air flow velocity can be calculated by using the Bernoulli's equation.

$$v = \sqrt{\frac{2\Delta p}{\rho}} \qquad (4)$$

where,

ΔP = Pressure different between the two tapping point gather from DP transmitter
ρ = air density at the room temperature, 1.205 kg/m^3

When fluid flows past a stationary solid wall, the shear stress set up close to this boundary due to the relative motion between the fluid and the wall leads to the development of a flow boundary layer. The boundary layer may be either laminar or turbulent in nature depending on the flow Reynolds number.

The growth of this boundary layer can be revealed by studying the velocity profiles at selected cross-sections, the core region still outside the boundary layer showing up as an area of more or less uniform velocity.

If velocity profiles for cross-sections different distances from the pipe entrance are compared, the rate of growth of the boundary layer along the pipe length can be determined. Once the boundary layer has grown to the point where it fills the whole pipe cross-section this is termed "fully developed pipe flow".

Reynolds Number (Re) Calculation

The Reynolds number is a measure of the way in which a moving fluid encounters an obstacle. It is proportional to the fluid's density, the size of the obstacle, and the fluid's speed, and inversely proportional to the fluid's viscosity.

$$Re = \frac{\rho v D}{\mu} \qquad (5)$$

ρ : Fluid Density = 1.205 kg/m^3 (at Room Temperature)
v: Fluid Velocity = $\sqrt{\frac{2\Delta\rho}{\rho}}$ (m/sec)
D: inside diameter of pipeline = 1 inch = 25.4 mm
μ : Coefficient of fluid dynamic viscosity = 1.8207 x 10^{-5} Ns/m^2

Table 8: Reynolds Number

Valve Opening	10%		20%	
Leak Distance (cm)	Re_{in}	Re	Re_{in}	Re
6	21665606.44	21117021	21665606	20553799
16	21665606.44	21117021	30639794	21117021
26	21665606.44	21117021	30639794	21117021
36	21665606.44	21117021	30639794	21117021
46	21665606.44	21117021	30639794	21117021
56	21665606.44	21117021	30639794	21117021
66	21665606.44	21117021	30639794	21117021
76	21665606.44	21117021	30639794	21117021
86	21665606.44	21117021	30639794	21117021
96	21665606.44	21117021	30639794	21117021

Based on the calculated result, all the Reynolds Number of the flow is in excess of 4000. We can conclude that Turbulent flow occurs in this experiment when the All the Reynolds number exceeds 4000.

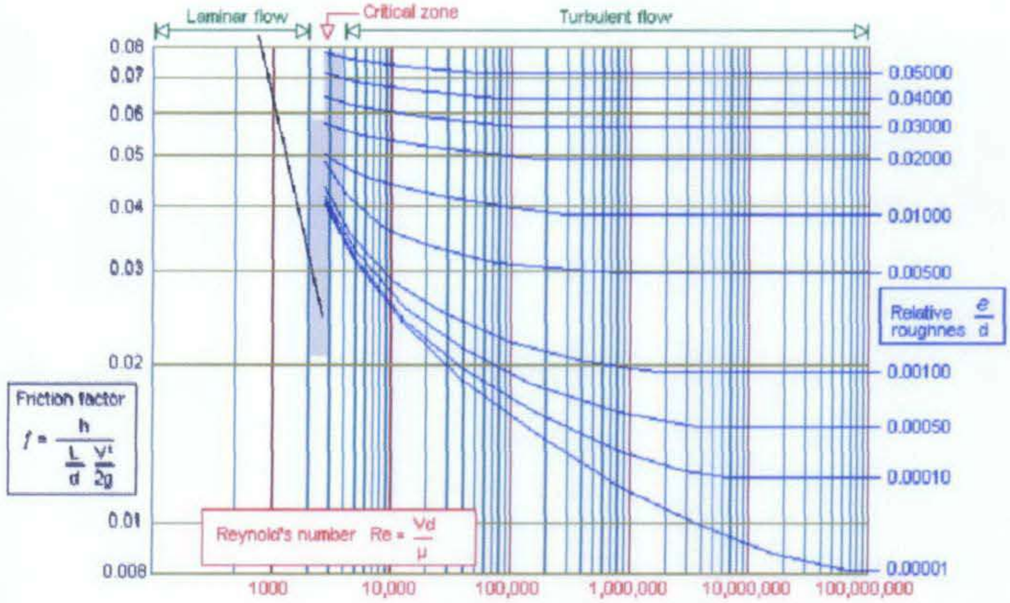


Figure 22: Laminar Flow and Turbulent Flow of Fluids

So because of the turbulence flow, Eddy currents are present within the flow and the ratio of the internal roughness of the pipe to the internal diameter of the pipe needs to be considered to be able to determine the friction factor. In large diameter pipes the overall effect of the eddy currents is less significant. In small diameter pipes the internal roughness can have a major influence on the friction factor.

The relative roughness of the pipe and the Reynolds number can be used to plot the friction factor on a friction factor chart. The friction factor can be used with the ***Darcy-Weisbach formula*** to calculate ***the frictional resistance*** in the pipe.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Below is the summary of the project outcome: -

5.1.1 Development and Design of a test rig

Test rig was developed in order to perform leak testing in the pipeline. Test rigs was be build to test the experiment so that the leak can be tested with various leak condition. The design of the test rig is based on the simulated situation in the previous research paper.

5.1.2 Selection of flow measurement system

Flow can be calculated by various methods. There are many instruments that can be used to measure the flow, but in this project a suitable instrument based on the available budget and also the range of sensitivity are needed. Manometer was selected because it simple, easy to use and also suitable with experiment range. Due to manometer restriction to large valve opening, it was change to differential pressure transmitter with range of 0kpa to 200kpa.

5.1.3 Validate the finding from previous research paper

Because of the author put more effort on building the test rig since he has little knowledge about it. Further validation is unable to be done. The formula used by the mathematical modelling also is very complicated to be understood. This can be continuing because the test rig is finish developed.

5.2 RECOMMENDATION

5.2.1 Validation of the model

Currently the author has not been able to validate the finding from the previous paper. So based on the test rig availability and finding continuous testing and further analysis can be done to validate the model used in the previous paper.

The first part of modelling already been analyzes but still needed improvement. Therefore, further studies regarding the behaviour of the fluid and its reaction to the experimental situations need to be done.

5.2.2 Varying the leak condition

As the literature review, there are many factors affecting the leak flow rate other than what has been considered by the author. Therefore, in the future work the author would suggest varying the leak condition such as the temperature and number of tanks to determine their effect in leak performance. This is important to detect the most influential factor in developing the better system for leak detection system.

5.2.3 Leak Localization

Based on the project result, it has been determined that the pressure analysis cannot be used to localizing a leak occurring in the pipeline. Therefore , the author recommend put more for effort in finding the best, inexpensive yet effective method in developing the leak localization system. This is a very crucial aspect in the leak detection system as it indicate the place of leak so that the plant operator can react to it with the slightest error in judging the leak placement.

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APPENDICES

APPENDIX A: Gantt Chart

Milestone for the First Semester of 2-Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■	■													
2	Preliminary Research Work		■	■	■											
					●											
3	Submission of Preliminary Report															
4	Seminar 1 (optional)					■	■	■	Mid-semester break							
										●						
5	Project Work					■	■	■								
6	Submission of Progress Report															
7	Seminar 2 (compulsory)										■	■	■	■	●	
8	Project work continues									■	■	■	■	■		●
9	Submission of Interim Report Final Draft		●													
10	Oral Presentation															

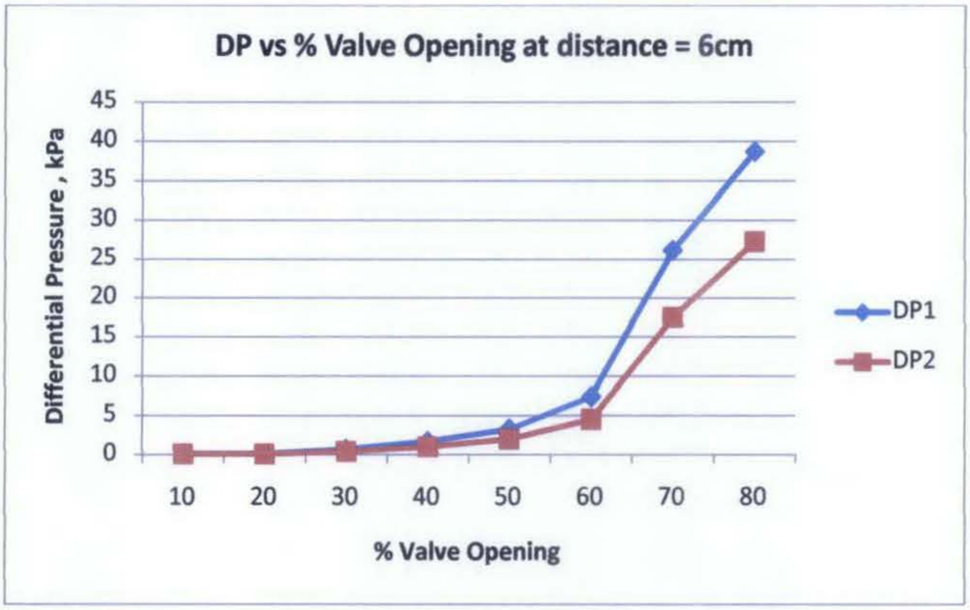
Milestone for the Second Semester of 2-Semester Final Year Project

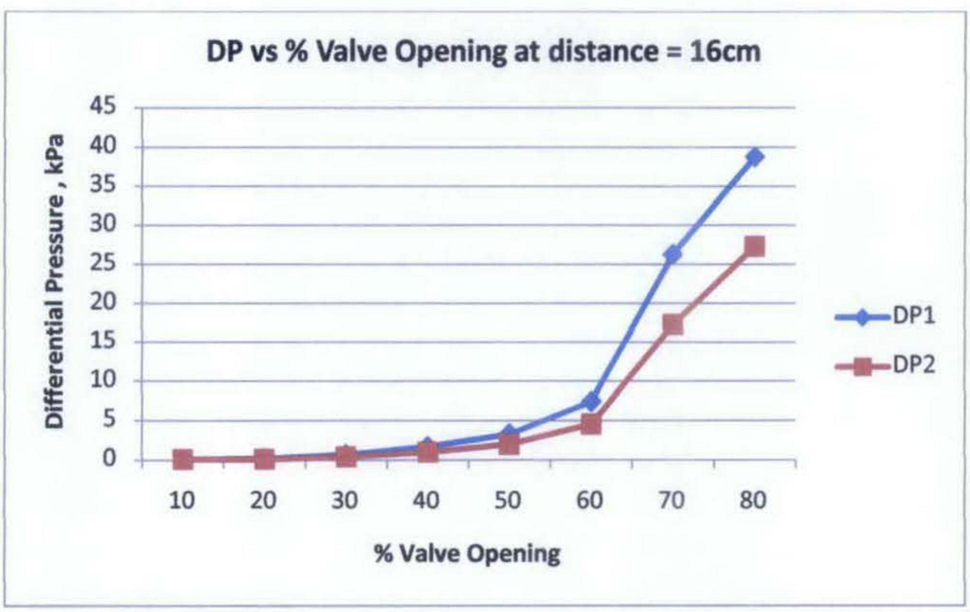
No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continue	■	■	■					Mid-Semester Break							
2	Submission of Progress Report 1				●											
3	Project Work Continue				■	■	■	■								
4	Submission of Progress Report 2									●						
5	Seminar (compulsory)										■	■	■			
5	Project work continue									■	■	■	■			
6	Poster Exhibition											●				
7	Submission of Dissertation (soft													●		
8	Oral Presentation														●	
9	Submission of Project Dissertation															●

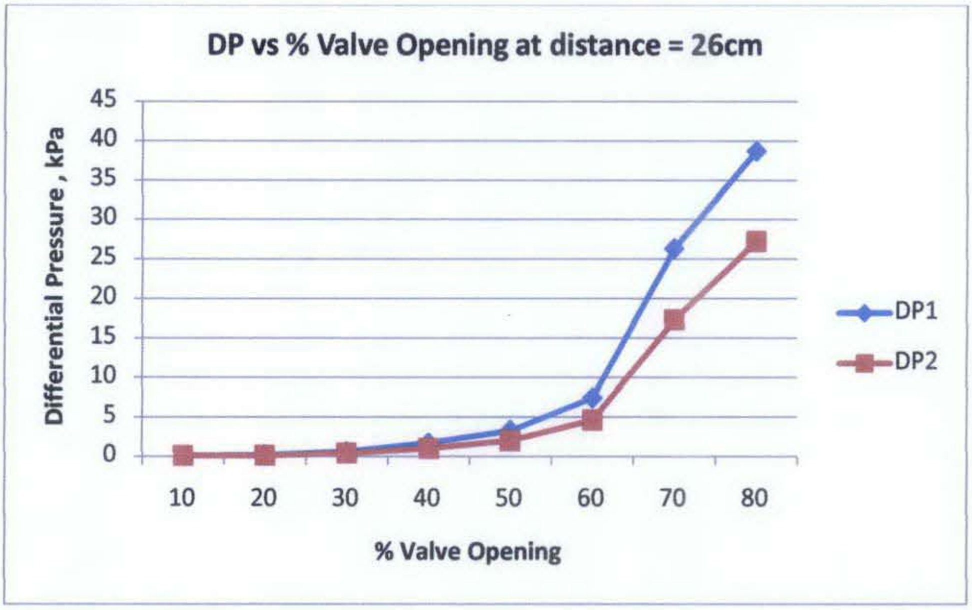
● Milestone

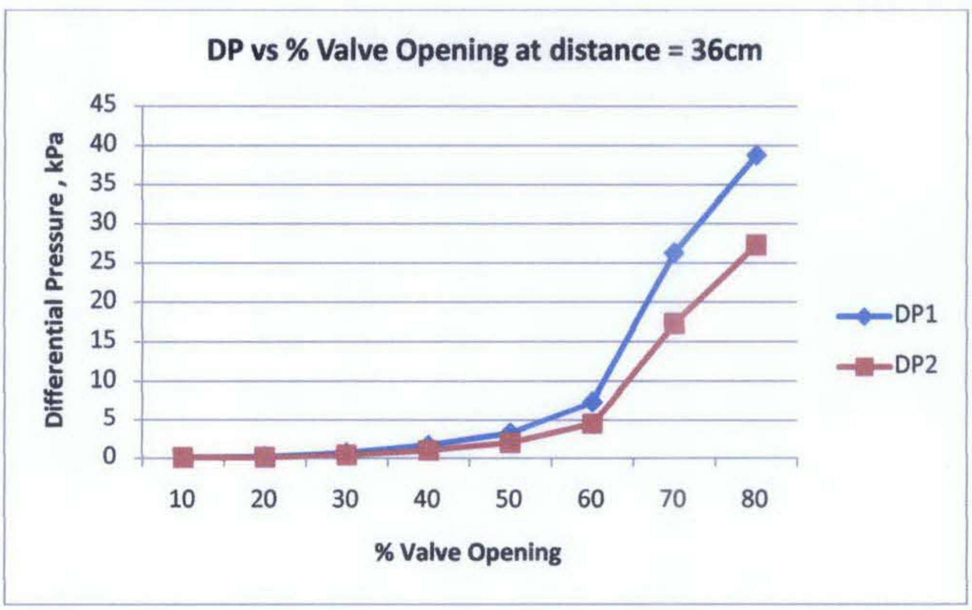
■ Process

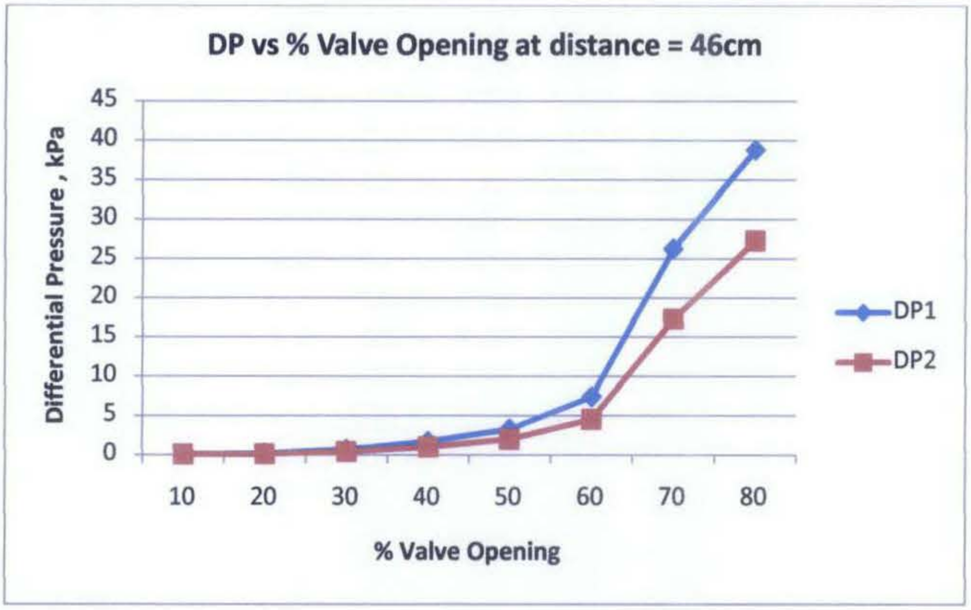
The graph of Differential Pressure against Valve Opening.

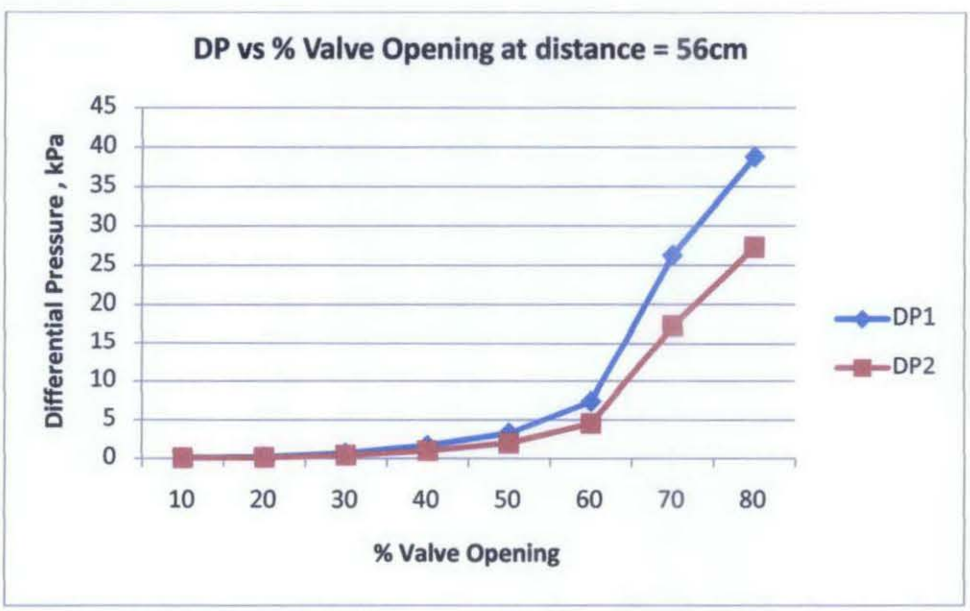


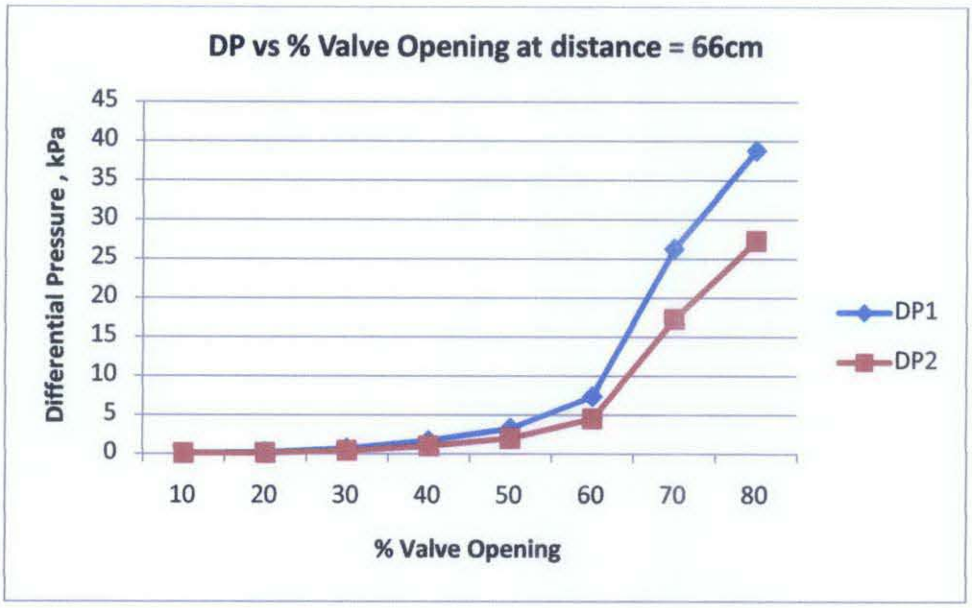


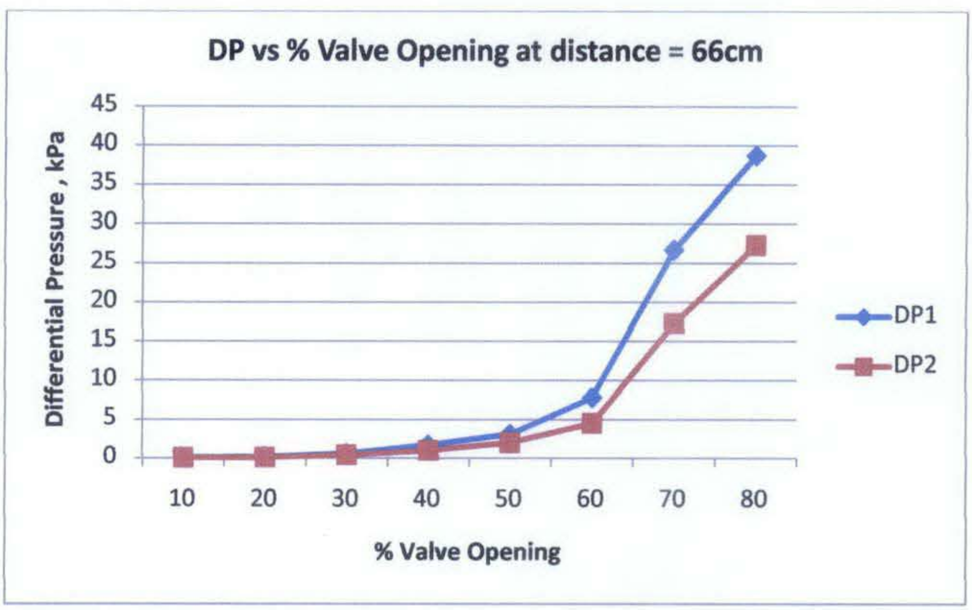

DP vs % Valve Opening at distance = 26cm
Differential Pressure , kPa
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

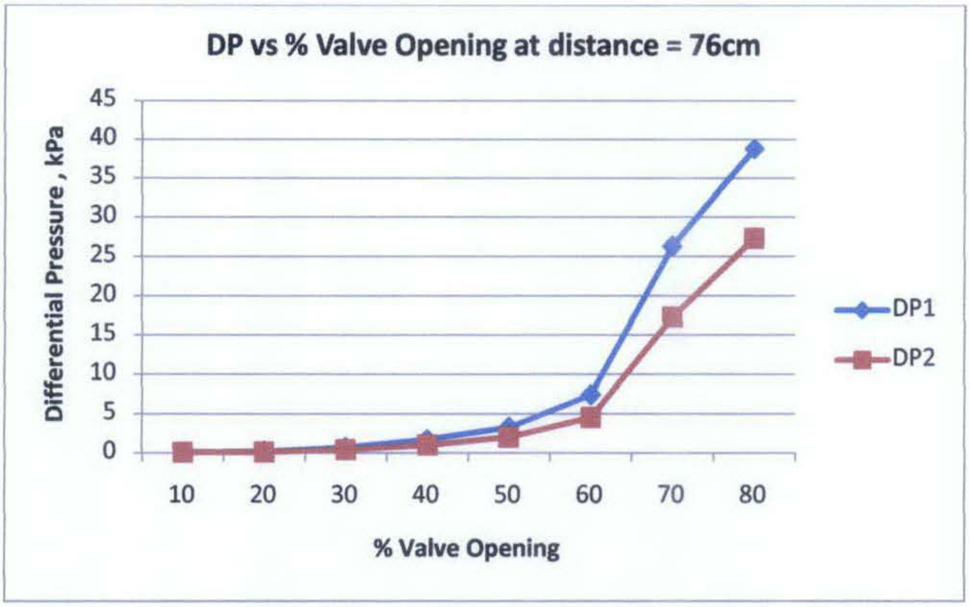

DP vs % Valve Opening at distance = 36cm
Differential Pressure , kPa
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

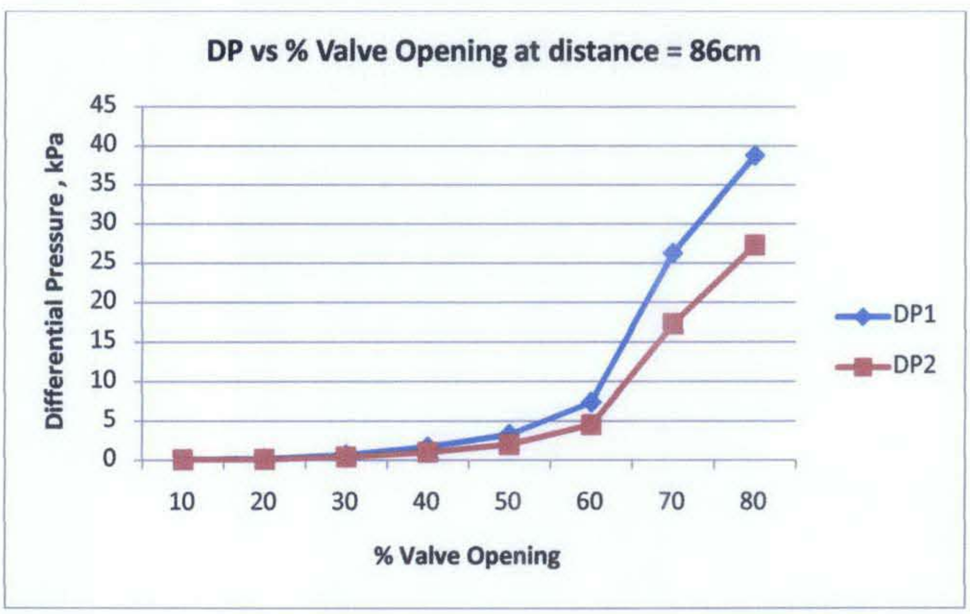

DP vs % Valve Opening at distance = 46cm
Differential Pressure , kPa
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

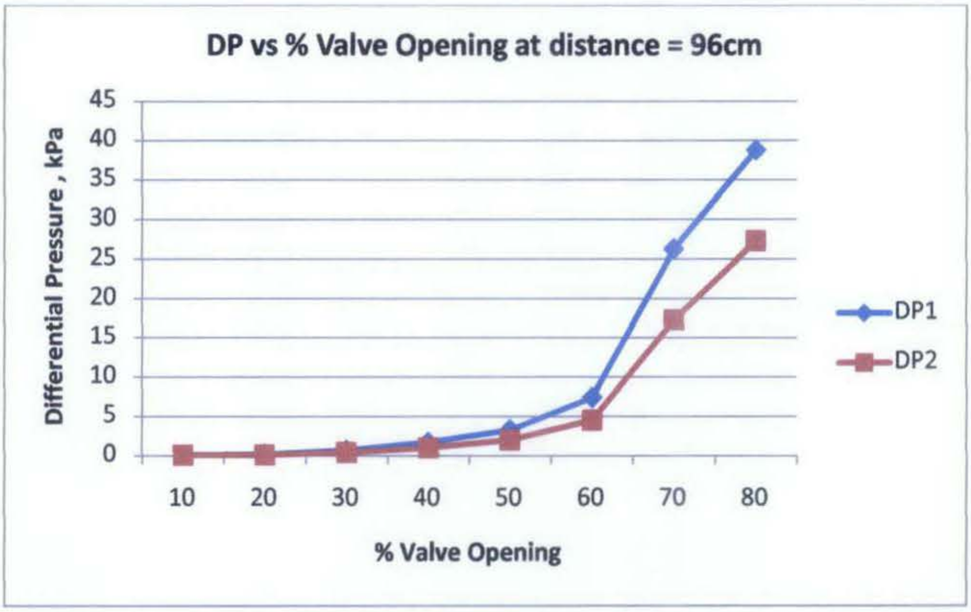

DP vs % Valve Opening at distance = 56cm
Differential Pressure , kPa
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2


DP vs % Valve Opening at distance = 66cm
Differential Pressure , kPa
0
5
10
15
20
25
30
35
40
45
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

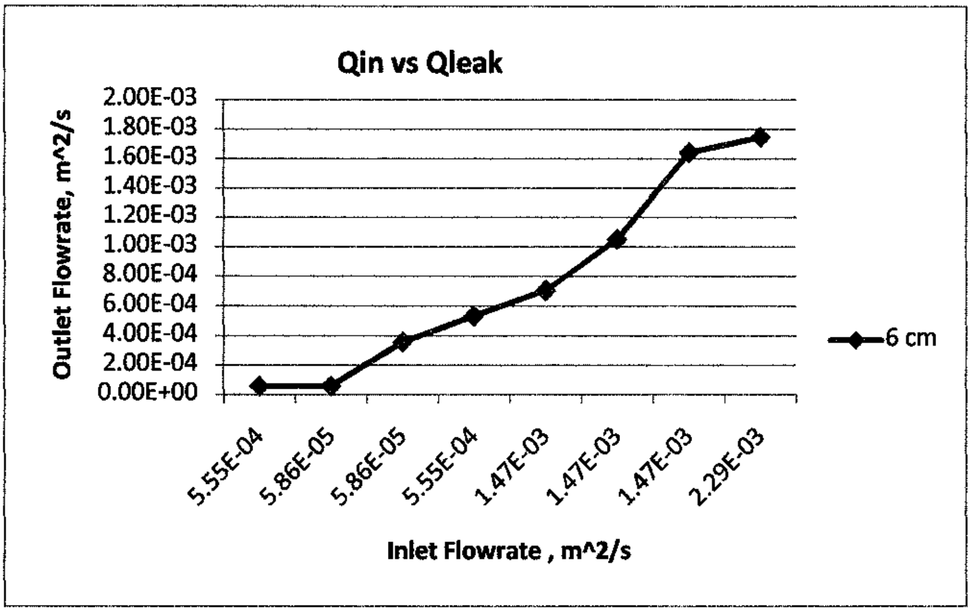

DP vs % Valve Opening at distance = 66cm
Differential Pressure , kPa
0
5
10
15
20
25
30
35
40
45
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

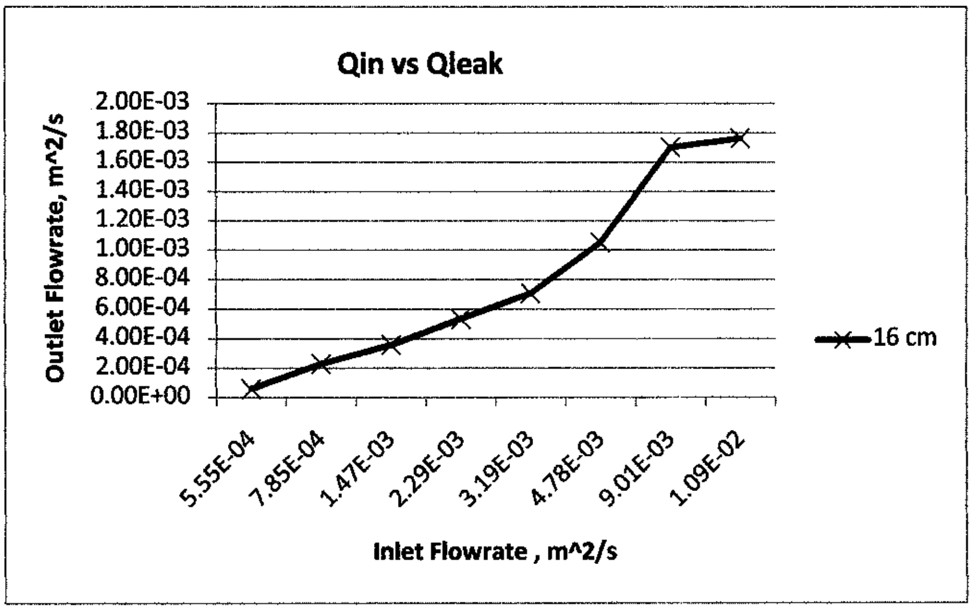

DP vs % Valve Opening at distance = 76cm
Differential Pressure , kPa
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

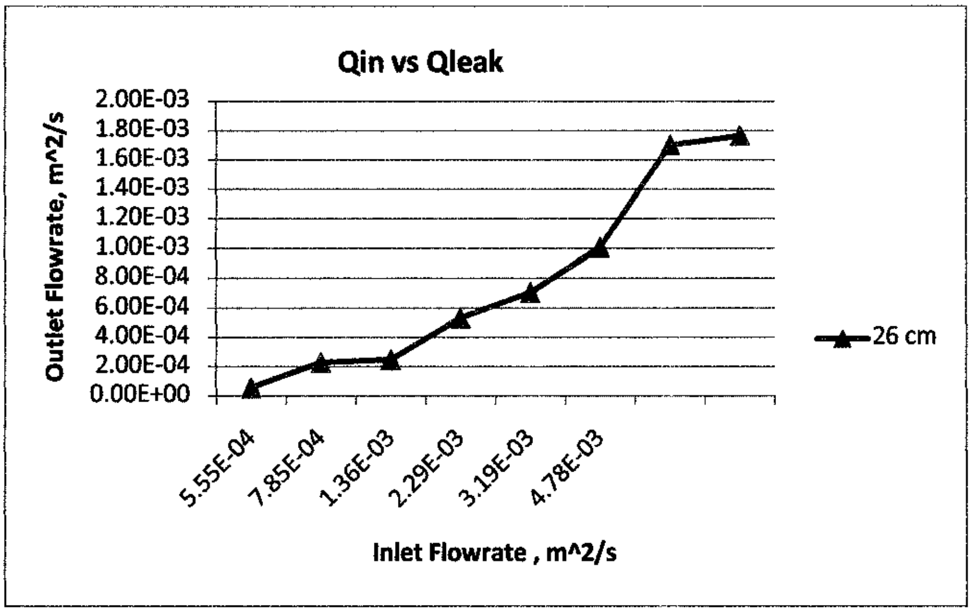

DP vs % Valve Opening at distance = 86cm
Differential Pressure , kPa
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

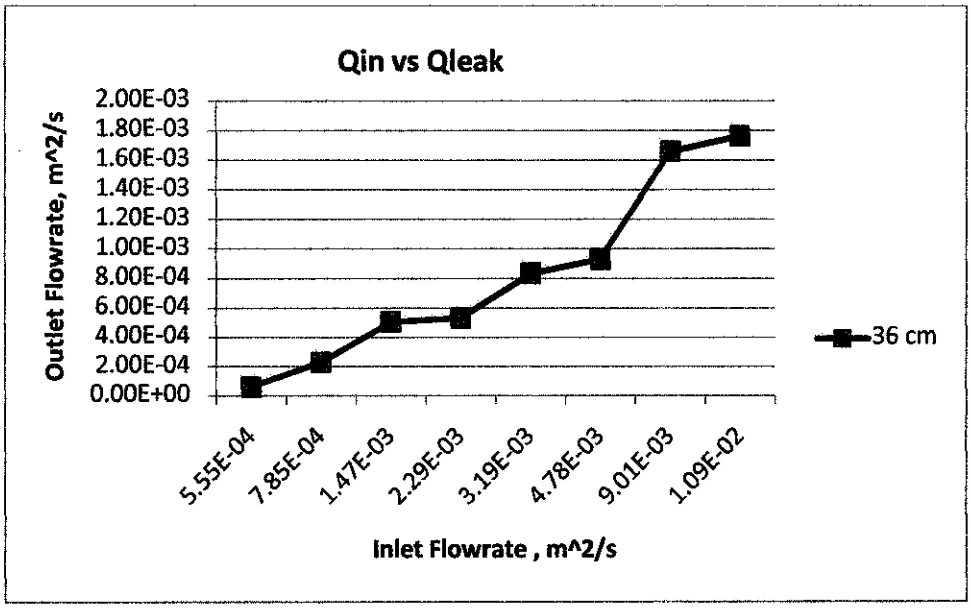

DP vs % Valve Opening at distance = 96cm
Differential Pressure , kPa
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
% Valve Opening
DP1
DP2

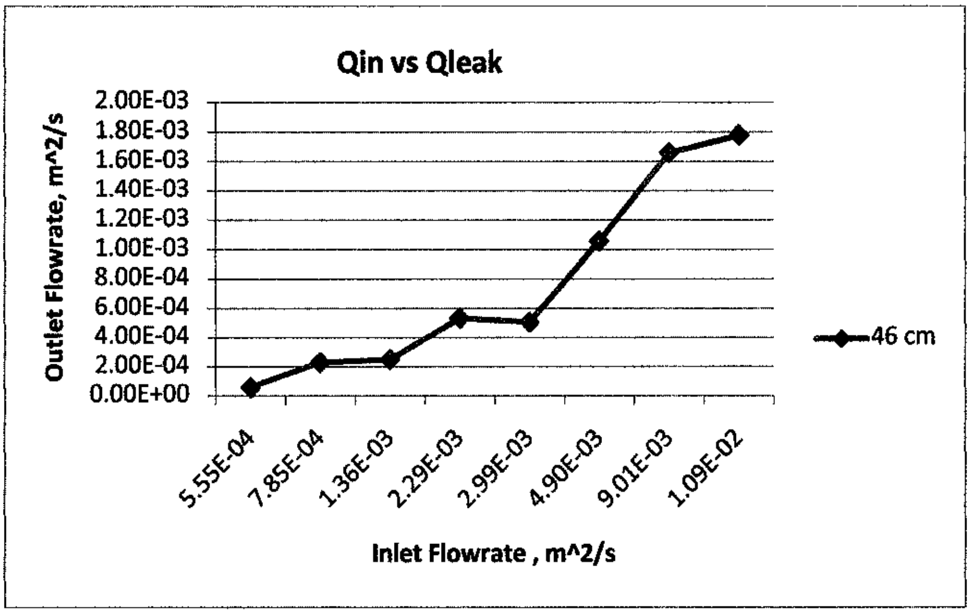
The Graph between Inlet Flow Rates against Leak Flow Rate

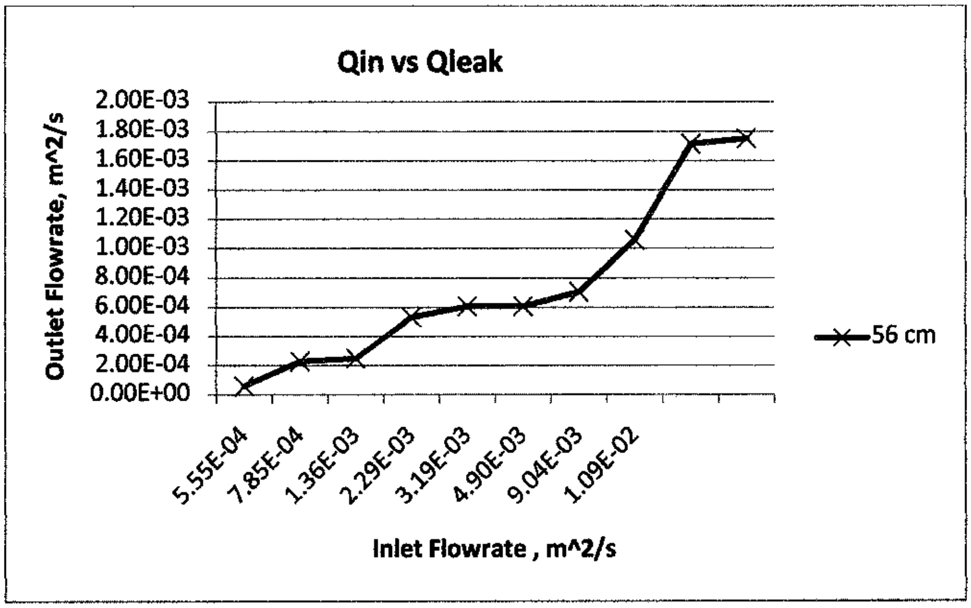


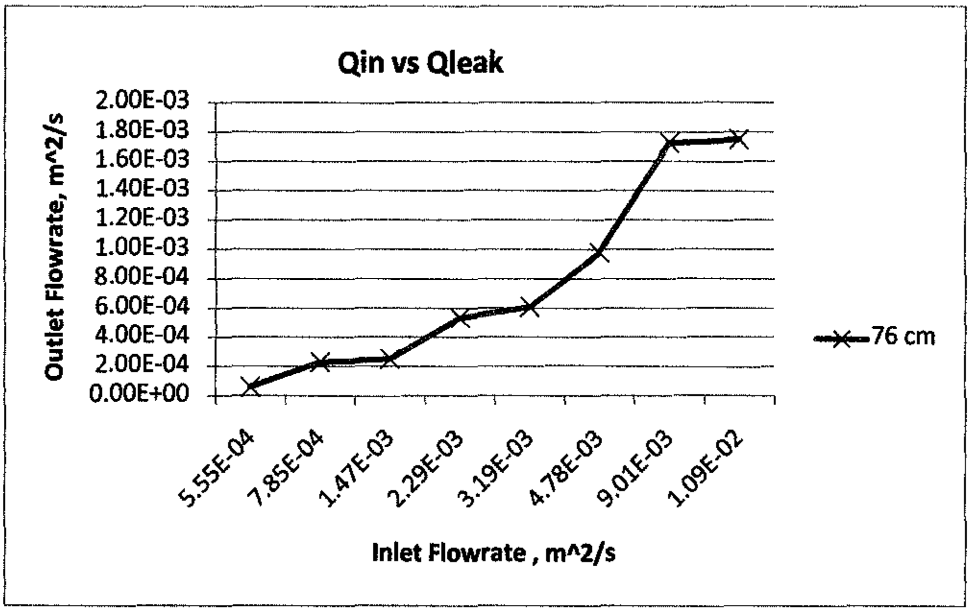


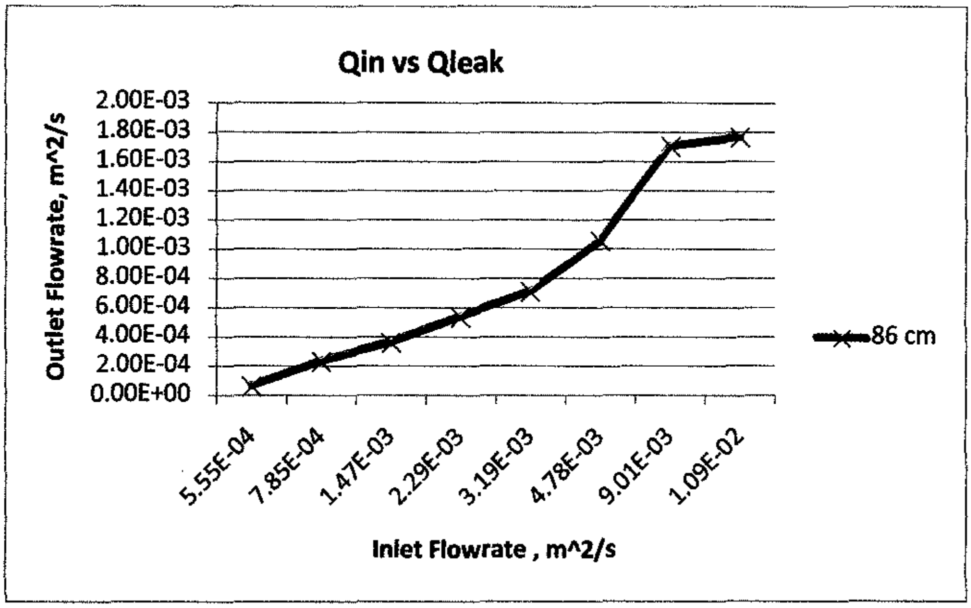

Qin vs Qleak
Outlet Flowrate, m^2/s
2.00E-03
1.80E-03
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
5.55E-04
7.85E-04
1.36E-03
2.29E-03
3.19E-03
4.78E-03
Inlet Flowrate , m^2/s
26 cm

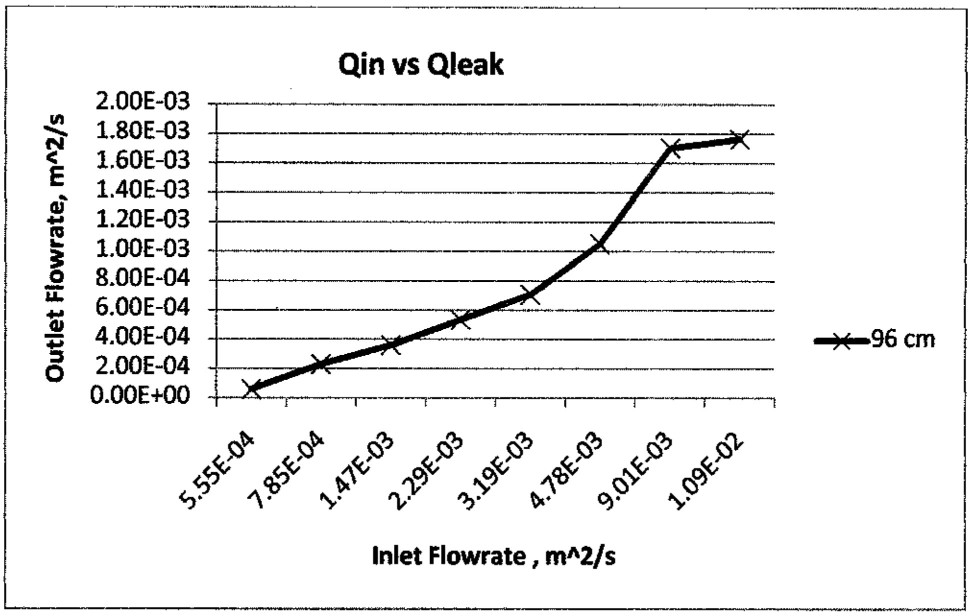

Qin vs Qleak
Outlet Flowrate, m^2/s
2.00E-03
1.80E-03
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
5.55E-04
7.85E-04
1.47E-03
2.29E-03
3.19E-03
4.78E-03
9.01E-03
1.09E-02
Inlet Flowrate , m^2/s
36 cm


Qin vs Qleak
Outlet Flowrate, m^2/s
2.00E-03
1.80E-03
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
5.55E-04
7.85E-04
1.36E-03
2.29E-03
2.99E-03
4.90E-03
9.01E-03
1.09E-02
Inlet Flowrate , m^2/s
46 cm


Qin vs Qleak
Outlet Flowrate, m^2/s
2.00E-03
1.80E-03
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
5.55E-04
7.85E-04
1.36E-03
2.29E-03
3.19E-03
4.90E-03
9.04E-03
1.09E-02
Inlet Flowrate , m^2/s
56 cm


Qin vs Qleak
2.00E-03
1.80E-03
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
Outlet Flowrate, m^2/s
5.55E-04
7.85E-04
1.47E-03
2.29E-03
3.19E-03
4.78E-03
9.01E-03
1.09E-02
Inlet Flowrate , m^2/s
76 cm


Qin vs Qleak
2.00E-03
1.80E-03
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
Outlet Flowrate, m^2/s
5.55E-04
7.85E-04
1.47E-03
2.29E-03
3.19E-03
4.78E-03
9.01E-03
1.09E-02
Inlet Flowrate , m^2/s
86 cm



Qin vs Qleak
Outlet Flowrate, m^2/s
2.00E-03
1.80E-03
1.60E-03
1.40E-03
1.20E-03
1.00E-03
8.00E-04
6.00E-04
4.00E-04
2.00E-04
0.00E+00
5.55E-04
7.85E-04
1.47E-03
2.29E-03
3.19E-03
4.78E-03
9.01E-03
1.09E-02
Inlet Flowrate , m^2/s
96 cm