University of Southern Queensland
Faculty of Engineering and Surveying

Performance Characterisation of Pressure Regulation Devices used in Broad-Acre Irrigation

A dissertation submitted by

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ABSTRACT

Large mobile irrigation machines are becoming a common sight in Australian broad-acre irrigation, replacing traditional surface methods. These machines give the potential of irrigating large areas with high efficiency and with a uniformity of above 80% when designed correctly.

A major component of the large mobile irrigation machine is the sprinkler application package commissioned with the machine. Pressure regulators are becoming a common part of the package when large mobile irrigation machines are commissioned.

Pressure regulators are installed upstream of the nozzle and provide a constant output pressure regardless of the input pressure into the pressure regulator. The device acts as a variable headloss. Input pressure changes are a common occurrence on large mobile irrigation machines and typically are from topographic changes as the machines travel through the field.

The application rate is directly influenced by the output pressure from the pressure regulator, thus this shows the importance of accurately understanding to performance of the pressure regulator. Reviewing previous literature it was known that the methodology development was a crucial part in understanding the pressure regulator performance. The development of a solid robust methodology was the primary objective of this dissertation.

Eight stages of testing occurred each with incremental changes to develop the methodology for testing. The way the testing was undertaking proved to influence the results of the test.

A statistical analysis in terms of an ANOVA and sample size calculations was undertaken on a limited set of data. It was found the for the 16 pressure regulators tested the means were not equal. 88 pressure regulators were found to be tested to understand manufacturing variation based on the normal model.

The methodology by which the test was carried out was found to influence the outcome of the pressure regulator. Each result needs to be interpreted with reference to the methodology. Much more testing is needed to fully understand the pressure regulators performance and how they function on large mobile irrigation machines.

University of Southern Queensland

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ENG4111 Research Project Part 1 &
ENG4112 Research Project Part 2

LIMITATIONS OF USE

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CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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‘...it is not the quantity of water applied to a crop; it is the quantity of intelligence applied which determines the results.’

Alfred Deakin 1890

Irrigation Pioneer to Australia

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Chapter 1 INTRODUCTION

This dissertation focuses on the performance of pressure regulators and their use in broad-acre pressurised irrigation. This introductory chapter establishes the importance of irrigation and related systems to agriculture; also provided is a discussion on the different irrigation application systems. This background discussion, gives the reader a good understanding about the importance of pressure regulators and their use with irrigation.

1.1 Background

Irrigation is defined by the Oxford English dictionary as the 'supply of water to land or crops to help growth, typically by means of channels' (Oxford Dictionaries 2011). Water is an important aspect of life. It is required by all plants and animals for survival. Making up a large proportion of plant and animal tissue, water is required to carry out photosynthesis and respiration processes which are required for new cell growth.

Irrigation is not a new technology however as rainfall has become more erratic and variable it has become under the public spotlight of being a large and wasteful water user. Irrigation in Australia has a much recent history when compared to other countries around the world and is an important part of Australian agriculture.

The continent of Australia is one, which is isolated from other countries in the world. This geographical isolation gives Australia a good position in keeping out pests and diseases. Consequently Australia has a well-established and diverse agricultural industry. In 2008-09 the Australian agricultural industry was worth $41.8 billion (Australian Bureau of Statistics 2010). The industry is a major driver of the country's social and economic growth and development particularly in rural and regional areas. Rainfall is a key input into any primary production. Australia is considered a dry continent with an erratic and variable rainfall. Table 1.1 shows Australia's average rainfall comparatively with other nations.

Table 1.1 - Comparison of the average rainfall totals of selected countries around the world

Country	Average Rainfall (mm)
Australia	420
United States of America	1740
South America	1350
Africa	710
Europe	610

(Hallows & Thompson 1995)

Australia, due to its later European settlement in 1788 has only a much recent irrigation history compared to other countries in the world. Since the 19th century, irrigation development throughout Australia has progressed steadily. This development around the country has mainly been focused on small schemes by private individuals who wanted to increase production on their farms. These small schemes continued for a number of years.

In the early 1900's Victoria's agricultural production was rapidly increasing within the Mildura and Renmark irrigation settlements. With a few exceptions most of the early information around irrigation technology came through Victoria and filtrated to the rest of the country from there. The Chaffey Brothers played a major part of the shaping of the early irrigation industry and its success to Australia. Both brothers were Canadian born civil engineers who came from California developing major irrigation infrastructure schemes. The brothers came to Australia bringing with them the technical expertises in irrigation design, pump design and agricultural irrigation technology (Hallows & Thompson 1995).

In 2008/09 Australia's total water usage was 7286 gigalitres. The same period 409.0 million hectares was reported to be being used for agricultural production, of this area less than 1% was under irrigation. The amount of water used by irrigation in 2008/09 was 89% of Australia's total water consumption, making irrigation Australia's single largest user. Irrigated pasture for grazing accounted for the greatest amount of irrigated land 23.8% and also 20.5% of the total irrigation water applied (Australian Bureau of Statistics 2010).

Surface irrigation remains the most popular form of irrigation. In 2008/09 45.6% of irrigation was under surface, with New South Wales and Queensland the two main states with this type of irrigation. A large proportion of agricultural production is grown on dark clay soils which have low permeability this makes surface irrigation the ideal irrigation type in Australia. Table 1.2 shows data extracted from ABS 2008 and reports the areas under different irrigation types by states (Australian Bureau of Statistics 2010).

Table 1.2 – Irrigation 2008/09 in Australia by type

	State	**NSW**	**VIC**	**Qld**	**SA**	**WA**	**Tas**	**NT**	**Aust.**
Percentage by Area	Surface	61.2	53.1	47.9	8.83	29.1	4.62	8.78	45.6
	Above-ground drip	9.00	13.1	4.00	40.5	36.4	3.41	20.1	12.3
	Subsurface drip	0.99	1.56	1.93	1.25	2.93	0.05	5.47	1.45
	Microspray	2.13	5.93	5.14	7.08	10.4	2.31	48.7	4.81
	Portable irrigators	4.51	3.99	4.52	0.70	2.55	18.5	0.31	4.61
	Hose irrigators	7.33	5.32	21.6	3.79	0.74	34.6	1.10	12.1
	Large Mobile Machines	10.3	11.5	11.4	30.4	12.9	33.5	10.2	14.3
	Solid Sets	0.84	4.68	2.94	3.49	8.89	2.27	0.34	2.88
	Other	5.75	5.27	4.07	5.89	9.17	9.04	5.78	5.40

(Australian Bureau of Statistics 2010)

1.2 Types of Irrigation

Irrigation can be separated under two broad areas, surface and pressurised irrigation. Surface irrigation was the main type of irrigation to be practised in Australia, and continues to be the main method used (Smith 2010).

1.2.1 Surface Irrigation

Surface irrigation is the oldest and most commonly used method of irrigation around the world. Surface irrigation involves the water being conveyed from the source to field via lined or unlined channels or low head pipelines. Water is then allowed to travel down the field and infiltrate into the soil, irrigating the crop or pasture. Furrow, border and level basin are the most common forms of surface irrigation (Smith 2010). Figure 1.1 illustrates the surface irrigation application method, where cotton is being irrigated with siphons.

Figure 1.1 – Cotton under surface irrigation in Australia

(Raine and Foley 2002)

Furrow irrigation is used widely throughout Australia and it involves tilling the cultivation into small furrows typically 0.75 to 1.5 m wide which allows water to pass down the furrow at a slope. The crop is grown on the furrow and thus is irrigated when water is passed down the furrow. This practise of irrigation is used for row crops such as cotton, maize, sugar and sorghum (Smith 2010).

Border irrigation is similar to furrow irrigation in that it allows flow in at the top of the field and it passes down the slope of the field to water the crop. The main difference however between border and furrow irrigation is that border irrigation has strips subdivided throughout the field. Typically these can be 10 to 100 m wide and range from 200 to 1000 m long down the field. There are no distinctive furrows in the stirps or bays, but small earthen banks. This method of irrigation is used most commonly to irrigate pastures. While border or bay irrigation is used extensively throughout Australia much of it is concentrated to the areas of southern New South Wales and Victoria (Smith 2010).

The third method of surface irrigation is known as level basin irrigation. Again this method is similar to border irrigation except there is no longitudinal slope down the length of the field and the lengths may be shorter. This method has been widely adapted in the United States of America; however it is not broadly practised in Australia (Smith 2010).

1.2.2 Pressurised Irrigation

Pressurised irrigation involves the use of energy to move and apply water in-field. The water is under pressure and delivered to the field by droplets. There are many different types of pressurised irrigation application methods which distribute the water in-field. Depending on the crop, soil, topography, production type and many other parameters will depend on the most effective pressurised irrigation application method (James 1988). These systems can be portable or fixed; large systems or small. Since the mid19th century, pressurised irrigation has developed and evolved over the years. Today where we have reliable, automated, but most importantly efficient and uniform pressurised irrigation systems

Portable and fixed sprinkler systems cover a wide range of irrigation systems across different agricultural and horticultural industries. However the main basic theory is applied to all systems. Water is pressurised to a series of pipes where emitters or sprinklers are fitted. Depending on the system layout and function will depend on how the water is discharged from the system to irrigate the crop. Considering a system of portable shift irrigation pipes, sprinklers are attached by riser pipes to a main pipe and arranged in a pattern throughout the field, coupled together via an easy insert on each pipe. When the system is operating, the sprinklers, usually the knock impact type travel around a full arc shooting out a velocity of water. These systems are usually used for horticultural crops where the area of irrigation is small. A fixed pressurised system covers a wide range of irrigation systems. Drip irrigation, microspray and handshift irrigation are examples of this. When in operation these systems do not move, there are fixed (James 1988). Figure 1.2 shows an example of fixed pressurised irrigation in the form of drip irrigation. Where small drip tape is fitted underneath the trees of grape vines and when the system is in operation water will be emitted at a controlled discharge to the crop.

Figure 1.2 – Drip irrigation fixed under grape vines

(Irrigation 2011)

Mobile irrigation machines are different to fixed pressurised machines, as they move when in operation. Typically these machines irrigate smaller areas then fixed sprinkler systems, and once they have irrigated an area need to be shifted to a new area to begin operation. An example of this is the travelling gun irrigation machine.

A travelling gun irrigator is essentially a big gun irrigator mounted on a heavy duty chassis which moves across a field. The travel gun irrigators a sector angle as it moves irrigates when in operation. The irrigator is usually fed from a flexible hose which is dragged behind the chassis and connected into a mains pipeline on the farm. These machines are characteristic of operating at high pressures around 500 kPa and can water a radius of up to 50 m. Travelling gun irrigators are widely used across eastern Australia, particularly in the dairy, sugar and horticultural industries (Big Gun Sprinklers n.d.).

Figure 1.3 – Cable tow travelling gun irrigator fed by flexible soft hose

(Irrigation Equipment 2011)

Figure 1.3 shows a cable tow travelling gun irrigation fed by a flexible soft hose which is shown irrigating a pasture crop.

1.2.3 Large Mobile Irrigation Machines

Large mobile irrigation machines (LMIM’s) refer to irrigation machines which are pressurised systems and cover broad-acre areas. LMIM’s are different to mobile irrigation machines purely by the area which these machines are able to cover and not be needed to be shifted such as the travelling gun irrigator. More commonly these machines are referred to as Centre Pivots (CP) and Lateral Moves (LM). These two types of machines are similar in that they are characteristic in operating at high flow rates and at low pressures. The fundamentally difference between the two machines is the way in which they travel in the field. As the name suggests a CP is fixed on one end and the machine pivots around this point irrigating the radius of the field at one time. A LM is not fixed and allowed to move the width of the field and travels down the length of the field in a linear fashion (James 1988). Figure 1.4 shows a 1250 metre lateral move irrigation machine in a field in New South Wales.

Figure 1.4 – A 1250 metre Lateral Move in New South Wales

(Center Irrigation 2010)

1.2.4 Background to Large Mobile Irrigation Machines

Large mobile irrigation machines were first developed in the 1940's in Nebraska, USA where Frank Zybach designed and built the first prototype. This machine involved the placement of impact sprinklers on a long steel pipe, which moved around the field in a circle. The system was shifted around the field by water pressure. Figure 1.5 shows Zybach's first design (Mander & Hays 2010).

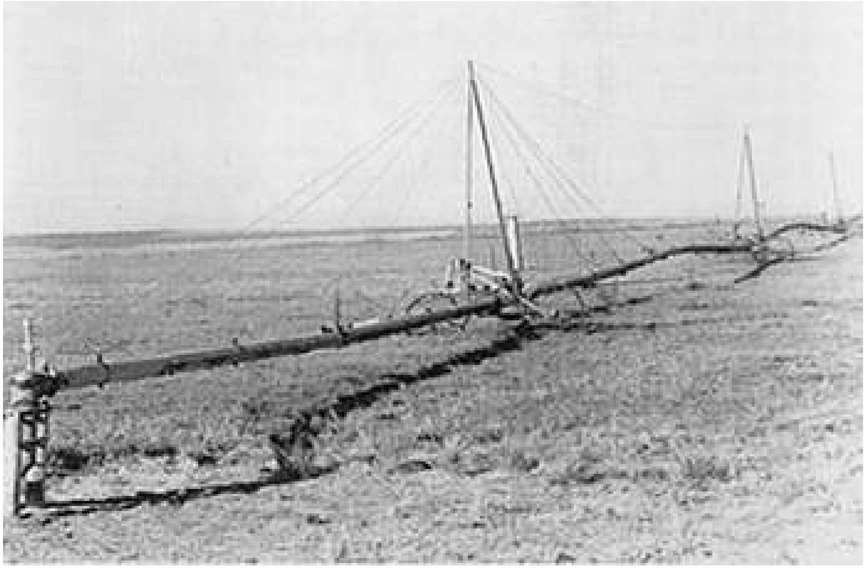

Figure 1.5- The first large mobile irrigation machine

Over the years Zybach and his business partners modified the original prototype, raising the lateral line higher to allow for irrigation of tall crops such as maize. The other significant change was the sprinkler system; impact sprinklers require a lot of pressure to operate correctly, which in turn raised the energy requirements for the machine. During the energy crisis in the 1970's a new water distribution system was required to lower running costs of the machine; this introduced low-pressure static plate sprinklers. These sprinklers were located in droppers under the main lateral line along the length of the machine (Foley & Raine 2001).

Valley, now known as Valmont Industries was the pioneer company, directed by Robert Daugherty, which first manufactured commercial large mobile irrigation machines. Since then more than 60 manufacturing companies realized the potential of these machines and so started manufacturing; today the manufacturing of all LMIM's in the world lies with a handful of companies. Among these are the four main manufacturing companies which have dominated the world market. These are, Lindsey Zimmatic, T&L, Valley and Reinke, all four companies have their company headquarters in Nebraska, USA (Foley & Raine 2001).

It has been said that the development of centre pivot irrigation has been the most important advance in agricultural technology since the replacement of tractors over the horse-drawn power. Since the invention of the LMIM's, the area under irrigation in the US as dramatically increased. Approximately 32% of all irrigation within the US is under LMIM. Australia was first introduced to LMIM's in the 1960's. South Australia and Victoria were the first states to adopt the technology with interest. In 2008-09 Australia's irrigation industry had about 15% under LMIM's (Australian Bureau of Statistics 2010).

1.2.5 Function of Large Mobile Irrigation Machines

Water is fed into the machine under pressure and travels the length of the machine via the main lateral pipeline. This lateral pipeline is supported by a series of towers which are spaced at 24 to 76 metres (James 1988). The length of this lateral pipeline will depend in its system type. In Australia, centre pivots are usually about 500 metres in length, commonly though they are around 400 metres long, which irrigates an area of 50.3 hectares. Lateral moves are not commonly used overseas. However their popularity in the Australia cotton industry has seen lateral moves being installed with a lateral pipeline of 1000 metres (Foley & Raine 2001). The main lateral pipeline can be manufactured of different materials depending on the individual's water quality these include, aluminium, stainless steel, chromium and nickel and galvanised steel. While the spans pipe size will vary with the manufacturer the most common internal diameters of the main lateral pipeline spans range from 135 to 247.8 mm with the most common sizes being 162, 197 and 213 mm, the typically pipe wall thickness of the span is 2.77 mm (Foley & Raine 2001).

The towers which support this main lateral pipeline above the crop canopy are powered either by hydraulic or electric motors. Gearboxes and drive wheels and shafts are also fitted onto each tower. For a centre pivot the rotational speed of the machine is controlled by the outermost tower and every other tower is moved with reference to this tower. A lateral move will travel at the same speed as it moves in a linear fashion down the length of the field. The water supply into a lateral move will typically be located either in the middle or one end via a cart-tower assembly which will typically also carry a mobile power plant.

From the main lateral pipeline of the centre pivot or lateral move hydraulic couplings are used to make a delivery point. Goosenecks are usually used which are installed into the top of the main lateral pipeline 19 mm plastic droppers are fitted into these either over boombacks or straight down to deliver the water to the sprinkler application package.

The sprinkler application package (SAP) is the most important component of the machine, as it is effectively is carrying this package over the crop. The SAP consists of a pressure regulator, nozzle and plate. This is a sprinkler type application type, low energy precision application (LEPA) systems are become more common as they direct the water into the furrow of the crop, without the traditional droplet method with sprinklers. There are two main manufacturers who produced the application packages, either sprinkler or LEPA, and these are fitted on the four manufacturers of the LMIM's. In 2001 it was reported that 58% of growers surveyed used pressure regulators with their LMIM's application packages (Foley and Raine 2001). 10 years later it is estimated that 90% of machines commissioned have pressure regulators installed with their application packages.

A pressure regulator which is located just upstream of the application package outputs a constant pressure, despite different input pressures into the pressure regulator along the length of the main lateral pipeline. This different input pressure may be due to topography changes along the length of the machine as it operates infield, differing input pressure due to changes of the pressure of the supply, such as a drawdown profile in a bore and fluctuations of the pump. However no matter what the changes of the input pressure the pressure regulator is reported to give a set constant output pressure.

1.3 Irrigation Performance

The performance of an irrigation system can have a different importance to different irrigators, depending on their operation and irrigation type. In describing the performance, a number of measures are taking into consideration. These measures are the application efficiency, requirement efficiency and various uniformity efficiencies.

The application efficiency is give below as equation 1.1

$$AE\ (\%) = \frac{Volume\ added\ to\ soil\ mositure\ store}{Volume\ delivered\ to\ field} \qquad \mathbf{1.1}$$

The water lost to canopy interception, evaporation and spray drift in pressurised irrigation, tailwater runoff and deep percolation in surface irrigation can be evaluated through the application efficiency (Smith 2010).

The requirement efficiency is a measure of how well the irrigation has brought the soil moisture store back up the required level. Equation 1.2 gives the equation to calculate the requirement efficiency (Smith 2010).

$$RE\ (\%) = \frac{Volume\ added\ to\ soil\ mositure\ store}{Volume\ required\ to\ be\ added\ to\ soil\ moisture\ store} \qquad \mathbf{1.2}$$

The third measure of discussion of irrigation performance is uniformity. Spatial variability will be present through different applied depths over the irrigated (surface or pressurised) field if one of the more is present:

- For surface irrigation, variations in applied depth along the furrow or bay as a result of the surface hydraulics/soil infiltration interaction.
- Variations in performance between furrows due to differences in the inflow rate, the infiltration characteristic or other hydraulic properties.
- Variations in applied depth in sprinkler irrigation due to the sprinkler pattern, sprinkler spacing (overlap) or lane spacing in the case of travelling irrigators.
- Effect of wind on the sprinkler pattern.
- Variations in the nozzle or emitter outflows along the length of any sprinkler or trickle irrigation pipeline.
- The stop-start pattern of movement of “continuously” moving systems, such as centre pivot or lateral move machines.

- For mobile systems (centre pivots and lateral moves) variations in the land surface and hence pipeline elevation.
- Variations in emitter or pressure regulator performance due to size or other variations occurring during manufacture of drip irrigation components.
- Other causes such as temperature variations, wear and blockage of emitters, and fluctuations in pump performance.

(Smith 2010)

The above list shows the importance of correct design and management in order to get the best out of the irrigation system whatever the system type may be. The Christiansen Uniformity Coefficient which is given by equation 1.3 below is the mostly widely used uniformity measure for sprinkler irrigation.

$$CUC = 100\left(1 - \frac{m}{xbar}\right) \qquad \mathbf{1.3}$$

$$m = \frac{\sum(x_i - xbar)}{n}$$

where m is the absolute deviation of the applied depth, xbar is the mean applied depth and n is the number of depth measurements.

Another uniformity measure is the Uniformity Coefficient (UC) which is given by equation 1.4

$$UC = 100[1 - 0.8\left(\frac{\sigma}{xbar}\right)] \qquad \mathbf{1.4}$$

where σ is the standard deviation of the applied depths. If the applied depths are normally distributed then CUC and UC are equal.

Distribution uniformity is used across both surface and pressurised irrigation, however it is most popular with surface irrigation.

$$DU(\%) = \frac{Mean\ of\ lowest\ 25\%\ of\ applied\ depths}{Mean\ applied\ depths} \quad \textbf{1.5}$$

The last uniformity measure is called the emission uniformity which is given below as equation 1.6.

$$EU\ (\%) = \ 100(1 - 1.27\frac{CV_n}{n})\frac{q_{min}}{qbar} \quad \textbf{1.6}$$

where: CV_n is the coefficient of variation of the individual emitters due to manufacturing differences, n is the number of emitters per plant, q_{min} is the discharge for an average emitter at minimum pressure and qbar is the average of design discharge for the emitters. The emission uniformity was developed for drip and trickle irrigation.

The effect of non-uniform irrigation can result in substantial changes in the yield of the crop being irrigated due to spatial variation. Along with this with the application and requirement efficiencies will evaluate the overall performance of the farms irrigation systems and this can give the irrigator a benchmark to improve their operations on farm.

1.4 Broad Aim

This project aims to accurately characterise the hydraulic performance of pressure regulators used on large mobile irrigation machines by developing a testing methodology.

1.5 Objectives

The main objectives of this work are to:

1) Review the test methodologies from formal literature in this area of study and to develop an understanding of the manufacture literature regarding these pressure regulator devices.
2) Design and develop a testing methodology to accurately determine the performance of pressure regulators.

3) Calculate the sample size and develop and evaluate the testing procedure which adequately characterises manufacturer's variation in pressure regulator manufacture.
4) Analyse gathered data sets and present performance of pressure regulators and their variation based on the developed testing methodologies.
5) Bed the initial work for the development of a mathematical model which accurately describes the hydraulic performance of the pressure regulators used in broad-acre irrigation.

1.6 Structure of this Dissertation

This chapter has provided a brief background to the subject area and has introduced the objectives of the remaining six chapters of this dissertation. Chapter two provides a formal literature review of this area of study and a summary of their finding. The literature review covers previous studies to understand pressure regulator performance and provides details of the manufacturers of pressure regulators and introduces their products. Chapter two also discusses basic theories behind pressurised hydraulic measurement and the introduction of statistical procedures which will be used in later chapters. Chapter three deals with the methodology taken with each testing stage and how the testing rig was used to obtain the results and also discusses the process of calibration of the sensors used in the testing rig. Chapter three also breaks the pressure regulator down into each individual components and explains the interactions each part has with each other and how they work together to perform its function.

Chapter four reports the results obtained in each testing stage. Chapter five provides a detailed discussion on the results presented in chapter four and their outcomes back to the industry. This chapter also compares the results from chapter four to the results from the formal literature. Chapter six outlines the key findings of this research and states the conclusions made on this study. Chapter seven outline recommendations made with reference to chapters five and six for further research needed in this area.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

This chapter introduces the reader to current and past literature on the topic of discussion and also establishes basic concepts which are used widely in later chapters which describe the processes in undertaking different tests.

2.2 Flow Measurement

In any hydraulic setup, whether it is a pipe or open channel the measurement or evaluation of the discharge of the system is crucial. Many design parameters and calculations need an accurate value for the systems discharge. The discharge of a system is made up of two components, velocity of the fluid and the area of which the fluid is flowing. The flow entry into a system will equal the flow exiting the system. This is described by the Continuity equation, shown by equation 2.1.

$$Q = AV \tag{2.1}$$

$$A_1V_1 = A_2V_2$$

where Q = Flow rate (m^3/s), A = Cross sectional area (m^2) and V = Velocity (m/s)

Depending the desired accuracy and system type will depend on the type of flow measurement used.

2.2.1 Flow measurement through pipes

It is through the use of the energy, continuity and momentum equations, where simple methods can be applied to measure the flow in hydraulic situations.

Following the law of the conservation of energy, energy cannot be created or destroyed. This provides the basis of Bernoulli's energy equation given below

$$\frac{p_1}{\rho g}+\frac{v_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{v_2^2}{2g}+z_2-h_f-h_m+h_p \qquad \textbf{2.2}$$

where p = Pressure (kPa), ρ = Density of fluid (kg/m^3), g = Local gravitational acceleration constant (m/s^2), v = Velocity (m/s), z = Elevation (m), h_f = Friction Loss (m head), h_m = Local Loss (m head) and h_p = Addition by pump (m head)

(Moore 2009; Nalluri & Featherstone 1982)

This equation forms the bases of the principle of how to calculate the flow within a venturi metre. With a venturi the pressure difference is created by from a sudden constriction in the cross sectional profile of the pipeline. From equation 2.2 when the fluid enters the smaller diameter pipe the velocity will increase. From the increase in velocity the pressure will decrease to compensate for the gain of energy in terms of velocity. It is through this relationship that a discharge can be derived.

A pitot tube is a simple piece of tube which is placed into the flow of a fluid, creating a ‘stagnation point’. Following the same basic principles in section 2.4.1.1 the flow can be measured. The column of water within this tube will be higher can the height of water being passed. The difference in height will be the energy created by the velocity of the fluid (Nalluri & Featherstone 1982).

There are several different flow meters currently on the market, each have their own measurement techniques. The flow meter used for this dissertation is an electromagnetic ultrasonic type. This type of flow meter induces a voltage across a magnetic field. The voltage across this magnetic field will be directly proportional to the velocity of the fluid. With an accurate cross sectional are known the discharge can be calculated via equation 2.1.

2.3 Pressure Measurement

Pressure is the unit of measure of force divided by area. The SI unit of pressure is the Pascal, and follows equation below.

$$P = \frac{F}{A} \qquad \textbf{2.3}$$

where P= Pressure (Pa), F = Force (N), A = Area (m^2)

There are three different meanings of pressures which need to be noted, these include gauge, absolute and standard atmospheric pressure. The gauge pressure is an arbitrary pressure measurement which is relative to the local atmospheric pressure. From this the absolute pressure may be positive or negative depending on the local atmospheric pressure. The pressure can be measured in two ways;

a) as a force per unit area (Pa)
b) as an equivalent height of column of fluid (Pa or metres head)

From the first pressure measurement, equation 2.3 is used to evaluate the pressure. The second is evaluated by equation 2.4 below.

$$P = \rho \mathrm{gh} \qquad \textbf{2.4}$$

where P = Pressure (Pa) and h = Column height of fluid (m)

Commonly within the water and hydraulic industries gauge pressure is expressed in metres head of water. The unit of head is defined as the energy per unit weight of fluid

$$h = \frac{P}{\rho g} \qquad \textbf{2.5}$$

(Chadwick, Morfett & Borthwick 1986; Nalluri & Featherstone 1982)

2.3.1 Pressure measurement through pipes

Bourdon Gauges

In almost all fluid pressurised systems, gauges would be used to monitor and measure the pressure in the pipeline or pressurised system. A gauge is a device which is fitted to a system usually by a threaded fitting. Fluid from the system is allowed to enter into the gauge via a small opening; the fluid fills a hollow metallic tube called at bourdon tube. When the pressure is raised this tube flexes and it is this flex movement which is transferred to a dial and a pressure reading can be read off the gauge (Factory Direct Pipeline Products 2011). There are many different types and qualities of gauges, depending on the application and accuracy required.

Electronic Pressure Transducers

A pressure transducer is another method is measure the pressure within a system. When calibrated and set-up correctly pressure transducers have the ability to give high accuracy and repeatability and transfer back the information to an automotive or electronic data collection system. A pressure transducer is effectively a strain gauge. The device is tapped into a system the same as a gauge and when the pressure in the fluid is raised a small diaphragm is displaced. This movement is measured and sent as a signal voltage to be read via some acquisition method (Beliveau 2011). As with pressure gauges, there are many different types of pressure transducers giving different degrees of accuracy in their function. Manufactures of Pressure Regulators

There are a number of pressure regulator manufactures currently in operation. Nelson Irrigation Co and Senninger Irrigation Inc are the two main manufactures of pressure regulation devices for Large Mobile Irrigation Machines. As well as these companies there are a number of smaller manufactures which deliver for other agricultural and horticultural industries.

2.4 Pressure Regulators Manufacturers

2.4.1 Nelson

Nelson Irrigation Co is a global sprinkler and irrigation manufacturing company. There headquarters are based in Walla Walla, Washington, United States of America. The company is a major supplier of many different sprinkler and fittings used on Large Mobile Irrigation Machines and is many other fixed sprinkler systems.

Nelson Irrigation Co manufactures two different models of pressure regulators, a *UNIVERSAL-FLO* regulator and a *HI-FLO* regulator.

The model of Nelson pressure regulators is the main product used on Large Mobile Irrigation Machines. The UNIVERSAL-FLO pressure regulator come in a range of different set pressures, these are, 6, 10, 15, 20, 25, 30, 40 and 50 PSI. There are four different types of connection types available with this model of regulator, depending on the intended application method. These are, the pipe thread connection, ¾” FNPT x ¾” FNPT, the 3000 series pivot connection, ¾” FNPT x 3000 ST, the hose thread connection, ¾” FHT x ¾” MHT, barbed 3000 series pivot connection, ¾” male barb x 3000 ST. The most common pressure regulator used on centre pivots and lateral moves in Australia is the ¾” male barb x 3000 ST, 10 PSI pressure setting. The flow setting for this model ranges from 0.0305 – 0.5055 L/s for the 6 Psi pressure setting and 0.0305 – 0.7555 L/s for the other outlet set pressures (Pressure Regulation, n.d.).

The Nelson *HI-FLO* pressure regulator model is similar to the UNIVERSAL-FLO model, however just as the name suggest this model allows for a greater discharge through the device. This is done by increase the area of the tube through the device.

2.4.2 Senninger

Senninger Irrigation Inc was established in 1963 and continues to be a world leader in the manufacturing and supplier of irrigation sprinkler packages and fittings to irrigation over many industries across the world. The company’s headquarters are located in Clermont, Florida, United States of America. Senninger manufacture eight different models of pressure regulators these include, *Pressure Regulator Landscape Grade*

(PRLG), Pivot Special Regulator (PSR), Pressure Regulator Low Flow (PRLF), Pressure-Master Regulator Medium Flow (PRM-MF),Pressure Regulator High Flow (PR-HF), Pressure-Master Regulator Extended Flow (PRXF), Pressure-Master Regulator Extended Flow – Limit Valve (PRXF-LV), Pressure Regulating Limit Valve (PRLV). The pressure regulators which are mainly used in broad-acre situations on either a centre pivot or lateral move include models, PSR, PRLF and PRM-MF (Mechanized Irrigation: Low Pressure-High Performance n.d.).

2.4.3 Rain Bird

Rain Bird Co was founded in 1933, and is a manufacture of irrigation products and services for a range of industries. The company headquarters are located at Azusa, California, United States of America. The company manufacture two models of pressure regulators, the *'L'* Pressure Regulator and the *'M'* Pressure Regulator (Agricultural Irrigation Products, 2011).

2.4.4 Valley

Valley Irrigation is a subsidiary of Valmont. The company began over fifty years ago is now a world leader in manufacturing and supplying Large Mobile Irrigation Machines around the world. The company, Valley Irrigation is based in Valley, Nebraska, United States of America. The company manufacture pressure regulators through Nelson Irrigation Co. There is only one model manufactured and patented by Valley Irrigation – the *Valley All-Range Pressure Regulator* (Valley Options, 2011).

2.4.5 Netafim

Netafim was founded in 1965 and today is among the largest irrigation companies in the world. The company headquarters are located in Fresno, California, United States of America. The company is focused on micro and drip irrigation. Netafim pressure regulators are different in their design compared to other manufactures of pressure regulator described. The company manufacture six models, ¾” Low Flow, ¾”, 1 ½”, 2” x 4, 2” x 6 and 3” x 10 (Pressure Regulators, n.d.).

2.5 Pressure Regulators and Large Mobile Irrigation Machines

This research has been set out to investigate and further understand the workings of pressure regulators, within the irrigation industry, primarily however with the use of large mobile irrigation machines. As described in section 2.4, they are many manufacturers and types of pressure regulators. The most commonly used pressure regulators on LMIM within Australia, are made by Nelson Irrigation Co and Senninger Irrigation Inc.

On a large mobile irrigation machine a pressure regulator is installed immediately upstream of the nozzle. There is one pressure regulator to each nozzle of the machine. Over the length of the machine this equate to a considerable number of pressure regulator, amounting to a significant cost. The nozzle and sprinkler package is installed directly downstream ensuring the constant output pressure from the pressure regulator is passed into the sprinkler and subsequently onto the crop. Figure 2.3 illustrates a typical installation of a pressure regulator on a LMIM.

Figure 2.1 - Pressure Regulator and a LMIM

2.6 Previous Research

This research work is concerned about determining the performance characteristics of pressure regulation devices used in broad-acre irrigation. As part of this Literature Review, previous literature on the performance of these devices was researched. There has been limited research on this field, with only a few research papers written. Most of this research has been collated in the 1980's when large mobile irrigation machines, particular centre pivots had been expanding rapidly. With soaring energy costs and with water use efficiency becoming major issues within the irrigation industry, there is a need to review this research and continue the development and understanding of the performance of pressure regulators.

In 1990 von Bernuth and Baird published a paper entitled 'Characterising Pressure Regulator Performance'. This research involved testing three popular brands of pressure regulators, Senninger, Nelson and RainBird. This paper is a very comprehensive study which set out to try to characterise performance of pressure regulators used in pressurised irrigation systems. The effect from variations of pressure entering nozzles, sprinklers or emitters within pressurised irrigation systems can lead to serious distribution uniformity and efficiency effects.

The study began as one which tested and reported the regulators performance and evolved to developing the testing procedure for testing and characterizing the performance of regulators. It was found from this study that the variation not only between pressure regulators but also between test repeats was greater than expected. Due to this, the methodology is critical in the characterisation of the devices.

A test stand was developed for testing. The rig incorporated an analogue calibrated magnetic pickup flowmeter upstream of a shutoff valve. A regulator was placed downstream of this between two quick couplings used for convenient placement into and out of the test stand. Fluid-damped pressure gauges and pressure transducers was used, either side of the quick couplings for inlet and outlet pressure measurement of the pressure regulator. To control the discharge a previously tested regulator was used and installed immediately upstream of a precision orifice from which the fluid exited from the test stand. Figure 2.2 shows the schematic setup of the test stand used to characterise the performance in von Bernuth and Baird research.

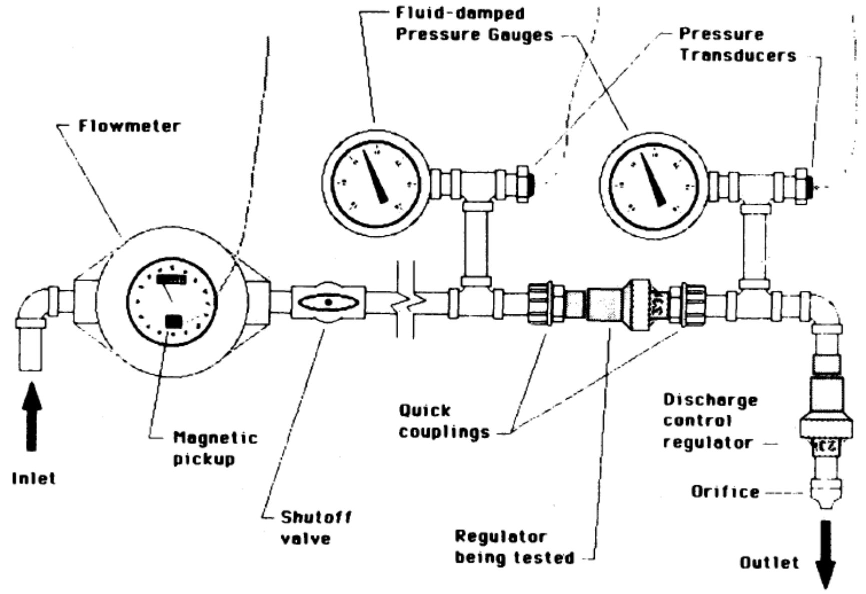

Figure 2.2 - Schematic of von Bernuth and Baird (1990) pressure regulator testrig

The test procedure for the experiment involved placing a pressure regulator from the respective manufacture into the test stand and checking for leaks. The inlet valve was throttled to vary the inlet pressure. Data was recorded via data logger. The valve was then adjusted, opened slightly, the system was then left to stabilise for a moment before a new recording was taken. Multiple points were then plotted, by opening the valve in increments and closing it until the inlet pressure reached zero. The discharge was kept at a constant value from the installation of the fixed orifice and a previously tested second pressure regulator.

The results were graphed. To describe the performance of the regulators the authors have used four straight line segments, two segments which follow the increasing pressure and two segments following the decreasing pressure. The difference between the two line segments is the hysteresis effect of the pressure regulator. Hysteresis is defined as *the phenomenon exhibited by a system, often a ferromagnetic or imperfectly* *elastic material, in which the reaction of the system to changes is dependent upon its past reactions to change* (Dictionary.com 2011). Hysteresis from the pressure regulator is formed from the friction of the tubes movement backwards and forwards through the O-ring. von Bernuth and Baird report the slope and x,y position of these line segments to quantify the performance of the pressure regulators (von Bernuth& Baird 1990). Figure 2.3 details the way von Bernuth and Baird have chose to report the results.

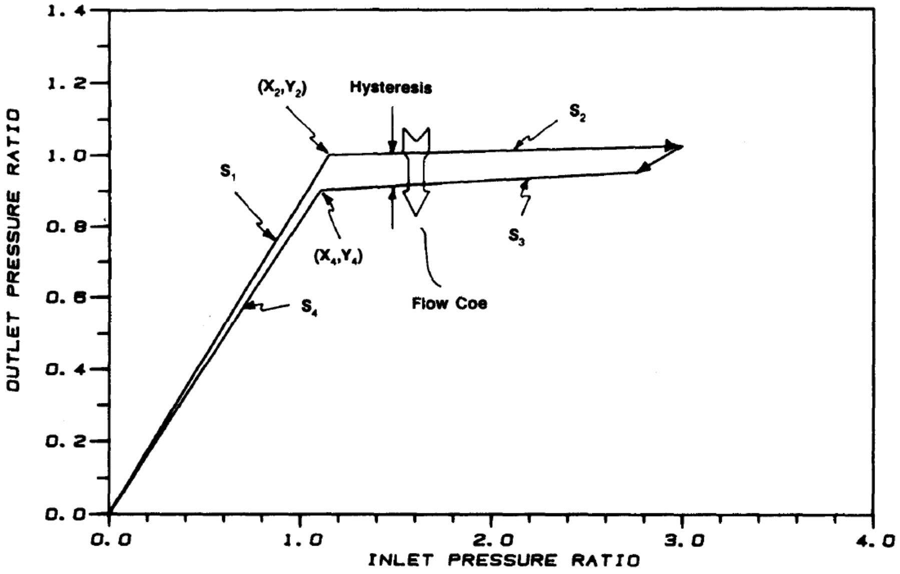

Figure 2.3 – Typical pressure regulator performance as described in von Bernuth and Baird

While the authors have reported the analysis of variance parameter by parameter they have also given the individual hysteresis graphs from the three different manufacturers of a 138 kPa (20 PSI) set pressure model at a discharge of 0.47 L/s) This graphs are reproduced below.

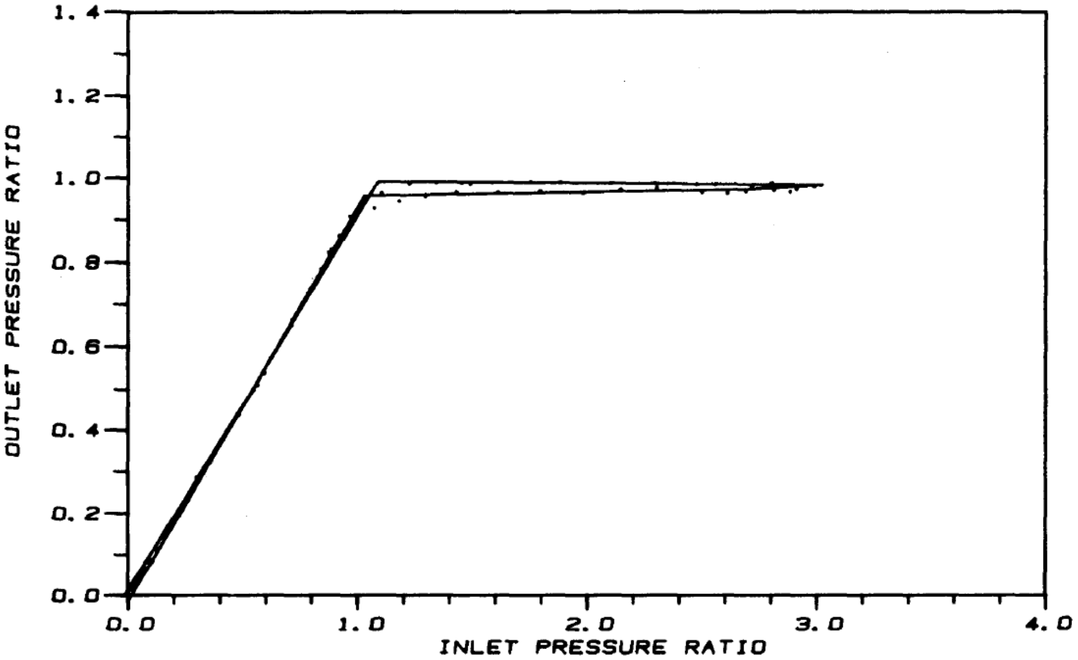

Figure 2.4 – Single test results of Senninger 20 PSI pressure regulator at 0.47 L/s

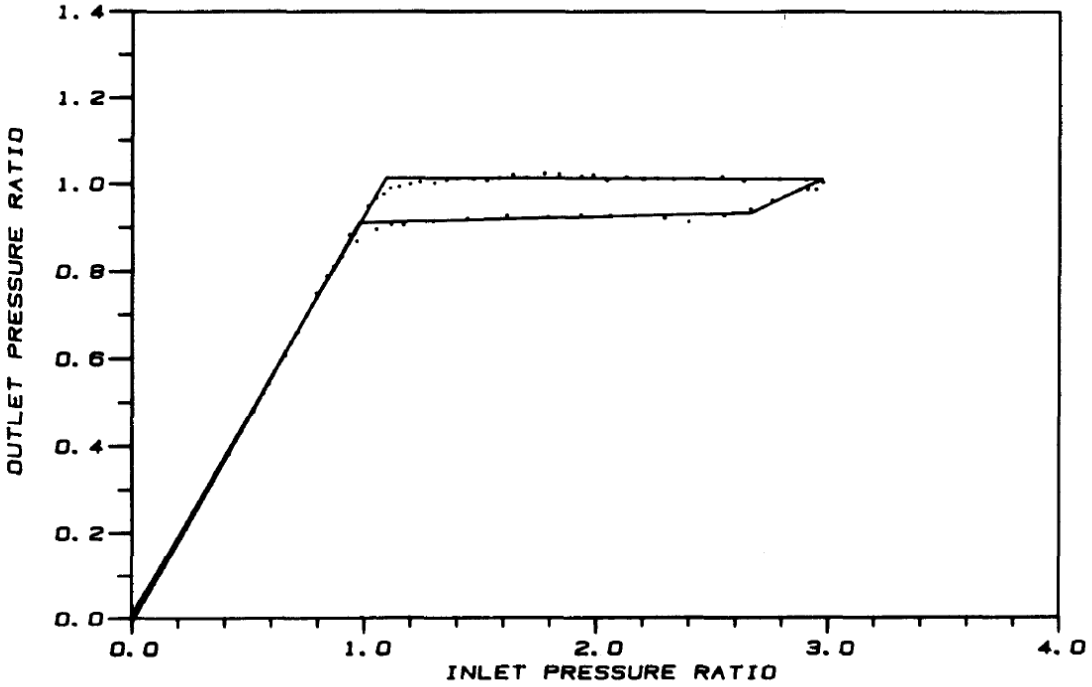

Figure 2.5 – Single test results of Nelson 20 PSI pressure regulator at 0.47 L/s

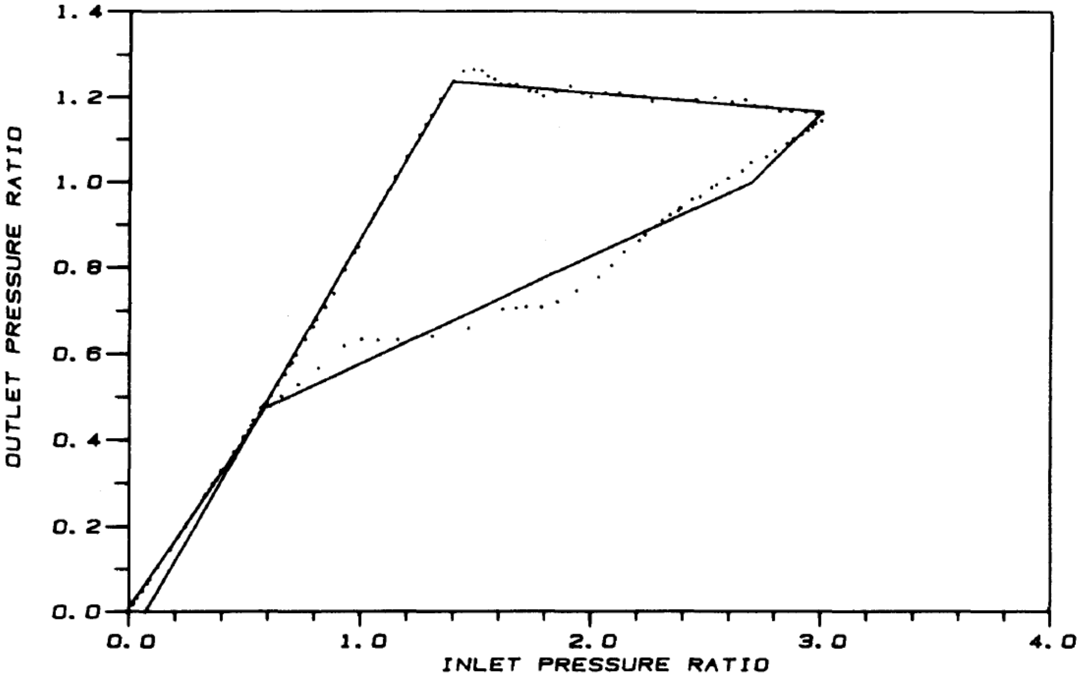

Figure 2.6 – Single test results of Rainbird 20 PSI pressure regulator at 0.47 L/s

Kincaid et al also reports the pressure regulators hysteresis effect as the performance characterisation. This study was sponsored by an agency of the United States Government and the purpose of the study was to evaluate the characteristics of irrigation components and to evaluate the economics of very low pressure irrigation devices used on centre pivot irrigation systems. This was a twofold study one side involved as investigation into the characteristics of pressure regulators and the other side was to evaluate low pressure devices application methods used in pressurised irrigation. The two methods investigated were spray nozzles and furrow drops (bubblers). Reservoir tillage was also evaluated with the use of low pressure devices on centre pivot and lateral move irrigation to see the effect and if it improved the irrigation. This literature review will only concentrate on the first stage of the study the characterisation of pressure regulators.

This study tested pressure regulators in a laboratory setting from two different manufactures, Nelson and Senninger. The purpose of the study was to evaluate the pressure regulation accuracy compared to the stated nominal output pressures. Five devices from each pressure set were tested and the results averaged. For the Nelson regulators, devices with pressure sets of 10, 15 and 20 psi were tested, and for Senninger regulators, 6, 10, 15 and 20 psi nominal pressure were tested. The experiment tested three different discharges, 0.252, 0.504 and 0.756 L/s (4, 8 and 12 US gpm). The different discharges were obtained by using different sized nozzles. The pressures both input and output were measured using calibrated pressure gauges.

The authors wanted to simulate the condition experienced to the pressure regulator as it is in the field on a LMIM. As the machine travels uphill the inlet pressure to the pressure regulator is decreasing, similarly as the machines travels downhill the inlet pressure is increasing. To simulate this effect on the lab bench, the outlet pressure was measured as the inlet pressure was increased from the pressure regulators nominal set pressure up to 551.58 kPa (80 PSI) at 68.94 kPa (10 PSI) increments. Once this limit was reached the pressure was then decreased back to the starting point. The same nozzle size was used for each test.

The results of this experiment show the hysteresis curve for different models of each manufacturer at a medium discharge of 0.504 L/s (8 US gpm).

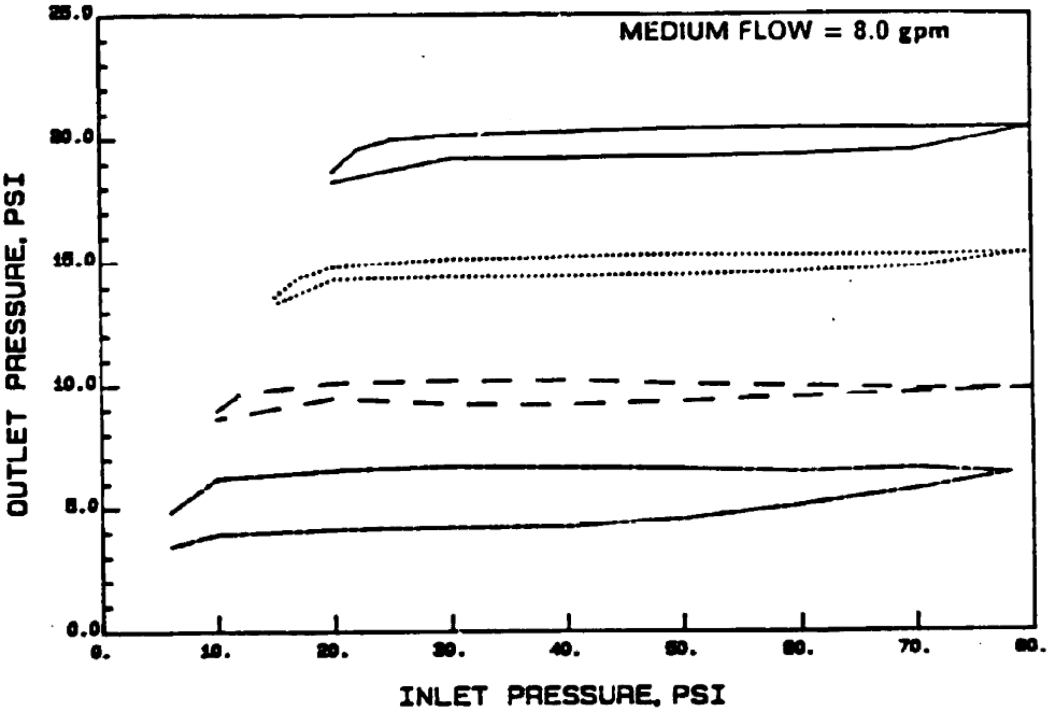

Figure 2.7 – Performance of Senninger 6, 10, 15 and 20 PSI Pressure Regulators

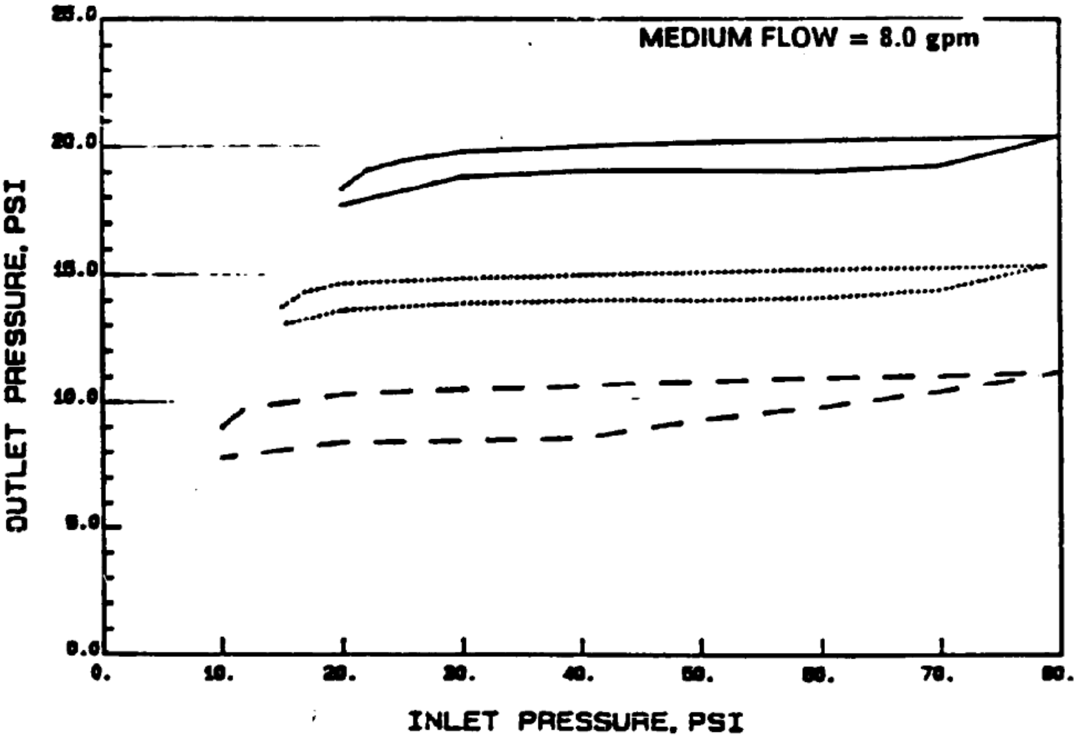

Figure 2.8 – Performance of Nelson 10, 15 and 20 PSI Pressure Regulators

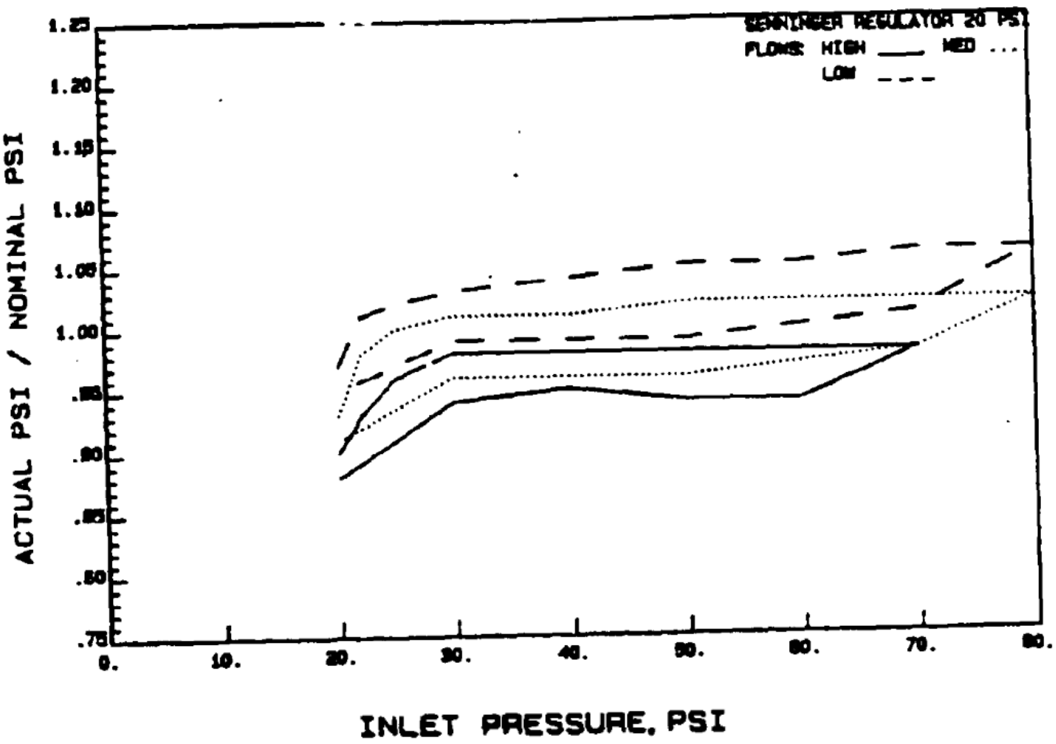

Figure 2.9 – Senninger 20 PSI Pressure Regulator at discharges 0.252, 0.504 and 0.756 L/s

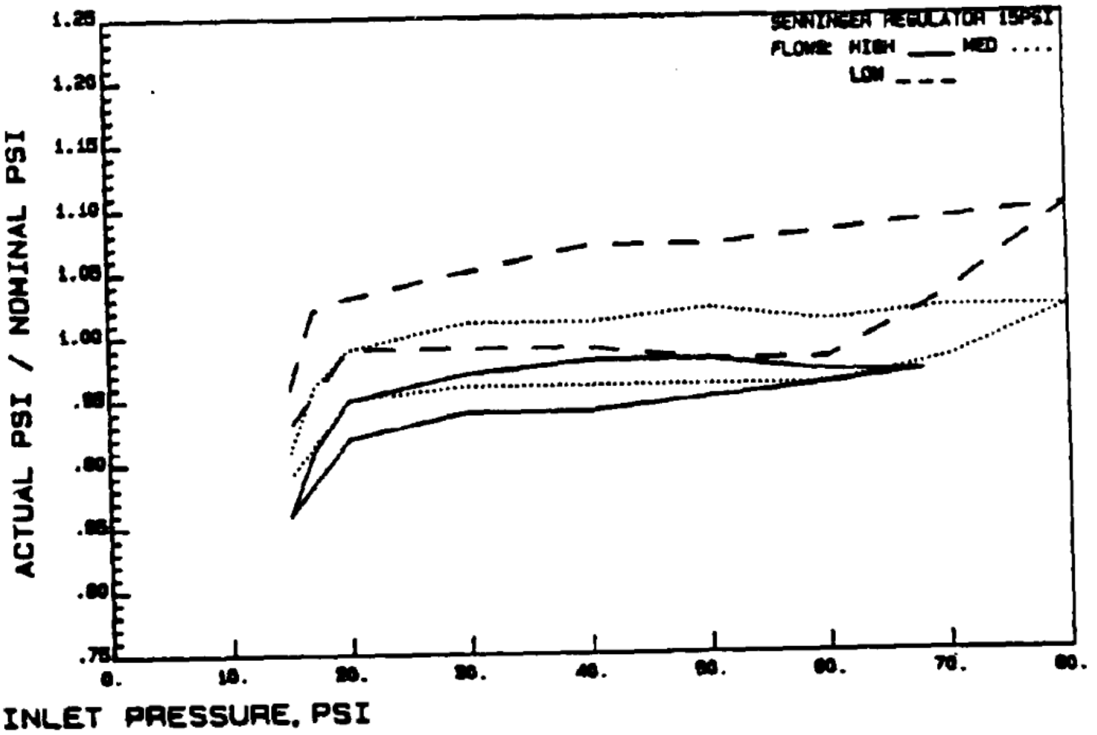

Figure 2.10 – Senninger 15 PSI Pressure Regulator at discharges 0.252, 0.504 and 0.756 L/s

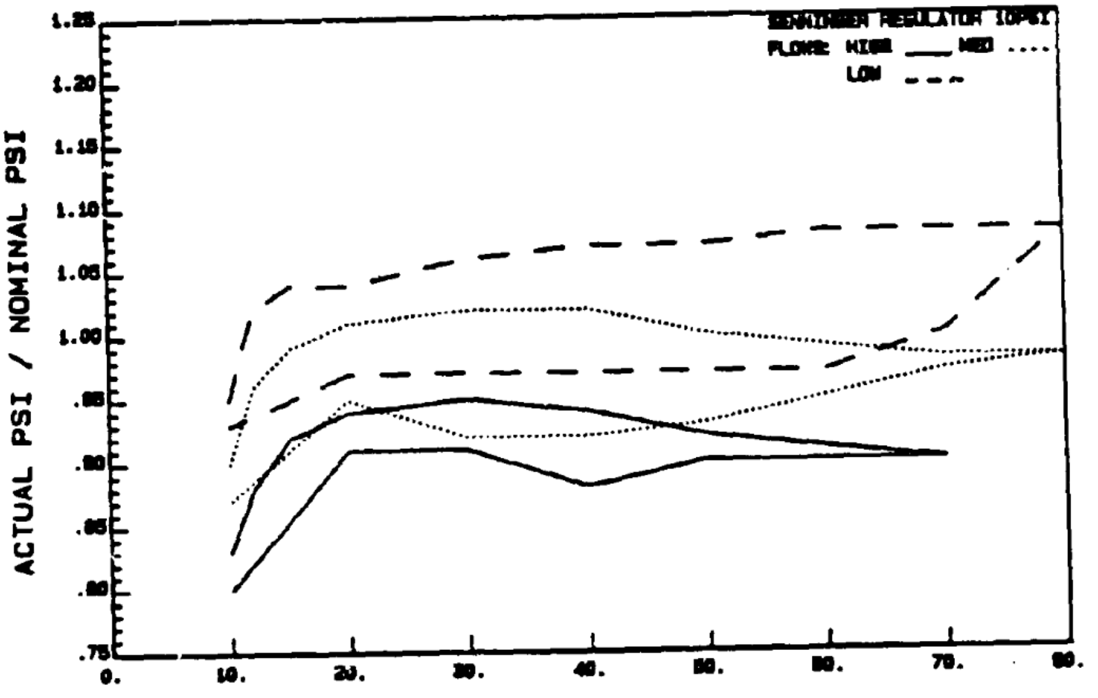

Figure 2.11 – Senninger 10 PSI Pressure Regulator at discharges 0.252, 0.504 and 0.756 L/s

The above figures (2.8 – 2.12) show the results of the study by Kincaid et al. As shown all the results are presented in a graphical form and all show the hysteresis characteristic curve for the respectively pressure regulator at the given discharge. The results shows and the report states that both brands tested Nelson and Senninger faired similarly and that there was no real difference in their performance. This is contrary to what is reported in von Bernuth and Baird (1990)

Kincaid et al state that as the discharge is increased the outlet pressure remains below the nominal pressure rating and at a lower discharge the nominal pressure is kept between a 6.894 kPa tolerance. The authors have stated that the increased hysteresis is due to increased internal friction or pressure surges.

Along with the pressure regulator performance tests through the hysteresis curves, surge tests were also performed. To do this a pressure tank was used to supply water to the pressure regulator at 689.475 kPa. The water was forced through a quick-opening valve and pass down a 1.828 m length, 19 mm diameter pipe striking the regulator. The authors simulated with this test the effect experienced by the pressure regulator when the LMIM is started up in-field, however as mentioned in the report the pressure experienced in this experiment would not happen on the machine. It is stated that this test caused some of the pressure regulators to fail, however the durability between Nelson and Senninger regulator are almost equal. It is noted that the long term durability of the new pressure regulators in unknown, however with protective measures equipped on the LMIM the devices should last at least five years (Kincaid, D. C, Busch, J. R, McCann, I, Nabil, M 1987).

Keller and Bliesner further on Kincaid et al research in their text *Sprinkle and Trickle Irrigation*. Keller and Bliesner state that the purpose of the pressure regulators is to hold the downstream pressure constant; however they have noted that the downstream pressure is discharge dependent. This has been drawn from Kincaid et al research – figures 2.6 and 2.7 as reproduced above. Keller and Bliesner state that the discharge dependence is predicable and therefore it can easily be included when designing the sprinkler, nozzle and pressure regulator package, however the authors have not described this process in detail.

Keller and Bliesner take a difference approach to describe how the hysteresis curves perform. Caused by mechanical friction within the devices, Keller and Bliesner explain that when the inlet pressure is rising the discharge (outlet) pressure follows the lower leg on the hysteresis curve, conversely when it is falling it follows the upper leg. The explanation is different to von Bernuth and Baird journal paper which is opposite to what is explain in Keller and Bliesner. Keller and Bliesner say that the average deviation of the outlet pressure due to varying inlet pressure is about 7 kPa (1 PSI), which for a 10 PSI set pressure regulator is a 10% variation.

In the three literature pieces detailed above, all have explained the importance of maintaining a 20.684 – 34.473 kPa (3-5 PSI) increase above the nominal set pressure of the pressure regulator. Keller and Bliesner have incorporated the discharge dependency through the following equation.

$$P_j = P_{pr} - (P_{cv})_j = P_{pr} - K(\frac{q_j}{cv})^2 \qquad \textbf{2.6}$$

where P_j = Available sprinkler operating pressure at radius r_j (kPa), P_{pr} = Average outlet pressure (which is usually the nomial pressure rating of the pressure regulator at low discharge (kPa), $(P_{cv})_j$= Minimum pressure loss across the regulator for q_j at the radius r_j, (kPa), q_j = Desired outlet discharge at radius r_j (L/s), cv = Flow coefficient that is numerically equal to the discharge when $(P_{cv})_j$ = 1 kPa and K = Appropriate unit pressure loss for the specific measurement units used (1 kPa).

Keller and Bliesner report that the ‘better' pressure regulators available for use in centre-pivots and lateral moves have a high flow coefficient. For a unit pressure loss of 1 kPa the *cv* value is approximately 0.24 L/s (unit pressure loss of 1 PSI, *cv* ~ 10 US GPM). It is noted the flow coefficient values are usually the same for pressure regulators with the same casing shape and configuration regardless of the devices set pressure rating. Keller and Bliesner also report that the weighted average coefficient of discharge variation for a pressure regulator with a fixed nozzle combination follows the equation,

$$v_a \approx 1 - (1 - 0.97)^{1/2} \approx 0.015 \qquad \textbf{2.7}$$

(Keller, J & Bliesner, R.D 1990)

2.7 Statistical Analysis

2.7.1 Introduction

In our modern world of mechanical and automated control of manufacturing engineering within factories, statistical variation has become an important factor of control. No two products produced on the factory floor will perform or behaviour in exactly the same way. However there needs to be tolerance boundaries put in place to maintain high degrees of control over the products variation. Depending on the product being manufactured and its intended use will influence the tolerance boundaries on the products manufacture. An example of this would be filling bottles of water. Down the factory line, bottles are placed on a conveyer belt and fed down the production line. No two bottles filled by the automation production process will be exactly the same volume. It is due to this reason the production line would need to be calibrated to a particular tolerances, depending on the accuracy and precision of the volume needed.

Pressure regulators are no different to filling bottles with water to a nominal volume. A Nelson 10 PSI Uni-Flo pressure regulator is made up of nine different individual components, a spring, two different sized O-rings, a tube and incorporated skirt seal, an internal casing, a redistribution plug, two parts of the external casing and six phillips head screws. Each of these components are made and assembled on the factory floor and each with their own individual tolerance limits. When all the components are assembled into their respective position these nine components make up the pressure regulator. The manufacturer states that the 10 PSI pressure regulator will maintain a constant output pressure no matter of the input pressure. This 10 PSI pressure rating however is a nominal value and will change from device to device. To understand this variation an important question is how many devices need to be tested or evaluated to know the manufacturing variability of the pressure regulators.

There are many different models of pressure regulator, all which have been described in section 2.7.1. From this it can be seen the vast number of makes and models of pressure regulators on the market. Furthermore in trying to quantify the pressure regulators manufacturing variability the test procedure to do this needs to be repeatable and expose each device to exactly the same hydraulic conditions to take all bias out of the testing procedure.

2.7.2 Statistical Methods and Analysis

One objective of this comprehensive study was to determine the number of devices which need to be tested to fully understand their manufacturing variability. This number is unknown, and it is not understood weather testing 5 devices or 500 devices would get a picture of the manufacturing variability.

To mathematical identify the number of pressure regulators which need to be tested to understand their manufacturing variability is an involved process. To do this initial tests are run, this data is then processed to determine the number of devices which need to be tested then the tests are repeated according to the sample size which was calculated

The Normal model or the standard normal distribution is a typical statistical tool used to describe and analyse datasets. The Normal model comes from the *Central Limit Theorem* which states: 'The mean of a random sample has a sampling distribution whose shape can be approximated by the Normal model. The larger the sample, the better the approximation will be'. A distribution which has a shape which is roughly symmetrical is best suited to the Normal model. Figure 2.12 graphical shows the Normal model. Under one standard deviation away from the mean contains 68% of the distribution. Under two standard deviations has 95% and under three contains 99.7%. This is sometimes referred to as the 68-95-99.7 rule (De Veaux, RD, Velleman, PF & Bock, DE 2006).

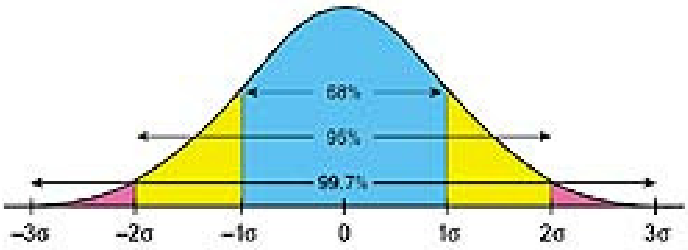

Figure 2.12 – The Normal Model

Modelling the data with the Normal model a z-score can be obtained using equation 2.7. From this z-score it can be know how many standard deviations away from the mean the observation is. Appendix C contains the areas under the normal curve by the corresponding z-score.

$$z = \frac{y - \mu}{\sigma} \qquad \mathbf{2.8}$$

where: z is the z-score, y is the observational point, μ is the mean and σ the standard deviation.

Care must be taken however as every model is not suitable to be described by the Normal model (De Veaux et al 2006).

From equation 2.8 the sample size is not included. When dealing with sample sizes and means equation 2.9 can be used and when rearranged becomes 2.10.

$$z = \frac{\bar{y} - \mu}{\frac{\sigma}{\sqrt{n}}} \qquad \mathbf{2.9}$$

$$n = \left(\frac{\sigma}{\frac{\bar{y} - \mu}{z}}\right)^2 \qquad \mathbf{2.10}$$

where: $\bar{y}$ is the Population or theoretical mean, μ is the mean and n is the sample size.

(Plank 2008)

2.7.3 Statistical Analysis described by Literature

As described in section 2.9 von Bernuth and Baird (1990) have characterised pressure regulator performance by four straight lined segments at a constant discharge. Figure 2.4 shows typical pressure regulator performance with the key parameters noted. The statistical analysis by von Bernuth and Baird (1990) performed an analysis of variance through a few different measured parameters. From their testing, there have recorded the location of the start and stop points and slope of each four line segments, which make the hysteresis curve, the following key shows this.

(X0,0) : Co-ordinate of initial end of segment one.

(0,YF): Co-ordinate of terminal end of segment four.

S_i: Slope of respective segment.

(X_i, Y_i): Intersection co-ordinates of respective line segments as a ratio for set pressure.

$MSSE_i$: Respective mean squares of error for each segment.

WMSSE: Weighted mean error for the four segments.

Further to this, the parameters were also subjected to an analysis of variance (ANOVA). Bernuth and Baird (1990) undertook the ANOVA to calculate the sum of squares of errors within regulators (σ^2w) and between regulators (σ^2B). The process is described in more detail in the following section.

2.7.4 Analysis of Variance (ANOVA)

The Analysis of Variance (ANOVA) is a statistical analysis procedure of comparison of different means of more than two populations. The ANOVA procedure is described by Weissand & Hassett (1987) in detail. There are multiple procedures to undertake an ANOVA, these are classes under two lots, One-Way ANOVA and Two-Way ANOVA. A One-Way test provides methods for comparing the means of populations classified to one factor, conversely a Two-Way ANOVA is for comparing means of populations according to two factors. For this study the One-Way ANOVA will be studied and used.

Procedure of Analysis of Variance (ANOVA)

The null (H_0) and alternative hypotheses (H_a) are first stated. These are statements usually stating that the means of population are equal, following equation 2.11 and 2.12:

$$H_0: \mu_1 = \mu_2 = \mu_3 \tag{2.11}$$

$$H_a: \mu_1 \neq \mu_2 \neq \mu_3 \tag{2.12}$$

Next the test statistic in question must be calculated, it is a ratio of variances between and within treatments. It is calculated as the quotient of the treatment mean square (MSTR) and error mean square (MSE).

$$test\ statistic = \frac{MSTR}{MSE} \tag{2.13}$$

where:

$$MSTR = \frac{SSTR}{k-1} \tag{2.14}$$

$$MSE = \frac{SSE}{n-k} \tag{2.15}$$

where:

n is the total number of pieces of sample data and k denotes the population being sampled and Treatment sum of square (SSTR) is calculated by equation 2.16 and error mean square (MSE) is calculated by equation 2.17.

$$SSTR = n_1(\bar{\mathrm{x}}_1 - \bar{\mathrm{x}})^2 + n_2(\bar{\mathrm{x}}_2 - \bar{\mathrm{x}})^2 + \cdots + n_k(\bar{\mathrm{x}}_\mathrm{k} - \bar{\mathrm{x}})^2 \tag{2.16}$$

$$MSE = (n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \cdots + (n_k - 1)s_k^2 \qquad \textbf{2.17}$$

The next step is to decide on a significance level from this then the critical value (F_α) is taken from the F-distribution. If the test statistic is greater than the critical value, the null hypothesis is rejected, and for a test statistic less than the critical value the null hypothesis is accepted.

(Weiss 1987)

2.8 Physical Analysis of Individual Components of Pressure Regulator

2.8.1 Introduction

A pressure regulator is a device which consists of different individual components which work in conjunction with each other to perform is designed function – to output a constant outlet pressure regardless of the input pressure. A physical analysis should be made of the individual components which contribute to the overall workings of the pressure regulator. The individual components within the pressure regulator include the spring and O-ring.

2.8.2 Spring

A mechanical spring is defined has *an elastic body whose primary function is to deflect or distort under load (or to absorb energy) and which recovers its original shape when released after being distorted* (Wahl 1963). Within the pressure regulators the spring is an important component; it counteracts the force being provided by the back pressure, to move the tube to its correct position in order to give the variable headloss. There are many different types of springs, and depending on the application will determine the specific type needed. The type of spring used in the pressure regulators are a helical compression or tension spring. These types of springs are the most widely type used and are made from wire coiled to form a helical shape. The load applied is transformed along the helical axis of the spring. Figure 2.13 below illustrates a helical spring with the load and dimensions. Figure 2.14 shows the dimensions from the top view of the spring.

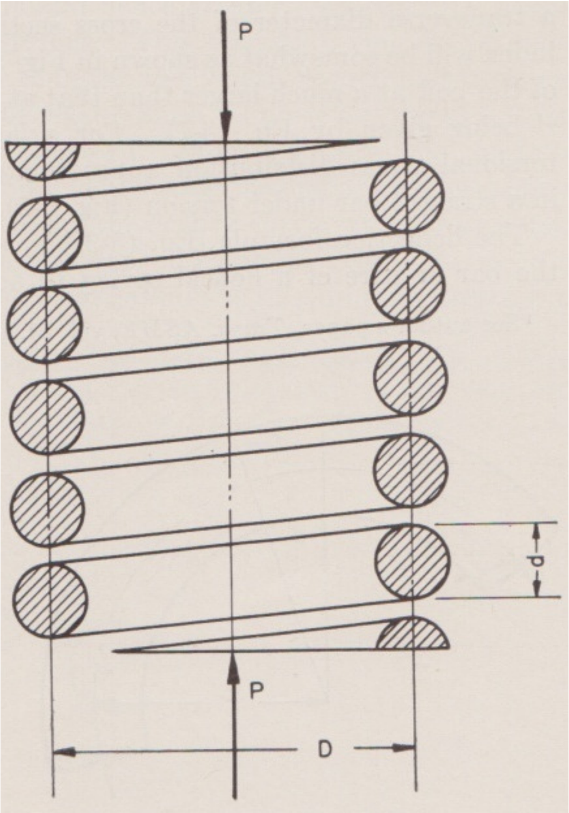

Figure 2.13 – Helical Compression Spring

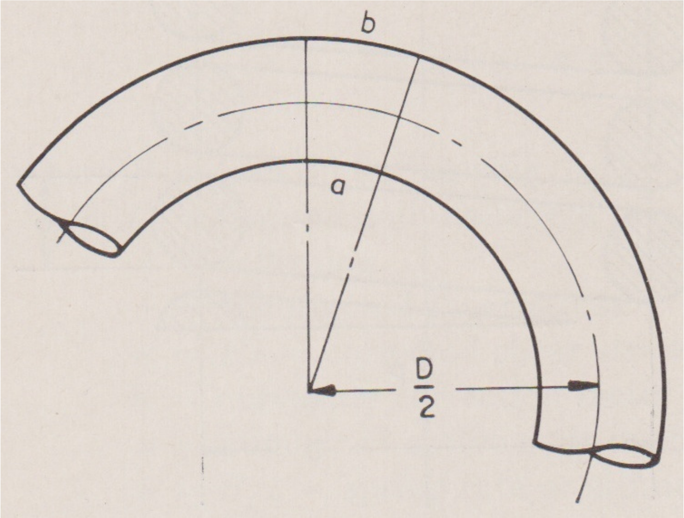

Figure 2.14 – Coil of a Helical Spring

(Wahl 1963)

The set pressure rating of the pressure regulator is determined by the physical attributes of the spring, such as the wire size, pitch and diameter.

When a spring is used either in compression or tension the force it exerts is proportional to its change in length. This phenomena is known as Hooke's Law which is the following equation,

$$F = -kx \qquad \textbf{2.18}$$

where: F is the resultant vector force, k is the spring constant and x is the displacement of the spring (A Hooke's Law Spring 2008).

2.8.3 O-ring

An O-ring functions as a seal. It seals by physical deformation of the O-ring. An O-ring is usually made out of an elastic material such as rubber. Figure 2.15 below shows a typical O-ring and the characteristic dimensions.

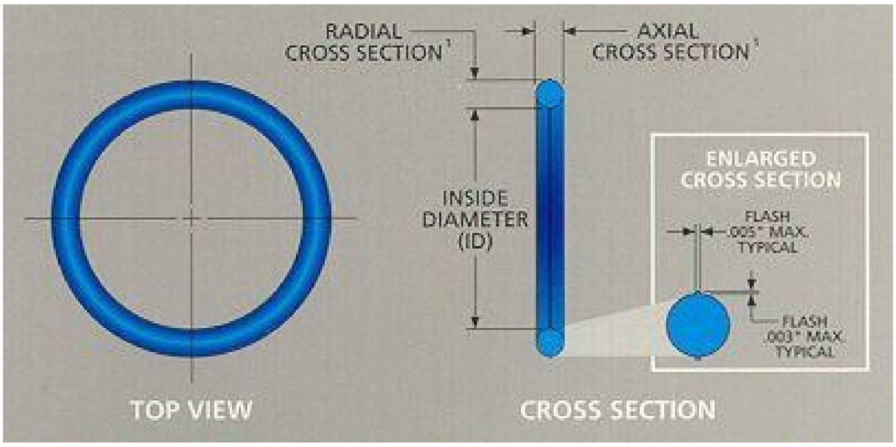

Figure 2.15 – O-ring Dimensions

(O-Ring Gland Design Charts 2003)

Within the pressure regulator there are two O-rings, both which are seated on the top of the internal casing. The larger O-ring seals the internal casing and the redistribution plug and stops any fluid going outside the area. The second O-ring fits in a moulded seat, with the tube moving up and down through the O-ring. This area is filled with water when in operation. As discussed in earlier sections, the hysteresis effect in the pressure regulator is caused by the mechanical friction of the tubes movement though the O-ring.

Friction is a term used to describe the resistance when two surfaces are in contact and is sometimes referred to as a 'frictional force'. It can be thought on a microscopical scale, when two surfaces are in contact. The two surfaces resist each other due to the molecular substrate of the two materials.

Palmer (1949) conducted a study to validate the 'Classical Laws' of friction, these are stated below:

1. Frictional force is directly proportional to load, that is, to the total force which acts normal to the sliding surface.
2. Frictional force for a constant load is independent of the area of contact.
3. Frictional force is independent of the velocity of sliding.
4. Frictional force depends upon the nature of the material in contact.

In the pressure regulator with the movement of the tube through the O-ring, the frictional force is developed by the plastic tube sliding through the contact area on the inside of the O-ring.

Much research has been performed on the concept of friction. The diagram below explains the concept of dry friction with two surfaces in contact.

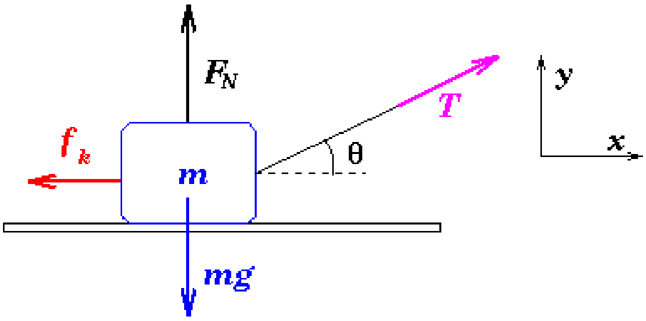

Figure 2.16 – Force Diagram

(Friction 2011)

With the frictional force (*Fs*) is directly proportional to the resultant normal force. This is mathematical describe below:

$$F_s = \mu_s N \qquad \textbf{2.19}$$

where: F_s is the friction force, μ is the coefficient of static friction and N is the normal force. Some typical values of the coefficient of static friction are tabulated below.

Table 2.1 - Typical values for coefficient of static friction

Contact Material	**Coefficient of Static Friction (μ_s)**
Metal on ice	0.03-0.05
Wood on wood	0.30-0.70
Leather on wood	0.20-0.50
Leather on metal	0.30-0.60
Aluminium on aluminium	1.10-1.70

(Hibbeler 2007)

To decrease the static friction coefficient which in turn would decrease the frictional force lubrication may be applied. This would make sliding the two surfaces easier with less force. To minimise the hysteresis effect in the pressure regulators a water based gel has been applied onto the outside surface of the tube for contact with the O-ring. Also, when in operation this area is submerged in water thus the friction is not dry it is wet. The value of wet friction is hard to quantify without experimental measurement, which is outside the scope of this research. The friction coefficient will be wet (much lower value then dry) for a rubber to plastic surface. A value of 0.07 is estimated for this situation (Coefficient of friction, Rolling resistance and Aerodynamics 2011).

Chapter 3 MATERIALS AND METHODOLOGY

3.1 Introduction

A crucial component of this research work and perhaps the most important, taking the majority of the time, was to develop a suitable and appropriate testing methodology which gave repeatable robust results. There has been no previous research work which describes a correct testing methodology to characterise the performance of pressure regulation devices used in broad-acre irrigation. Different approaches were used to try and achieve the repeatability and to present the raw data in such a way which would accurately describe the performance characteristics and differentiate between manufacturing variability, testing procedure and its actually real test bench performance. To start the testing and to begin the first stage of the methodology the Hydraulics Laboratory was used to setup the basic materials used in the methodologies.

3.2 Hydraulics Laboratory Experimental Setup

The University of Southern Queensland, Faculty of Engineering and Surveying's Hydraulics Laboratory has extensive infrastructure to perform and carry out hydraulic testing and modelling. It was decided to carry out this projects tests and experimentation in this laboratory.

3.2.1 Hydraulics Laboratory Constant Supply Header Tanks

Part of the hydraulics laboratory Z113 infrastructure is a low and high constant head supply header tanks. Both header tanks have the capacity to deliver a constant supply of head to the laboratory. The tanks are bolted onto the side of Z block. The tank's design has two sections, an inner and outer part. Water is pumped up into the inner section of the tank via a 200 mm diameter polythene pipe. When the inner section of the header tank fills it overflows into the out section of the tank. There are two more pipes connected to the header tank, one pipe carries the spilled water in the outer section back to the reservoir and the other pipe carries the inner section part of the tank to the laboratory.

The hydraulics laboratory reservoir is a 30, 000 litre tank which is situated underneath the floor of the laboratory. Water is pumped up to the header tank, providing a constant head supply to the experiment. The floor of the laboratory has been designed to be drained, it is in sloped sections and allows water to drain back into the underground reservoir.

The 200 mm supply line from the high header tank delivers the supply to the back of the hydraulics laboratory with three outlets. A butterfly valve is connected to each outlet. This provides the water supply to the experiment setup. There are separate lines each from the low and high header tanks.

To understand the exact pressure being provided to the experiment it was decided necessary to perform a level run survey from a fixed point in the laboratory where the testing was being performed up to both header tanks. This would give millimetre accuracy on the vertical height of the constant supply level in each header.

To perform this survey a Leica automatic level was borrowed from the surveying department of the University of Southern Queensland, along with a staff, tripod and bubble for the level. The Leica automatic level was setup on the tripod and levelled using the three footscrews, with the help of a staffman, a backsight reading was taken and recorded. It was made sure that when all readings were taken, the staff was held perpendicular by the staffman from reference with the bubble. Keeping the distances between readings similar to minimise error a foresight reading was taken and recorded, the instrument was then moved to a new location and the points booked. The level run went from a specified point near the testing rig to the weir lips on both high and low header tanks. This was done by three different level runs from and back to known points. Appendix E shows the booking sheet for the three separate surveys, the surveys have been booked down the page. From the survey it was calculated the elevation difference between the low and high header tanks and the specified point near the test rig is 6.390 metres and 16.181 metres respectively with +/- 0.001 metre accuracy.

3.3 Test Rig and Kit

3.3.1 Introduction

As with many research and experimental projects many different components are used in formulating the kit used in the experiment. This project was no different as it used many different components in the test rig.

3.3.2 Experiment Discharge Measurement

The flowmeter selected for this experiment was an ABB Instrumentation MagMaster HA3 Electromagnetic Flowmeter. The flowmeter's serial number is P/23730/1/1. This flowmeter has a 15 mm bore size and two flange fittings for the inlet and outlet of the flowmeter. The flange fittings were specially made to bolt into the flowmeter's inlet and outlet with a male 12.7 mm end connecter being able to be threaded into these flanges. The rated accuracy for this model is +/- 0.15%. This flowmeter was purchased some years ago, however has not been used. The experiment is the first usage of the meter since purchase.

3.3.3 Experiment Pressure Measurement

Pressure measurement in this project was both manual and automated. For some stages of pressure measurement, pressure gauges were used. These gauges are WIKI fluid-dampening pressure gauges, with a reading accuracy of +/- 0.5 %. The inlet pressure measurement was taken with a gauge which ranged from 0 to 600 kPa with 10 kPa increments and the outlet pressure gauge ranged from -100 to 300 kPa with 5 kPa increments (the negative reading being vacuum pressure, which was not valid in this experiment, but the gauge still used).

With automation testing, pressure transducers were needed to be included in the test rig. The pressure transducers used were a Druck PMP 4030 type. Two transducers were used in the experimental kit, one upstream of the pressure regulator measuring the input pressure and one downstream of the pressure regulator measuring the output pressure. Because from these two different positions there would be unregulated pressure and regulated pressure (upstream and downstream respectively) two different pressure ranges were used. For the upstream readings a 0 to 400 kPa pressure transducer was used and for the downstream readings a 0 to 250 kPa pressure transducer was used. The serial numbers of these Druck PMP 4030 pressure transducers were 1833125 and 1820216 respectively. A 12 volt DC regulated power supply was used to power the pressure transducers. The specifications give the standard accuracy of these pressure transducers as +/- 0.08% FS (Full scale) BSL (Best straight line).

3.3.4 Experiment Pipes, Fittings and Valves

The plumbing of the experimental test rig was based on using 19.0 mm polythene pipe. The reason for this was that the standard size of the pressure regulators being tested was 19.0 mm and also that the pipe fittings for this size were relatively available. For most of the testing the flowmeter was directly plumbed from the supply, this line then continued on to the experiment test rig. A specially built table was designed and built for the testing. This table separated and contained the wet from the dry side of the experiment. The computer monitor, keyboard, mouse and valve levers were operated from the top and underneath housed the pressure regulator being tested with the necessary fittings and valves.

Measuring the pressure, the pressure transducers were tapped into the line via two tapping saddles one upstream and one downstream of the pressure regulator. 6 mm barbed fittings were then fitted into these tapping saddles with 6 mm plastic tubing connected back to the top of the table were the pressure transducers were placed. The elevation difference between the pressure transducer and the tapping point was always accounted for in the processing of the raw data.

Two valves were used in this experimental testing rig one upstream and one downstream of each pressure transducer tapping point. The two valves were used in conjunction with each other and were an integral part of the testing rig. The valves used were a Belimo R218 type. These valves had a special insert inside them which meant their headloss coefficient (K), no matter the stage the valve was turned would always be 1.

3.3.5 Electronic Data Acquisition

As part of the automation process, the flowmeter and the two pressure transducers were connected to a data acquisition board (DAB). This took the signal being produced by the three sensors and converted it to a voltage were it was read by the computer software. The pressure transducers were wired up into the DAB with the power, ground and signal wires into their specified positions. The signal produced by the pressure transducers was a signal voltage. The specifications state that for the upstream pressure transducer (0 to 400 kPa) the signal voltage ranges from 0 to 5 volts; whereby if the signal being received is 5 volts this is 400 kPa being experienced by the sensor in the pressure transducer. Similarly for the downstream pressure transducer (0 to 250 kPa) its signal ranges from 0 to 5 volts so at 5 volts the pressure transducer is sensing 250 kPa. These were the uncalibrated theoretical readings.

The ABB MagMaster flowmeter outputs a similar signal however the signal output is a current signal not voltage. This signal is a 4 to 20 milliamp output for a 0 to 0.9 L/s flow range. For the DAB and software to read this the signal needed to be converted to a voltage signal.

$$V = IR \qquad \textbf{3.1}$$

where: V = voltage (volts), I = current (ampere) and R = resistance (ohm)

From equation 3.1 it can be seen the relationship between voltage and current. To obtain a voltage for a 1 to 5 volt range from the 4 to 20 milliamp current signal from the flowmeter, a 250 ohm resistor is used. The signal being converted needed to maintain high precision, thus a special resistor was used for this conversion. The resistor used was a Vishay ultra high precision Z201 Z-foil 250 ohm resistor, which had a standard tolerance value of +/- 0.005%.

3.3.6 Labview: The Data Acquisition Software

From the data acquisition board these signals were connected into a computer. The program Labview was used to write a program which read the signal voltages from the flowmeter and two pressure transducers and displayed these on an interface. This program was created by Dean Beliveau of the University of Southern Queensland for this project. Labview was the program which is loaded and used for the automation tested. The program has the capacity to output text files where each line being outputted is an average of 20 readings taken over one second. This is due to the 20 Hz cycle which the DAQ and labview is setup. Each line (each second) has a discharge, input pressure and output pressure recorded respectively along with a data and time stamp every time the program is hit to record.

3.4 Calibration of Electronic Measurement Devices

Undertaking scientific measurements using electronic measurement apparatus, an understanding of the accuracy, repeatability and limitations of the devices needs to be known, in order to know the accuracy of the readings. This study is no different in terms of this need, in fact the understanding of the limitations of the measuring devices help to understand and interpret the raw data. With this project there are two main measurements taken, discharge and pressure. High accuracy was needed to understand the small differences between measurements

3.4.1 Flowmeter Calibration

The flowmeter was calibrated before purchase on the 20th July 2003. The calibration was taken place at a Narda accredited facility. The certificate of calibration for this electromagnetic flowmeter is included in Appendix D.

3.4.2 Pressure Transducer Calibration

The pressure transducers did not come with a certified calibration certificate from the supplier, thus less confidence was placed on its stated accuracy limit. An independent calibration of the pressure transducers was needed to confirm the accuracy and linearity of the measurement device.

To begin this calibration process a Dead Weight Pressure Tester (DWPT) was used. The DWPT consisted of a hydraulic loading cylinder. Within this loaded area there is an opening to place a tapping point; the pressure transducer (or other pressure device being calibrated) is placed. Also within the same loaded area another tapping point is fixed, however this point is closed. Weights are loaded into this rod (which is fixed within a casing in this point) and it rises up and down depending on the load placed by the hydraulic cylinder. To load the DWPT a wheel was turned which directly pushed a piston forward and placed a load on the two tapping points. When the rod was raised with the weight, it equalled the same pressure applied on the pressure transducer. Figure 3.1 – Dead weight pressure tested calibrating the pressure transducers shows the DWPT setup.

Figure 3.1 – Dead weight pressure tested calibrating the pressure transducers

This calibration testing took place on the 28th of February 2011. Oil was the fluid being used to calibrate the pressure transducers, which is fine, however it is a more viscous fluid compared to water and harder to get all air out of the system. The pressure transducers, data acquisition board, and computer was taken to the DWPT and set up. The 4.0 bar pressure transducer was used to be calibrated through the DWPT first. This transducer was filled with hydraulic fluid with an adaptor fitted; carefully this is attached to the pressure tapping point on the DWPT making sure no air was entrapped within the fitting. A ‘5 PSI’ rated weight was placed onto the rod which is lifted when 5 PSI of pressure is applied. The mass of the weight was not known or taken, as it already has a rating placed on it. With the computer and Labview turned on and the data acquisition board active the test was began. Slowly a load is placed onto the pressure transducer by turning the wheel around to push the piston forward. Small movements were given and when the rod pushed upwards the applied load was stopped. The rod with the weight on top was spun around to make sure no viscous friction was pulling back on the rod and that it was only under the influence of the load induced by the hydraulic cylinder. The pressure displayed by labview was then recorded, as well as the signal voltage transmitted by the pressure transducer into the data acquisition board against this rated ‘5 PSI’ weight. A fluke 110 series digital multimeter was used to measure the signal voltage output. The load was then backed off and an extra 5 PSI load weight added and the process repeated. Increments of 5 PSI were tested up to 55 PSI for the 4.0 bar pressure transducer and 35 PSI for the 2.5 bar pressure transducer. The elevation difference between the pressure transducer sensor and the top of the rod was measured for both transducers and used in the calculations to get the correct gauge pressures for calibration.

After discrepancies in the calibration of the pressure transducers with this method using the DWPT, a second means of calibration for the pressure transducer was needed.

This second calibration used an electronic way of calibration. To do this a Druck DPI 880 multi-function calibrator was used, connected into this was a Druck PV211 Pneumatic pressure and vacuum pump.

To calibrate, the pressure transducer was fitted into the pneumatic pressure pump and used to pump up to a particular pressure. The fine adjustment was used on the side of the pump to slightly increase or decrease the pressure. The pressure being produced by this pump is experienced by both the pressure transducer and the Druck multi-function calibrator. Making sure that the level of the sensors in both devices were the same, the pressure read by the Druck multi-function calibrator was recorded and the corresponding voltage was measured using a fluke 110 series multimeter. The accuracy for this multimeter for the reading of DC voltage is +/- 0.5%. A number of different measurements were taken over the 0-5 signal voltage range; five different repeats were done for the two different pressure transducers.

This electronic calibration while it did give better repeatability results then the DWPT, the calibration still was not good enough for the level expected. After two methods of using an electronic and mechanical means to read a corresponding pressure from the pressure transducer and comparing to the calibration method to calibrate, it was decided to use the header tank setup as a third very accurate method for calibration.

The theory which stems from this is related to the equation 2.3. If the elevation, density and gravitational acceleration variables are known or are calculated or measured with high accuracy then the static pressure would be also accurate. With the existing infrastructure with the hydraulics laboratory there are two header tanks, a low tank and high tank. With these two measurements from the header tanks and taking a third smaller measurement of around 1.5 metres at ground level, this would cover the pressure transducers operational range and give a highly accurate calibration in the form of a linear equation which could be inputted into the Labview software which would take the pressure transducers signal voltage and calculate the ‘real’ pressure and display it through Labview.

A level survey between the low and high header tanks and the point of calibration in the laboratory had been performed; this has been explained in section 3.2.1. This gives a very accurate elevation difference between these two points. With the pressure transducer sitting on the floor (the point where the level run was taken to) the diameter of the pressure transducer was measured with a set of verniers with 0.002 mm reading accuracy. The sensor of the pressure transducer is assumed to be in the centre of the pressure transducer, so the radius of the pressure transducers was taken away from the elevation difference between the low and high header tanks for the calibration process. For the very low head measurement the column of water was measured with a tape measure (accuracy +/- 1 mm) and the radius of the pressure transducer also taken away from the elevation measurement.

The next variable of focus is the gravitational acceleration constant used in equation 3.2. The two factors which determine the value of the gravitational acceleration constant is the latitude and altitude which plays a smaller part. Many professional engineers and scientists use a generic value of 9.81 m/s^{-2}, however this value will change with location. An accurate value of the gravitational acceleration constant was needed for this calculation for the calibration.

The value can be obtained from equation 3.2.

$$g = 9.80617 \times \tag{3.2}$$

$$(1 - 0.00264 \cos 2\emptyset + 7.0 \times 10^{-6} cos^2 2\emptyset) - 3.086 \times 10^{-6} z$$

where g = Gravitational acceleration constant (m/s^{-2}), $\emptyset$ = Latitude (radians) and z = Altitude (metres) (Australian Pump Manufacturers' Association Limited 1997)

The testing for this project only took place at the University of Southern Queensland, Toowoomba. Therefore only one latitude and altitude are needed and one gravitational acceleration constant value used in the calculations. The latitude was found for this site to be 27.601887° and converted to radians for this calculation, 0.48174380 rad. The altitude for the specified point for the calibration, as the survey is in AHD (Australian Height Datum), the level is 693.780 metres above sea level. Performing the calculation the constant comes to 9.7892779 m/s^{-2}. This value is the local gravitational acceleration constant for the University of Southern Queensland, Toowoomba Queensland Australia; and was used in the matlab calculations and computations for the analysis of the data.

The next parameter which needs to be discussed is density (ρ). As the temperature of a fluid increases the density decreases, thus the temperature of the water needs to be known when the calibration is undertaken. Relating the temperature back to the density, equation 3.3 is used.

$$Density = -0.004 \times Temperture^2 + 0.001 \times Temperture + 1000 \qquad \textbf{3.3}$$

This equation is based off a polynomial trend line fit to data. Figure 3.2 shows the relationship between the density of water and the temperature of the water, the equation is seen on this graph. The data which has been graphed in figure Figure 3.2 has been sourced from The Engineering ToolBox (2011).

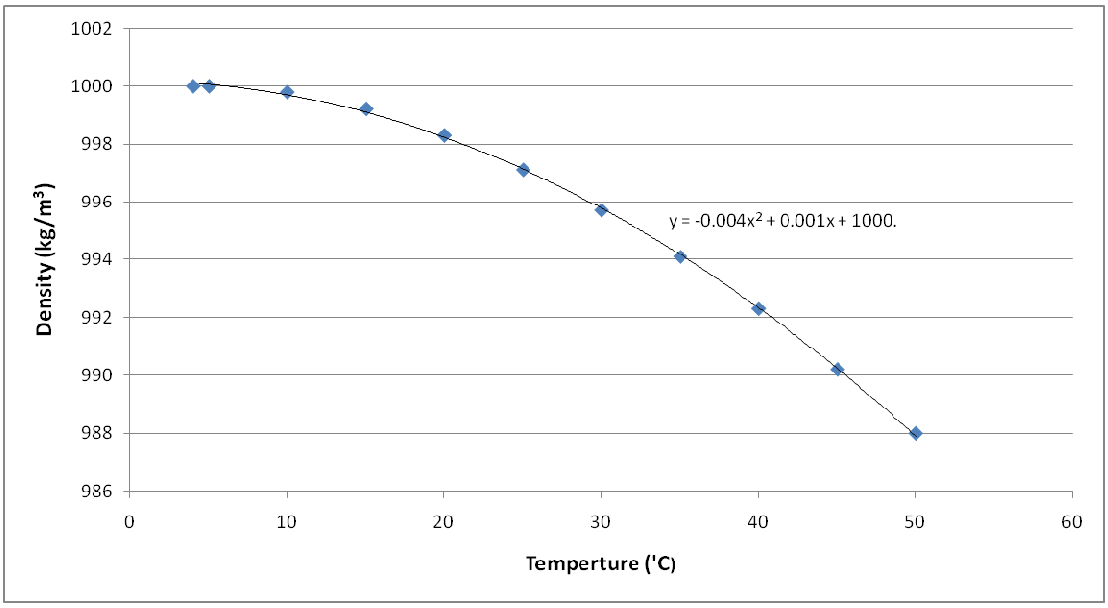

Figure 3.2 – Relationship between density and temperature for water

While the load was applied on the pressure transducer the signal voltage given from the pressure transducer was measured. Making sure high accuracy readings were kept, a digital multimeter with a six digit readout was used. 34401A was the model of this multimeter used. The calibration certification for this multimeter is included as appendix F; it was calibrated on the 21st April 2011.

With high accurate values known, the points for the low level measurement and for the two header tanks were plotted for both the 2.5 and 4.0 bar pressure transducers. A linear regression line was plotted between these three points and the calibration equations for the 2.5 and 4.0 bar pressure transducers was found. These equations are given below.

For the 4.0 bar pressure transducer equation 3.4 is shown and equation 3.5 is given for the 2.5 bar pressure transducer.

$$Pressure\ (kPa) = 80.107268 \times Signal\,Voltage - 1.004808 \tag{3.4}$$

$$Pressure\ (kPa) = 52.891850 \times Signal\,Voltage - 6.033053 \tag{3.5}$$

These equations were put into Labveiw for a direct calibration and the values output from labview then only needed the elevation difference accounted for. However for the early testing the equations were used in matlab to convert the pressures back to real pressures.

3.5 Function of the Nelson 10 PSI Pressure Regulator

Not much literature has been written on the working of pressure regulators used in pressurised irrigation. To gain an understanding about the internal workings and functionality of the pressure regulator, the device was dissembled, measured and drawn to firstly understand how the device performs its designed function.

The pressure regulators task is to maintain a set output pressure, no matter the change in input pressure, from this it could be said the device is a variable headloss, in constant change to keep the set output pressure. A typical device used on LMIM is Nelson UNI-Flo 10 PSI pressure regulator. To dissemble this device, six phillips head screws were removed. There are five main components within the device, spring, tube, redistribution plug, internal casing and two section of the external casing.

Tracking the movement of water through the pressure regulator the function of the pressure regulator can be understood. Water is entered into the pressure regulator via the input connection of the device. The first component in the pressure regulator which is encountered is the redistribution plug. The redistribution plug’s purpose is to break the streamline flow of the water as experienced through the input of the regulator. In the Nelson UNI-Flo type regulator the redistribution plug is designed to allow the flow to go through the plug. There is an obstruction in the centre of the plug; this obstruction is attached to the edge of the plug. On the underside of this obstruction is a downward lip.

The next component in the pressure regulator past the redistribution plug, is the tube – the main component in the device. The inlet of this tube is slightly angled outwards, which draws the flow into the tube. The tube moves upwards and downwards depending on factors happening at the other end of the tube. The position of the inlet of the tube in relation to the downward lip of the redistribution plug forms the basis of the variable pressure loss of variable headloss of the pressure regulator.

Once in the tube the flow passes down the length of the tube and is discharged into the second half of the external casing of the pressure regulator. Where the outlet of the tube is inserted into the external casing there is 0.3 mm clearance between the outside diameter of the tube and the casing. On the end of the tube there is six indentations into the base of the tube, this allows some the fluid being discharged to be passed around the outside of the tube and fill the void between it and the external casing. One of the indentations has an opening cut which goes down the outside edge of the tube towards the middle and then out bottom side of the base which has the rubber skirt around the circumference of this base. Once the water enters into this area it pressurises and forms a force which acts on the tube upwards.

The tube is fixed inside an internal casing. As shown in appendix B inside the internal casing encases the spring. The two ends of the spring are seated in the internal casing, the spring chamber, one side of the spring seated on the upstream side of the diaphragm skirt and the other on the downstream side of the spring chamber. It is this seating of the spring which provides a good transformation of the forces provided by the spring. When the device is not in operation the spring pushes the tube in its furthest possible position. It is then these two forces which form the basis of the resultant force to position the tube to regulate.

To seal all the parts of the pressure regulator, rubber O-rings are used. As mentioned above the rubber skirt is one seal which provides a flexible seal between the second part of the external casing and the bottom of the internal casing. The second seal is a typically O-ring. This seals fits onto a sit on the top of the internal casing. The redistribution plug is installed on top of the casing. This stops water going down the outside of the internal casing and filling the void between it and the external casing. The third O-ring, is of more interest to knowing the performance of the pressure regulator. It has a smaller diameter then the second O-ring described. It also fits into a moulded sit on top of the internal casing. The tube then fits up into it. It provides a stable working platform for the tube and keeps it parallel to the redistribution plug. As the tube moves, there is a frictional forces between it and the O-ring. It is this force which gives the pressure regulator its hysteresis effect. To overcome the hysteresis, the manufacturer has put lubricant onto the outside of the tube, to lower the frictional force.

When all the components are fitted together and the seals in place, to overcome void spaces becoming pressurised, vents have been included in the design. To vent the spring chamber, there is a smaller cut away section within the internal casing. As mentioned above, on the bottom of the tube, there six segments slightly shorted then the other six segments. When in a fully open position, air is still able to get into the system. Both of these incorporated designs allows the pressure regulator to function used atmospheric pressure conditions and at no stage is the device able to build up pressure which would affect the workings and functionality of the pressure regulator.

3.6 Development of Testing Methodology

3.6.1 Introduction

The essence of this dissertation is to experimentally develop a testing methodology by which pressure regulators can then be tested to accurately describe their performance. Experimental development of the testing rig involved incremental alterations of the apparatus and methodology. The first stage of testing aimed to replicate the results from von Bernuth and Baird (1990).

3.6.2 Stage One – Result Replication from von Bernuth and Baird (1990)

This stage of testing which set out to replicate the results from von Bernuth and Baird (1990), first constructed the testing rig. Fluid dampening pressure gauges were used to measure the input and output pressures from the pressure regulator. The ABB MagMaster ultrasonic flow meter was used to measure the discharge within the testing rig. Valves were used, once each side of the pressure regulator to control the flow and manipulate the pressure. To control the discharge a nozzle was placed downstream of the downstream valve, this nozzle acted as an orifice. Figure 3.3 shows the testing rig for this stage of testing.

Table 3.1 – Valves effect on experiment

		Resultant Flow Effect	Resultant Input Pressure Effect	Resultant Output Pressure Effect
Upstream Lever	Opening	Increased	Increased	Increased
	Closing	Decreased	Decreased	Decreased
Downstream Lever	Opening	Increased	Decreased	Decreased
	Closing	Decreased	Increased	Increased

Once the test rig was constructed, testing began to try and replicate the results from von Bernuth and Baird (1990) experiment. This involved getting different input pressure and recording the output pressure at a constant discharge. Two pressure regulators were tested a Valley 6 PSI and a Nelson 10 PSI. The pressure regulator was coupled into the testing rig via two quick coupling fittings. A Nelson 3TN #48 nozzle was fitted at the end of the pipeline within the test rig to maintain a constant discharge through the system. The whole testing rig was flooded to ensure the system was free of air. In replicating the results of von Bernuth and Baird (1990), the 'hysteresis curve' was tried to be produced by obtaining multiple points around this curve. As described in chapter two, hysteresis within the pressure regulator is due to the frictional force of the O-ring against the movement of the tube. To get the points on the boundaries of the curve either a rising or falling input pressure was needed.

With the high header tank system on the butterfly valve was turned on and the static head was recorded from the fluid-dampened pressure gauge. The upstream and downstream valves were then turned on allowing, water through the system. The upstream valve was turned on 90% of the way. The downstream valve was then adjusted to obtain the constant discharge value. For a rising pressure, being on the upper limb of the hysteresis curve, it was made sure that the very last movement of either valve was to get a rising. Similarly for a falling pressure, on the lower limb of the hysteresis curve, it was made sure the last movement was to obtain a falling pressure. To get an accurate and precious desired discharge requires very small adjustments on the levers on upstream and downstream valves. Once the correct discharge was arrived at making sure that the last movement of the two valves was to either get a rising or falling pressure from the pressure regulator; the upstream and downstream pressures were read manually off the WIKI pressure gauges and recorded. The flowmeter also was manually read and recorded. Once multiple points had been obtained around the hysteresis curve, the second pressure regulator was placed in the testing rig and tested. The raw data was processed and graphed in Microsoft Excel. Figure 4.1 andFigure 4.2 show the results for the result replication from the literature of von Bernuth and Baird (1990).

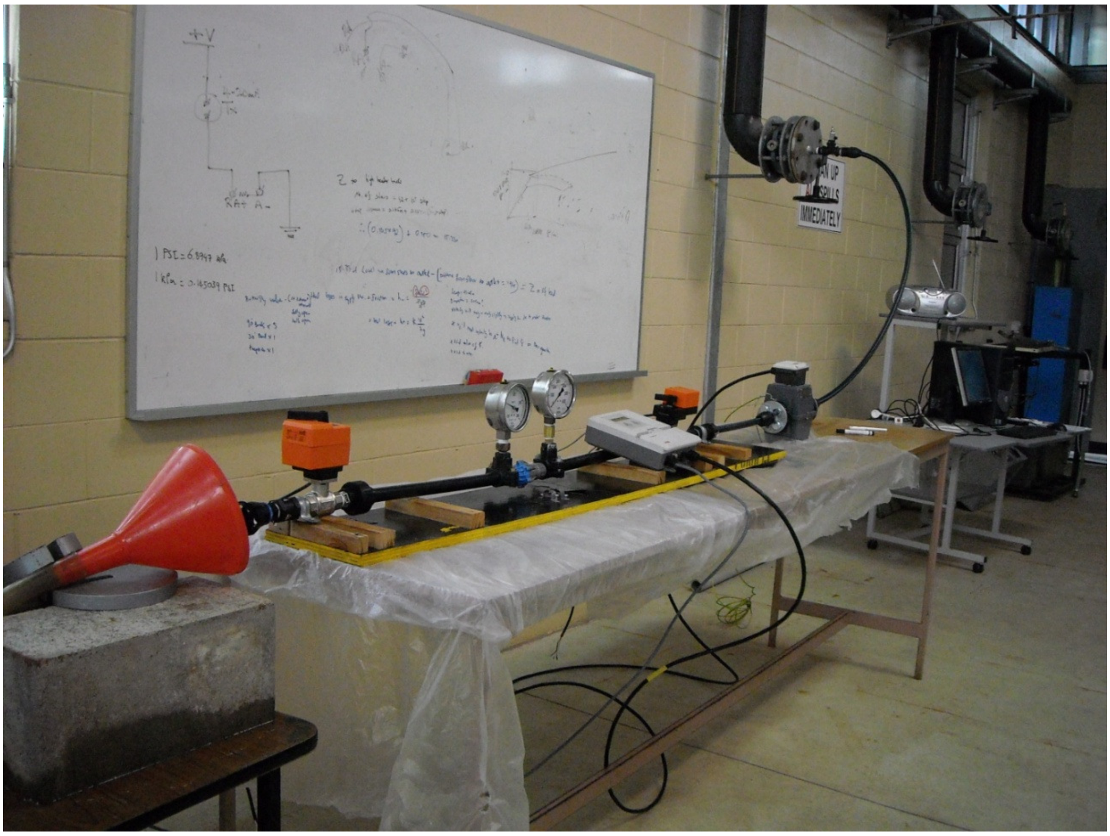

Figure 3.3 – Stage one testrig Results replication from von Bernuth and Baird (1990)

3.6.3 Stage Two – Automatic data acquisition

Setting up the stage two testing rig took time, as the automation data acquisition needed to be incorporated into the hydraulic setup. Section 3.3 details the materials used in stage two testing and how stage one was further with the existing equipment such as the flowmeter, valves and pipe fittings. **Error! Reference source not found.** shows the testrig setup for this automatic data acquisition stage.

Once the testing rig for the automatic data acquisition was assembled, with all pipe fittings checked for leaks and the high header tank system on, the butterfly valve was turned on and the experiments allowed to be flooded to allow air to escape from the system.

With the computer powered, the flowmeter turned on and the data acquisition board with power, the program Labview was opened. The butterfly valve being opened gives a constant level water supply to the experiment from the high header tank.

Figure 3.2 shows a red 25.4 mm gate valve attached to a galvanised dropper from the flange attached to the butterfly valve. With the butterfly valve fully open, the red gate valve allowed finer adjustment control of the discharge into the experiment. The first discharge of interest is 0.05 L/s. To vary the input head the upstream lever was moved.

For a rising pressure the upstream lever was opened, this allowed the discharge to go above the discharge band rate allowed in the labview program. To compensate the downstream lever was closed very carefully and slowly. This brought the discharge back into to the discharge of interest, while still the pressure was rising. The system was allowed to settle for 3-5 seconds. The software was then allowed to record this point and write it to a textfile. Multiple rising pressure points were obtained at this constant discharge.

Falling pressure points were then obtained. To do this the upstream valve was adjusted to get the discharge below its final value. The downstream valve was then opened to move the discharge to its final value. This process was then repeated to obtain multiple falling output pressure points. Another discharge value was tested for the rising and falling pressures. For this stage of testing, automatic data acquisition discharges of 0.05 through to 0.3 L/s at 0.005 L/s increments and 0.5 L/s. At the start and end of each discharge measurement the temperature of the water was measured by an alcohol filled thermometer.

Figure 3.4 – Stage two testrig Automatic data acquisition

Appendix G shows two output text files for this stage of testing of 0.30 and 0.50 L/s. These output files have been taken straight from Labview. After the testing the textfiles needed to be processed so the raw data can be presented in a way which is easier for interpretation. To do this process matlab was used and appendix H shows the matlab code which was used to take each textfile and brought it into matlab and processed the discharges, input and output pressures.

When the testing was in progress and labview was allowed to recorded, occasionally two seconds of data would be recorded, meaning two lines of data would be written to the textfile. When the textfile was input into matlab, both lines of data have been analysed and the discharge closest to the one of interest is accepted with their corresponding input and output pressures. After all the data was taken from the textfiles and put into matlab the pressure calibration was undertaken. Section 3.4.2 describes the importance of calibration and details the process taken to calibrate the pressure transducers. When this testing was carried out, labview has the signal voltage for the pressure transducers as a direct linear relationship, after calibration is was proved not to be correct. The matlab code takes both the input and output pressures and converts them back to signal voltages and then takes these signal voltages and runs it through the respective calibration equation to arrive back to the correct pressures (kPa).

The water temperatures which were measured and recorded at the time of the test, these were entered into the matlab and the corresponding densities were calculated by the equation 3.3. The pressure offset from the tapping point into the experiment to the position of the pressure transducer was also measured accurately and this was entered into matlab. With all this information and the local gravitational acceleration constant for Toowoomba was calculated from equation 3.2, and the pressure head was calculated. Matlab was then used for plotting and its graphical editor feature utilised for easier formatting of the matlab figures.

3.6.4 Stage Three – Automatic data acquisition with higher input heads

In this stage of testing saw the addition of a pump to the test rig. Figure 3.3 shows the setup for this stage of testing. The 25.4 mm red gate valve used in stage two testing was also used in stage three testing to give control over the discharge of the pump and regulate the flow into the experiment. It is important to monitor the head going into the experiment due to the pressure transducers. If too higher head was experienced while the transducers are attached, this would damage the diaphragm in the transducer. Thus before the pump was started the red gate valve was turned off. Appendix I shows this Southern Cross HX-C pump’s performance curve. This stage of testing saw extra input head added to simulate the input head that the pressure regulators experience in the field on large mobile irrigation machines. A similar methodology was used in stage three has in stage two tests.

Figure 3.5 – Stage two testrig Automatic data acquisition with higher input heads

Once the experimental rig in figure 3.3 was assembled, the pumps to the high header tank were switched on ready to start the experiment. With the computer and data acquisition board on the butterfly valve was then turned on, flooding the pipeline. The red gate was turned off before the Southern Cross pump was switched on, than the gate valve was turned on very slightly. Depending on the discharge being tested, depended on the amount the red gate valve was allowed to be turned on. Stage three testing saw discharges 0.2 through to 0.7 L/s with 0.1 L/s increments being tested. Once flow was going through the experiment from the red gate valve being turned on the upstream valve was altered. The downstream valve was then adjusted accordingly to get the discharge onto its correct position while still only having a rising pressure. This procedure was repeated, obtaining multiple rising output pressure points. Once it was decided enough rising points were achieved, falling points were then obtained. To do this the upstream valve was adjusted just below the discharge of interest. The downstream valve was then opened to arrive at the discharge for a falling pressure.

Again as with stage two a textfile is written which outputs the raw data from labview. Appendix J shows the raw data output for this stage of testing for automatic data acquisition with higher input heads for discharges of 0.2 and 0.4 L/s. A simular matlab script as shown in appendix H was used for the analysis and processing of the raw data.

3.6.5 Stage Four – Continuing Valve Movement Test

In this stage of the testing procedure no major changes to the testing rig were seen, however a different approach in how the testing rig was used to try and further the understanding in how the pressure regulators function.

Stage four testing started by tracking the input head around the hysteresis curve and using the two levers, up and downstream of the regulator, simultaneously in order to keep the discharge in a tight band. Because the reading were continuous and not steady like stages two and three, this meant that the discharge could not be a set constant. The levers however provided good control and thus allowed for very small movements which meant the smallest possible changes in discharge possible.

To begin this stage of testing the testing rig was configured as in stage three. With the high header tank system turned on the butterfly valve was opened and the system flooded. The Southern Cross pump was switched on and the red gate valve adjusted according to the specific discharge being aimed. The first aimed discharge was 0.2 L/s. With both the upstream and downstream levers which are attached to the corresponding valves upstream and downstream of the pressure regulator in the fully shut position the bandrate was entered into the labview software. The bandrate was 10% of the discharge of interest. The levers were then altered to get the lowest possible input head while maintaining the discharge. As with previous tests the water temperature was measured and recorded before the beginning of the test. This began the starting point of the test, and the software was then hit to record. The upstream lever was slowly opened to allow extra input head into the system while keeping a close eye on the discharge trace not letting the flow going outside the specified band rate. The downstream lever was then closed slightly, this raised the pressure but also increased the discharge which compensated for the previous change of discharge, again the discharge was kept within the band rate.

This tedious process continued to the maximum allowable input head which could be received by the pressure transducer ≈ 400 kPa, this then was the rising pressure. While the system was still recording the test then was in the falling pressure stage. The upstream valve was slightly closed; again making sure the discharge did not go outside the band rate. The downstream valve was then slightly opened which compensated for the discharge change. The process continued until the input head was at the lowest possible point for the discharge to be kept in the band rate. This whole process was then repeated; however instead of going to 400 kPa, at each 50 kPa increment from 400 the falling pressure was began. The software was allowed to record for this cyclic measurements around the pressure regulators hysteresis curve.

Once difference approaches were taken from the upper to the lower limb of the hysteresis for this aimed discharge of 0.2 L/s with the set bandrate of 10%, the test was repeated for another aimed discharge of 0.4 L/s and 0.6 L/s. Matlab was used for the processing of this data and analysis.

3.7 Creep test

A different approach was taken with this stage of testing, the creep testing. This stage investigated the movement of the tube within the pressure regulator with the device is functioning for a long period of time. To perform this test it was split into two sections, a rising and falling section. Using the same testing rig and materials as in testing stages two (automatic acquisition test), the computer and software was started up to begin the test. As in stage two the high header tank was used as the supply to the experiment, making sure there was no air in the supply line the butterfly valve was turned on. Using the two levers simultaneously a rising input head was selected at a specified discharge. Making sure the last move of the levers was a rising input head, either the upstream lever was opened or the downstream lever was closed to get to the specified discharge.

Once this point was arrived at the labview software was started to record. Both levers and the butterfly valve was then not touched or altered. Immediately after the software is started to record the temperature of the water passing through the experiment is measured and recorded. The test was left to run for 24 hours. Every three to four hours over the 24 hour period the temperature was measured and recorded and fed back into the analysis for use with the raw data. After this 24 hour period the experiment was stopped and the levers altered to arrive at a falling output pressure. Labview was then left to record for 24 hours. The temperature of the water was measured every few hours for both the rising and falling tests for analysis purposes.

3.8 Friction test

The same methodology was taken with this series of tests as the continuing valve movement tests which is outlined in section 3.6.5. There were three sections to the friction tests. The first stage, which is called normal lubrication, involved taking the pressure regulator and testing it using the same procedure as described in section 3.6.5. The pressure regulator was then dissembled and the lubrication wiped away from the tube and the O-ring using a soft cloth, the pressure regulator was then resembled very carefully and retested. This tested is referred to as no lubrication. After a second testing the pressure regulator was dissembled and a water based lubrication was applied onto the tube. The device was then retested and this test was referred to as extra lubrication. Extra care was taken when dissembling and reassembling the pressure regulator and its components between tests as damaging the tube could affect the performance of the device.

Two pressure regulators were tested, both Nelson 10 PSI types, NL10-2 and NL10-3. The NL10-2 was tested without the extra input head of the pump, only the high header tank was used as the supply for the experiment. NL10-3 testing used the pump for obtain extra input head for testing.

3.9 Displacement of Tube inside Pressure Regulator

This stage involved tracking the movement of the tube inside the pressure regulator. The movement of tube is the regulating component of the device, thus if a relationship can be formed between this tracking movement and the other three parameters, discharge, input and output pressures; a better understanding can be formed about the function of the pressure regulator.

The methodology and materials used in stage six testing was different compared to previous tests. The experiment was connected directly onto the flange connected to the high header tank. From the 50 mm tee-piece coming off the flange fitting a valve was fitted. This valve was the same type of valve used in previous experiments, only one valve was used. The pressure regulator was fitted downstream of the value. To measure the input and output pressures of the pressure regulator the tapping points were fitted directly upstream and downstream of the pressure regulator using 19 mm polythene tee-pieces. 6 mm tube was then connected back from these tapping points to the pressure transducers and the elevation difference accounted for and recorded.

To measure the discharge a different set up needed to be constructed, as the experiment needed to exit the pressure regulator via a nozzle which acted as an orifice under free flowing conditions. The ABB MagMaster Ultrasonic flowmeter was used to measure the discharge. To pass the flow through the flowmeter a meter length of 90mm PVC pipe was plumbed into the inlet of the flowmeter with the appropriate reducing fittings to the flowmeter’s 19.05mm threaded flange fitting. On the outlet side of the flowmeter, the appropriate fittings were installed to a 90mm PVC pipe reducer. This creates a headloss across the flowmeter. From the nozzle, the experiment is discharged directly into the 1 metre 90mm length attached to the inlet of the flowmeter. The high velocity being discharged into the PVC length is dampened by the column of water held in the PVC pipe. The water is then passed through the flowmeter by the head provided in the PVC pipe. This forms the basis of the discharge measurement for this stage of testing. Figure 3.6 – shows the test rig for this testing stage.

To track, gauge and measure the tube movements, non stretch was glued to the inside of the tube with plastics glue. The fishing line used was a braid line, which provided limited stretch and was a relatively easy material to glue to the tube. The tube is a very smooth plastic material. To provide the adhesive *Selleys Plastics Glue* was used, this was the only glue which could give a good bond to the smooth tubes surface.

The line was taken out of the experiment through the nozzle and threaded via two pulleys; a weight was loaded on the other end of the line in the form of a bolt which took the slack out of the line. When the supply to the pressure regulator is turned on and an increasing input pressure is resulted on the tube moves forward to create a headloss and regulate. Conversely when the supply is turned off and the input pressure is decreased the tube moves backwards. Referring to appendix B, this action can be visualised. When the tube moves either direction the load moves with it, to quantify this movement a dial gauge is used.

A dial gauge is a measurement device used to determine small distances. The device used for stage six testing is a Baty 10 mm travel length device with an increment step of 0.002 mm. A bolt is used at the load on the end of the line. On the bolt is a nut, by holding the nut stationary and screwing the bolt a fine adjustment can be made of placing the load onto the dial gauge. An indentation has been drilled into the head on the bolt for the dial gauge to fit into. On the bottom of the bolt, a hole has been drilled and treaded for an eye hook to screw into it. The line is tied to this eye hook. Two pullies are used to shift the dial gauge and the load – the bolt away from the path of the jet of water being discharged into the PVC pipe attached to the flowmeter. Figure 3.5 shows an overview of stage six testing. Figure 3.6 shows the dial gauge setup in detail.

Figure 3.6 – Testrig for Tubes movement

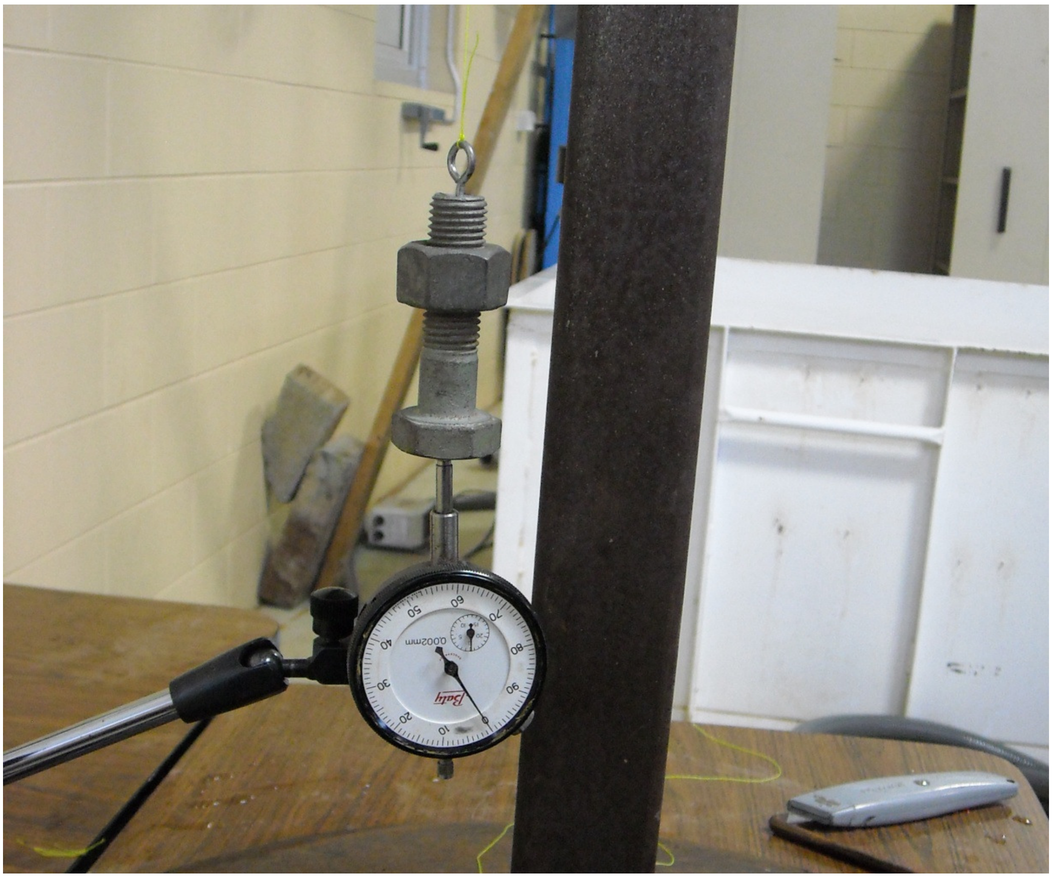

Figure 3.7 - Dial gauge overview used for tubes movement

Beginning stage six testing, the valve is fully opened; this is to be the starting position for the test. After the experiment has been assembled, the is valve turned on and the dial gauge zeroed at this position; a video camera is set up in front of the dial gauge to record its movement. The software is started and the data recording. A verbal start mark is made, when the software is started to record. This is so make marrying up the two separate datasets, the tubes movement and the software text file easier. The valve situated upstream of the pressure regulator is then slowly turned on, taking at least 90 seconds to do this movement of the valve from fully open to fully shut. This process is then repeated, however starting shut and going to fully open. This will move the tube forward, taking load off the dial gauge, thus at time zero the dial gauge is loaded and the position noted, the valve is then turned on slowly, while the software and camera both record their corresponding articles. Two sized nozzles are tested, which give two different final valve discharge values. The nozzles used were the 3TN #15 and the 3TN #28.

3.10 Statistical Analysis Testing Methodology

This was the first and only series of tests which multiple pressure regulators were tested. The high header tank was used as the supply for this experiment. The same equipment setup was used in this series of tests as in automatic acquisition tests explained in section 3.6.3.

To begin the test the computer and data acquisition board was all switched on. With pumps running and high header tank system on the butterfly valve was fully opened. The downstream valve was also fully turned on with the upstream valve fully off. With a pressure regulator fitted in the test rig and all the air out of the system, Labview was hit to record the upstream valve was then fully turned on and record stopped. Five repeats were taken of this process before the pressure regulator was replaced and the process repeated. 16 Nelson 10 PSI pressure regulators were tested. 5 had connection fittings 19 mm female to square and 11 had barbed to square (inlet to outlet fittings).

The last recorded line of data was used in the analysis process. Excel was for the data analysis.

Chapter 4 RESULTS AND ANALYSIS

4.1 Introduction

This chapter contains the results and analysis from the experimental procedures and evaluations conducted in accordance with their respective procedure from Chapter 3.

4.2 Result Replication from von Bernuth and Baird (1990)

The first stages of testing set out to replicate the results by the literature of von Bernuth and Baird (1990). With the testing rig set up the way it was with valves either side of the pressure regulator it was found output pressure effect by moving each effect as well as the flow effect, tableTable 4.1 – Test rig valve effect on flow and pressure show the effect.

Table 4.1 – Test rig valve effect on flow and pressure

		Resultant Flow Effect	Resultant Input Pressure Effect	Resultant Output Pressure Effect
Upstream Valve	Opening	Increased	Increased	Increased
	Closing	Decreased	Decreased	Decreased
Downstream Valve	Opening	Increased	Decreased	Decreased
	Closing	Decreased	Increased	Increased

Figure 4.1 shows the result replication test from manual observation testing of the Valley 6 PSI set pressure regulator at a constant discharge of 0.344 L/s.

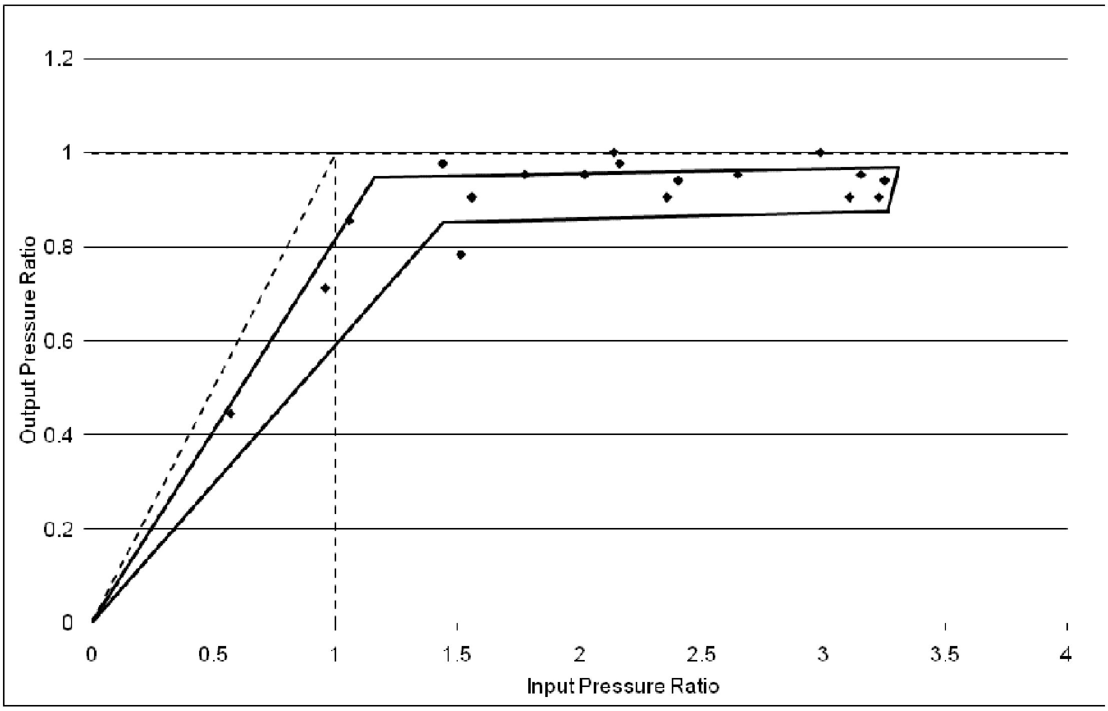

Figure 4.1 – VL6-1 Manual Singular Point Test at Q = 0.344L/s

The horizontal broken line in figureFigure 4.1 represents the output pressure setting of the pressure regulator; similarly the vertical broken line represents the pressure setting of the device on the input pressure axis. The broken diagonal line is a 1:1 line from the origin to the point of intersection of the two broken lines. The axes of the figure are reported in a ratio manner. This is the observed pressure in ratio to the set pressure of the pressure regulator. Thus an output pressure ratio of one is an observed pressure of 41.36kPa divided by the pressure set of the device, which in this case is 41.36kPa, giving an output pressure ratio of one.

The four solid lines have been fitted to the data, to describe and compare the data to the literature.

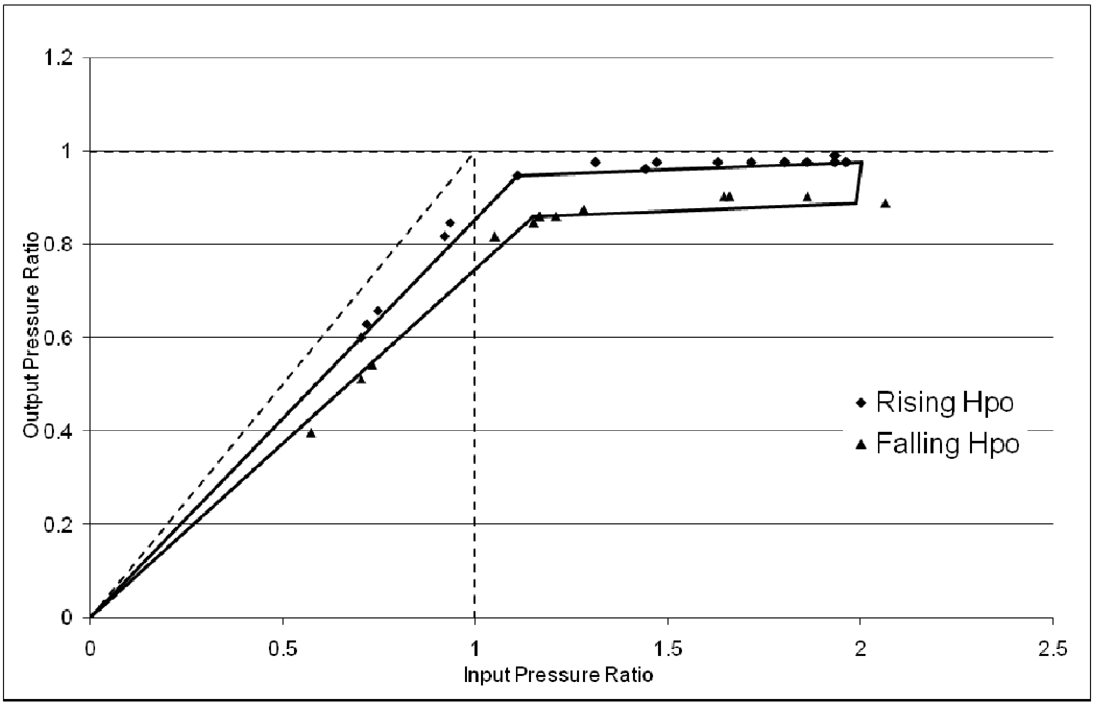

Figure 4.2 - Nelson 10 PSI (NL10-1) Pressure Regulator Hysteresis Performance at Q = 0.344 L/s

Figure 4.2 shows a repeat of the testing, however with another pressure regulator, the Nelson 10 PSI set pressure device with connection fittings threaded female to female. The test was done at the same constant discharge as for the VL6-1 pressure regulator, 0.344 L/s. The unbroken lines represent the set pressure rating of the device and the axes are pressure ratios. A different approach was taken with this test that the rising and falling output pressure points have been plotted separately. The four solid line segments were fitted to the rising and falling points. By doing this the four segments could be better fitted to the data and a truer understanding be made of the hysteresis effect caused by the internal friction of the tube on the O-ring. Without having the separation of the rising or falling pressures the four segments were fitted manually for the Valley pressure regulator test.

Table 4.2 – Comparison of manual singular point tests to published literature

	S1	X0	S2	X0	Y2	S3	Y4	S4	YF

Literature Ideal Value	1.000	0.000	0.00	1.0000	1.000	0.000	1.000	1.000	0.000
VL6-1	0.816	0.000	0.011	1.159	0.946	0.013	0.851	0.590	0.000
NL10-1	0.852	0.000	0.031	1.108	0.947	0.035	0.858	0.746	0.000

Table 4.2 show a comparison of the two pressure regulator tested, VL6-1 and NL10-1. These values have been compared to the ideal values published from the literature of von Bernuth and Baird (1990). It must be remembered that while both pressure regulators were tested at the same constant discharge of 0.344 L/s, each pressure regulator is of a different set pressure rating and different model. The compassion gives an indication that the methodology of the testing does replicate the results to what the literature describes as the ideal values for particular parameters. However the table does show the NL10-1 performed truer to the literature ideal valves for most parameters. This does not mean it necessarily has a better performance than the VL6-1 pressure regulator.

The parameters in the table refer to the slopes and start and end values of the four line segments fitted to the data. FigureFigure 2.3 – Typical pressure regulator performance as described in von Bernuth and Baird describes these parameters. From tableTable 4.2 it does seem that both the Valley and Nelson pressure regulators perform fair, with the Valley device slightly better in terms of the parameter values being closest to the literature ideal values. However the lines in the data were manually fitted and there was no differentiation between a rising or falling pressure. It does prove that the testrig used from this testing does reproduce data from the literature Bernuth and Baird (1990).

4.3 Automatic Data Acquisition

Following the improvements of the testing rig and procedure the automation testing began with obtaining singular points around the output pressure range of the pressure regulator. The methodology used for this test is outlined in section 3.6.3. The following figures show the results from these tests with each graph representing a set discharge. One pressure regulator was used for these tests and it was a Nelson 10 PSI pressure set type with female to female thread as its connection fitting, this pressure regulator was given the code NL10-1 for designating purposes. This was the same device used for the manual singular point test which set out to replicate the results from Bernuth and Baird (1990).

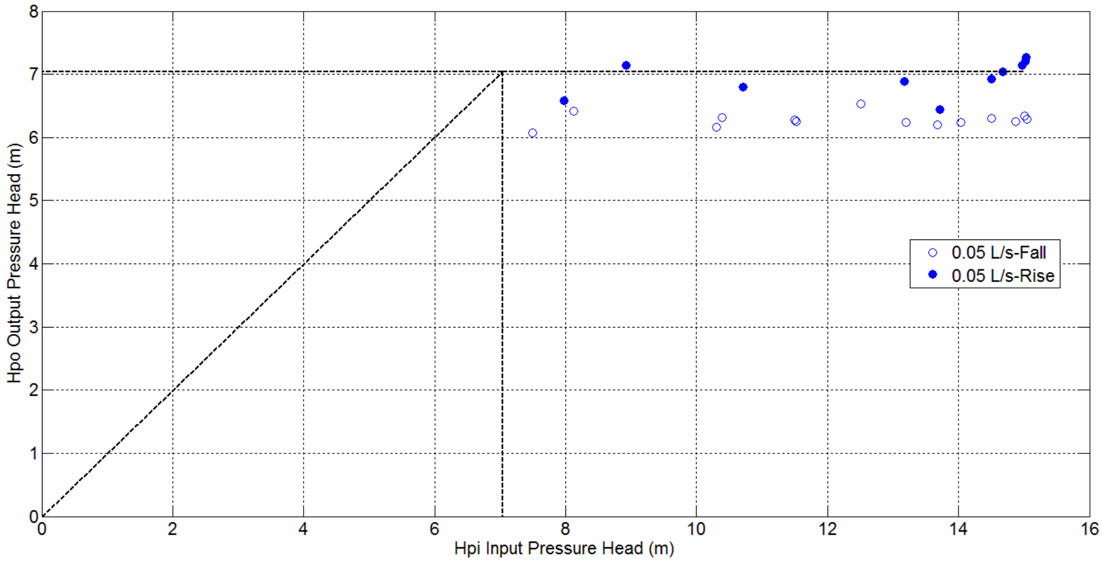

Figure 4.3 – NL10-1 automatic acquisition test at 0.05 L/s

Figure 4.3 shows singular points which represent a rising or falling input pressure at a constant discharge of 0.05 L/s. The solid dotted lines represent the set pressure of the pressure regulator in metres head. The diagonal solid dotted line represents a 1:1 line from the origin to the incept point of the vertical and horizontal lines which are the input and output set pressures of the pressure regulator respectively. The observed input and output pressures in this figure have been presented, unlike the presentation of figuresFigure 4.1Figure 4.2 which reported the ratio of pressure to set pressure. Figures

Figure 4.3 through toFigure 4.9 show the multiple points for different constant discharges of 0.05 through to 0.30 L/s with 0.05 increments and 0.5 L/s with the rising and falling input pressures.

While it is clear that generally in figure Figure 4.3 the rising point are above the falling points, the difference between the lines is hard to differentiate. The difference between the maximum and minimum output pressure of figure Figure 4.3 is 1.2 metres head which equates to a variation of 11.75 kPa. No points were obtained for this discharge at lower input pressure because of the limitations imposed by the testrig and effects of the movement of the valves have on the discharge and input and output pressures.

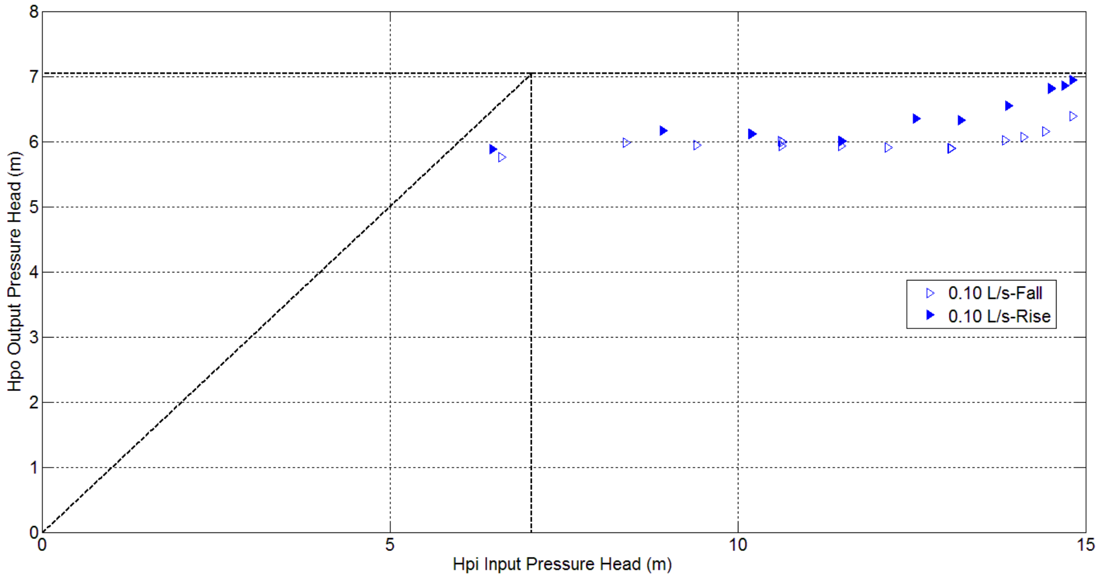

Figure 4.4 – NL10-1 automatic acquisition test at 0.10 L/s

Figure 4.4 shows the test results for a discharge of 0.10 L/s. From this graph the rising and falling points appear to be on the one output pressure, around 6.0 metres head. However at high input pressures, both the rising and falling point increase and the hysteresis difference appears. The hysteresis band is more distinct in figure Figure 4.5, where the discharge tested is 0.15 L/s. While the falling pressures above the set pressure are positioned about the same output pressure the rising pressure points do not. Figure 4.6 which shows the discharge of 0.20 L/s again has all the falling pressures about the same output pressure. Not as many rising pressure points have been taken for this discharge a comparatively large variation is seen.

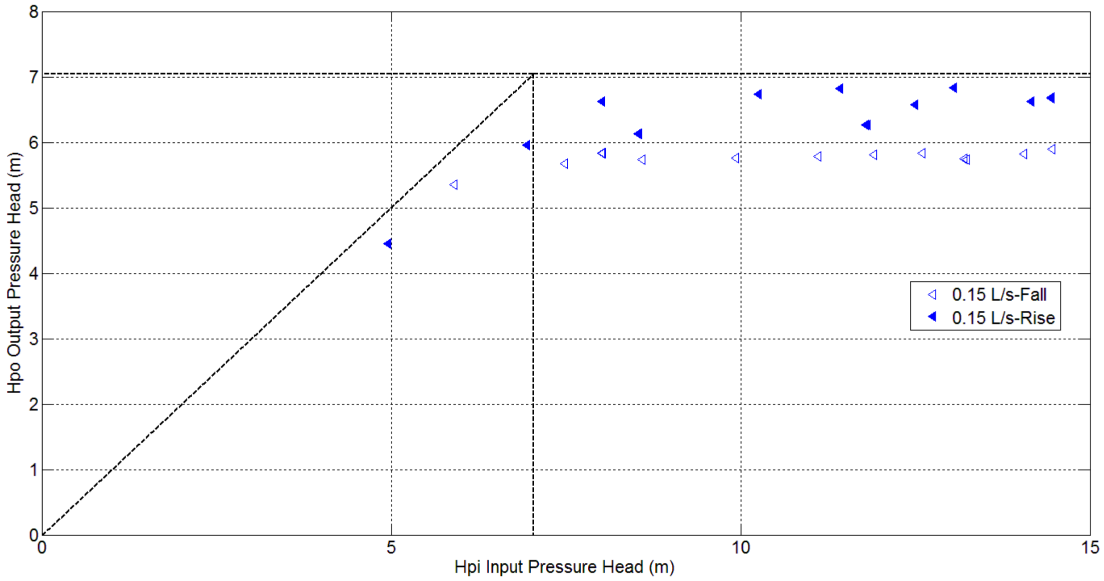

Figure 4.5 – NL10-1 automatic acquisition test at 0.15 L/s

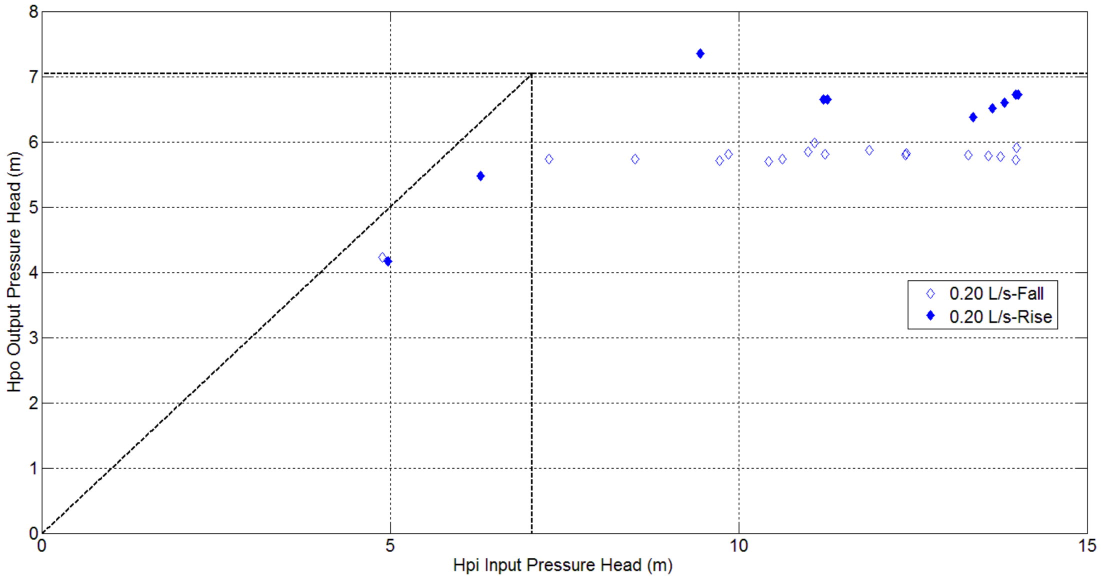

Figure 4.6 – NL10-1 automatic acquisition test at 0.20 L/s

Figure 4.7 shows a point pattern of the rising and falling points which is similar to the literature. Again as with previous discharges, the falling points are around the 6 metres head output pressure. This figure also gives a good indication to what happens at input pressures before the set rated pressure of the pressure regulator. Both the rising and falling points follow the same imaginary line, of same slope as the 1:1 line. However the imaginary line is on an offset from the 1:1 line. This is due to the headloss between the input and output pressure tapping points, upstream and downstream of the pressure regulator respectively. The points follow the one line, before the reach the pressure rating of the pressure regulator because the pressure regulator has not began regulation yet and the whole system is still giving out a constant headloss.

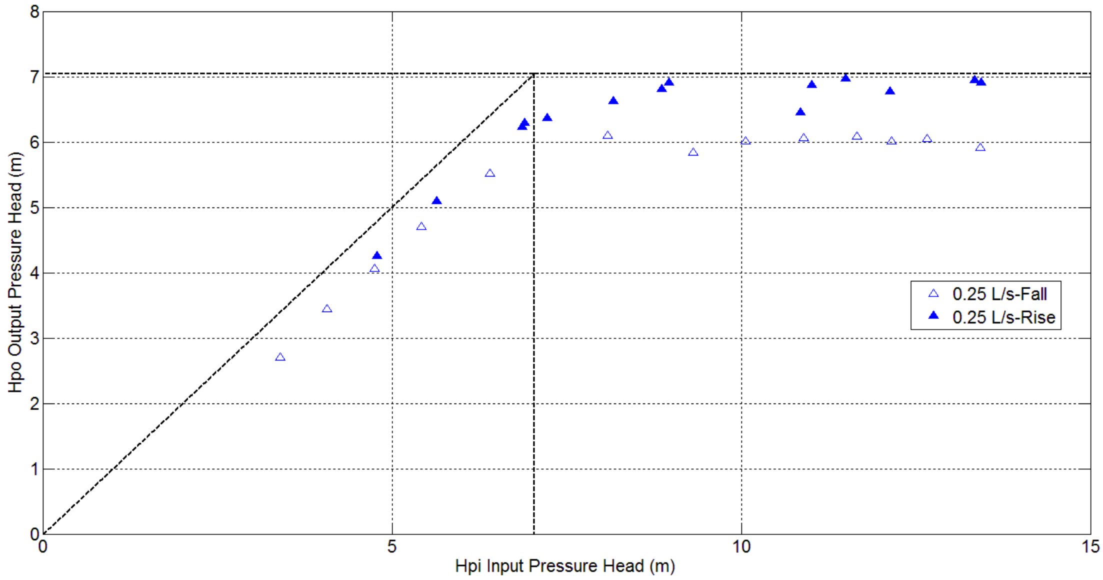

Figure 4.7 – NL10-1 automatic acquisition test at 0.25 L/s

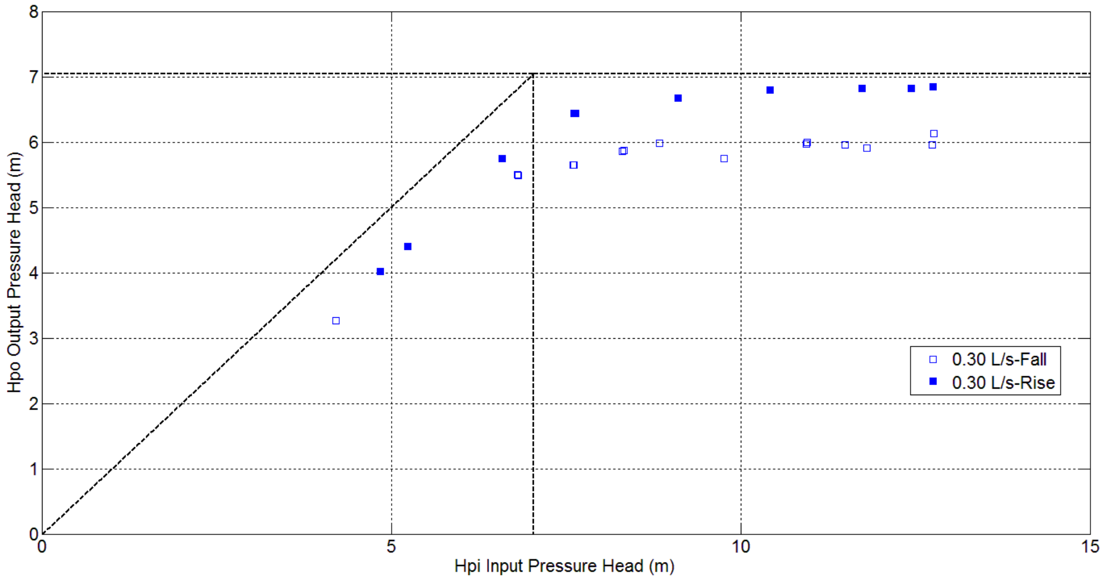

Figure 4.8– NL10-1 automatic acquisition test at 0.30 L/s

Figure 4.8 like figure Figure 4.7shows a good point pattern, with both the rising and falling points below the pressure regulators set pressure value following an imaginary constant sloped line, before the variable regulation kicks in and the rising points separate from the falling points.

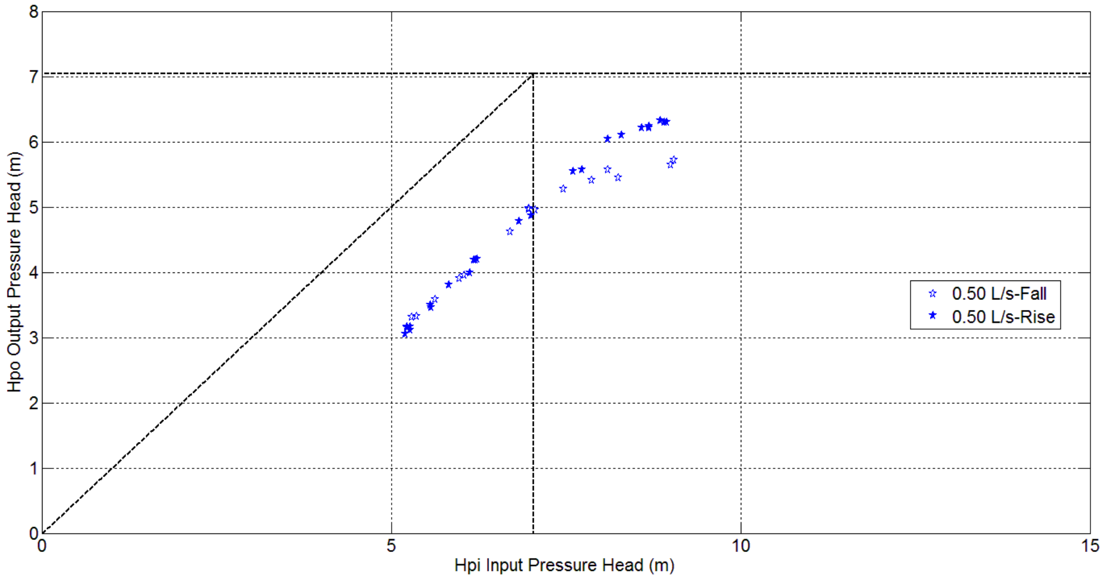

Figure 4.9– NL10-1 automatic acquisition test at 0.50 L/s

Figure 4.9 show the discharge value of 0.5 L/s. This figure does not show points over an input pressure of about 9 metres head. This is due again to the limitations of the water supply into the experiment. The surveyed high header tank gives a static pressure supply of 16.181 metres head. However with the required discharge of 0.5 L/s, this decreases the maximum possible input head. In figure Figure 4.9, though rising and falling points are seen to follow an imaginary line, at an offset under the 1:1 line, the offset again is the headloss received between the inlet and outlet tapping points which are connected into the pressure transducers. Above the pressure set rating the separation of the rising and falling points can be seen.

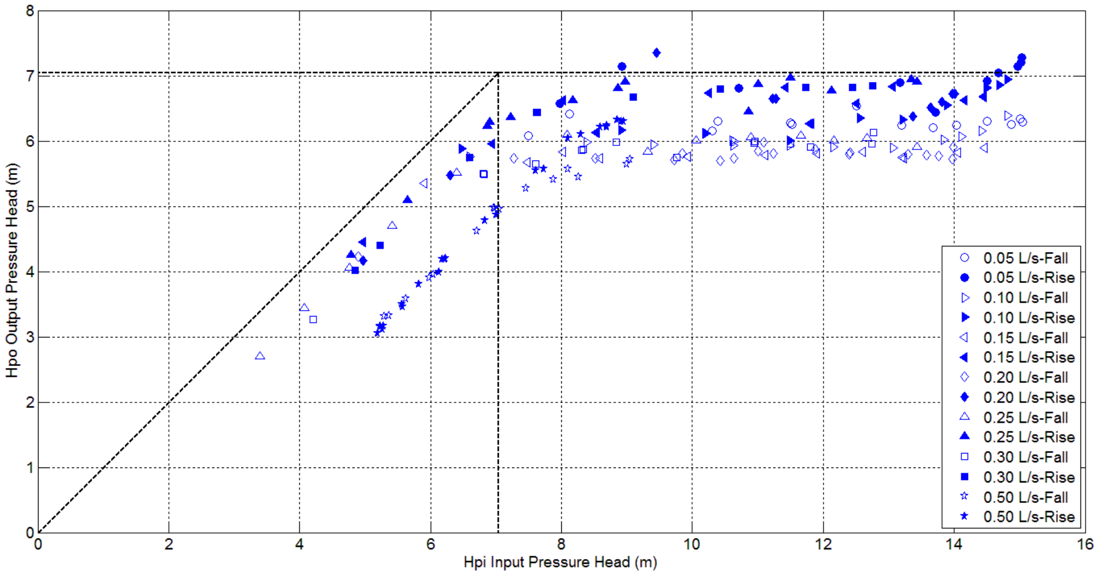

Figure 4.10– NL10-1 automatic acquisition test with all discharges

Figures Figure 4.3Figure 4.9 give the automatic data acquisition tests shown with separate discharge values, figure Figure 4.10 shows this data again, but on the one graph. At first glance of this graph the separation of the rising points and falling points can be seen. The majority of the points all fall under the pressure regulator set pressure of 10 PSI, this is represented by the horizontal broken line in the figure. There is a very identifiable band of points in this figure, which holds the same width as the input pressure increases. This band width is about 1.3 metres head with equates to a variation of 18.45% when compared to the pressure set rating of the pressure regulator.

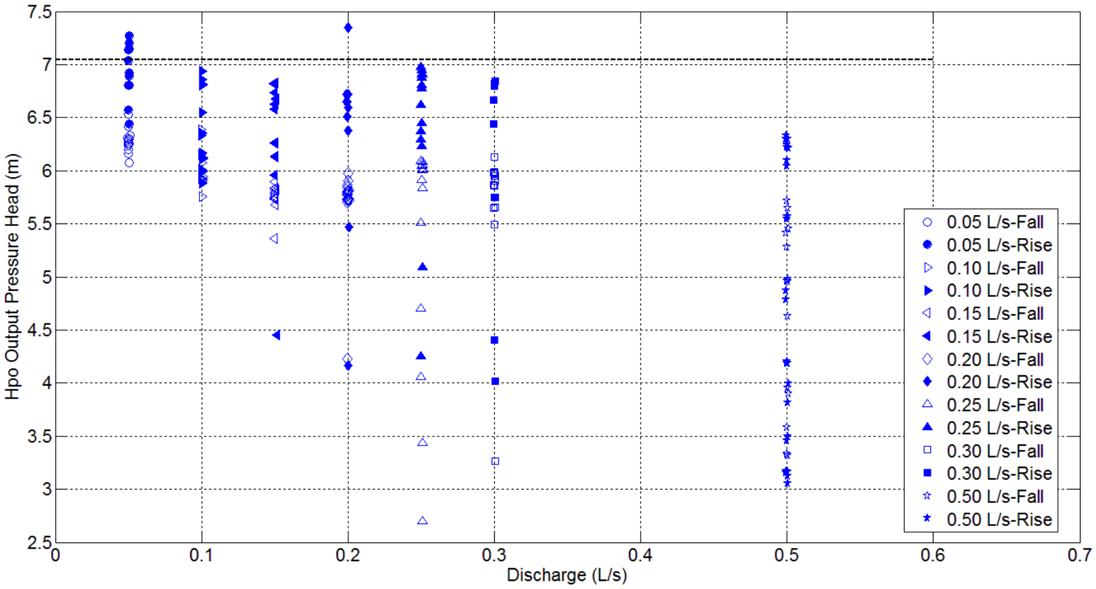

Figure 4.11– NL10-1 automatic acquisition test showing discharge distribution

To compare the output pressure and discharges, figure Figure 4.10 is reproduced with the discharge in the z axis, figure Figure 4.11 shows this distribution. This figure shows that each point was plotted with a constant discharge, with a different input and output pressure. A general trend can also be seen that with an increasing discharge the maximum output pressure decreased.

4.4 Automatic data acquisition with higher input heads

The automation testing with their figures shown above used the supply for the experiment from the high header tank which had a surveyed constant water supply level of 16.181 metres. This gave maximum input pressures of around 150 kPa when losses are taken into consideration.

Analysis of the results from the automation testing showed that at high discharges obtained singular points at increased input pressures was not possible. This is due to the required movement of the valves to get the correct discharge value. However at this position of the valves the pressure is too low. To overcome this higher input pressure into the supply of the experiment is needed, for this a pump is included.

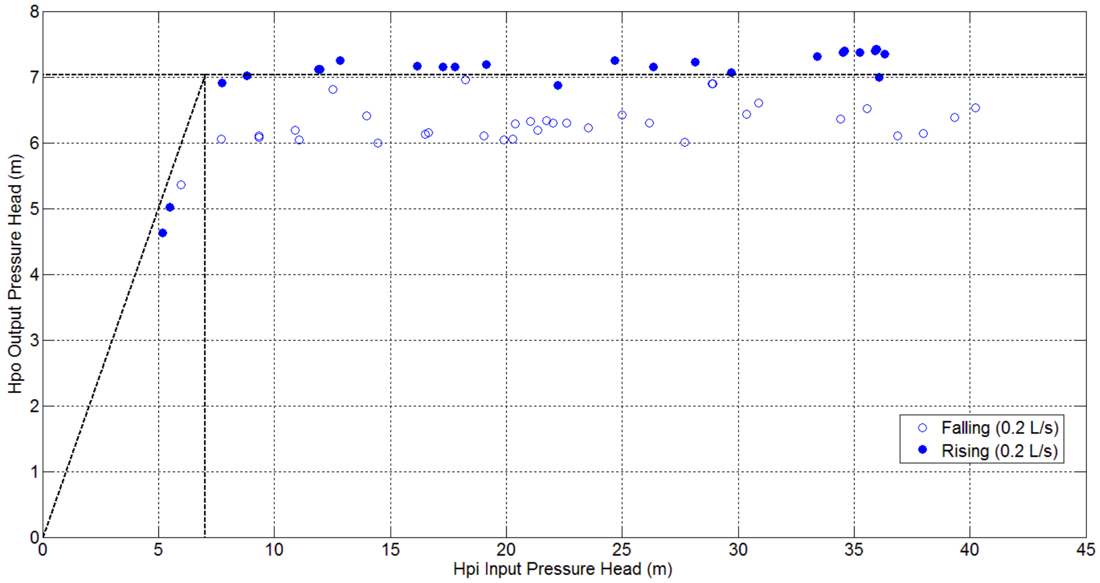

Figure 4.12 – NL10-1 automatic acquisition test with increased Hpi at 0.2 L/s

Figure 4.12 shows the first figure for automatic data acquisition tests with increased input head. Like with the stage two tests the rising and falling points are differentiated. The horizontal broken line represents the set regulation pressure of the pressure regulator and the vertical broken line also representing the set regulation pressure but on the x axis. The diagonal line is a 1:1 line from the origin to the interception of these lines. The figure shows most of the rising output pressure points to be above the horizontal broken line, which is the pressure regulators set constant output pressure. All of the falling points are positioned below this line and there does seem that is scatter amongst the falling points. All the points on this figure are for a constant discharge of 0.2 L/s.

Figure 4.13 shows the figure for the automatic data acquisition test with higher input pressures for a constant discharge of 0.3 L/s. Like figureFigure 4.12 the rising pressure points are generally positioned just above the pressure regulators set constant output pressure. The falling points have more scatter the deviate about 1 metre output pressure head.

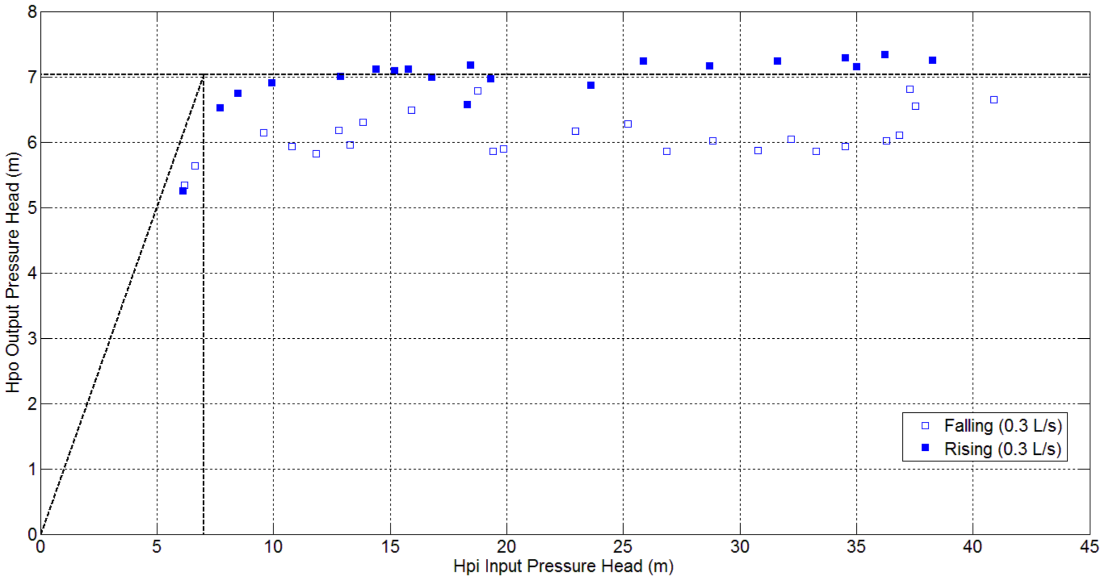

Figure 4.13 – NL10-1 automatic acquisition test with increased Hpi at 0.3 L/s

Figure 4.14 shows the graph for a constant discharge of 0.4 L/s. This is the first graph of this stage of testing where points are shown on the offset from the 1:1 line leading up to regulation. This figure reports about the same amount of deviation of scatter for both the rising and falling points of about 0.5 and 0.9 metres head respectively.

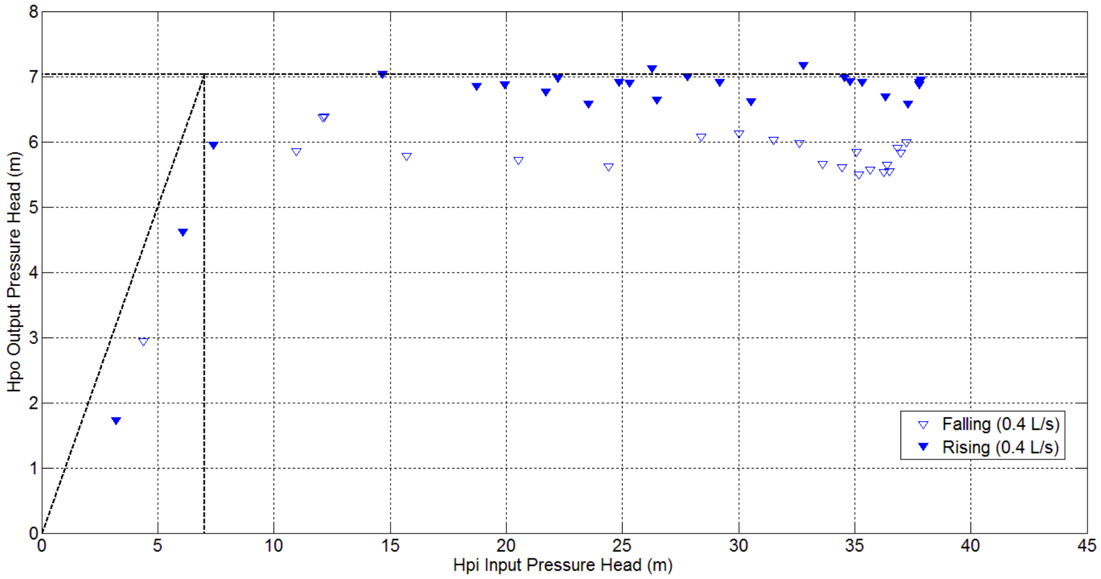

Figure 4.14 – NL10-1 automatic acquisition test with increased Hpi at 0.4 L/s

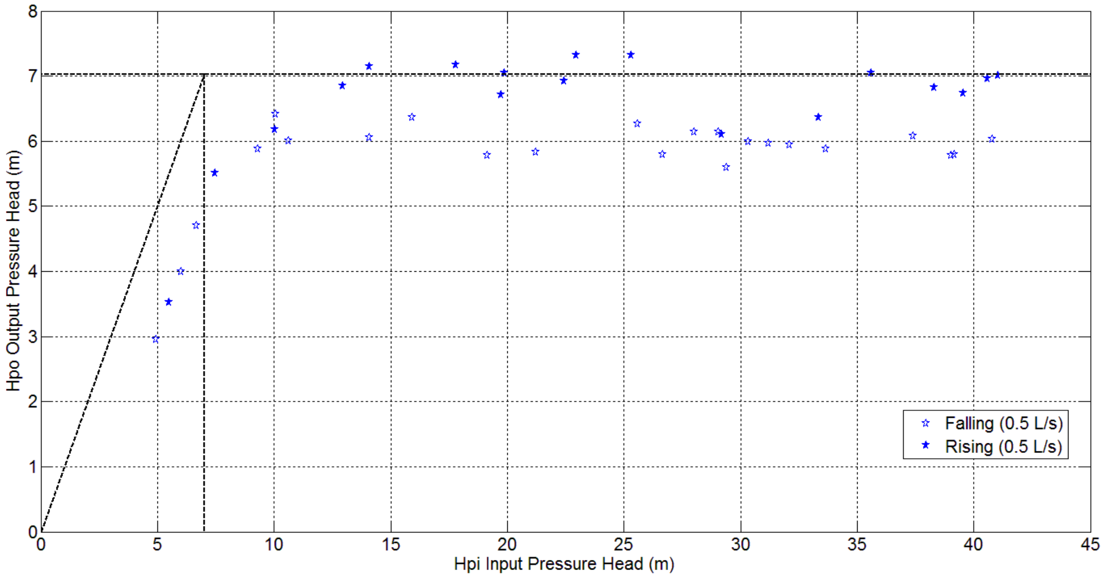

Figure 4.15 – NL10-1 automatic acquisition test with increased Hpi at 0.5 L/s

Figure 4.15 reports the rising and falling points for a constant discharge of 0.5 L/s. This figure shows the most scatter seen thus far for this test. There are only a few rising output pressure points above the pressure regulators set pressure, with many of the points, mainly falling point positioned on the 6 metre output pressure head line. There is also an increased offset of the points from the 1:1 line.

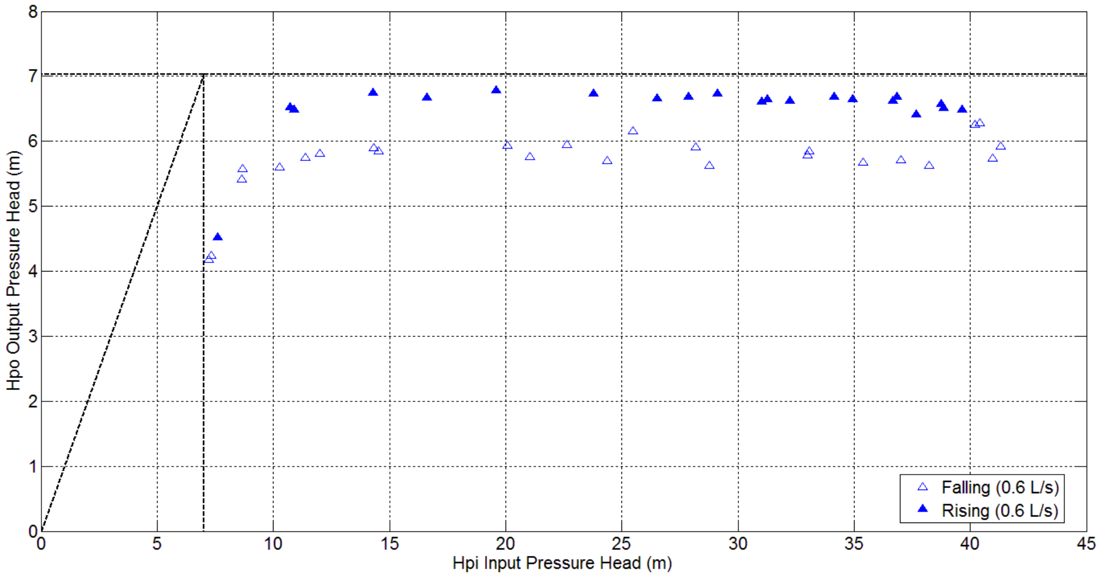

Figure 4.16 – NL10-1 automatic acquisition test with increased Hpi at 0.6 L/s

Figure 4.16 shows a good representation of a 'typical' hysteresis curve. While all the points are below the pressure regulators set pressure rating the rising points all follow the one trend without any noticeable scatter. The same is true for the falling points; however there is some scatter with these points. Figure 4.16 shows the graph for a constant output pressure of 0.6 L/s.

Figure 4.17 is the last discharge tested for this stage of testing for the automatic data acquisition with increased input heads. The constant discharge shown in this figure is at 0.7 L/s. There is no distinguishable trend between the rising or falling output pressure points. All the points are scattered and fall between 5.9 and 7 meters output pressure.

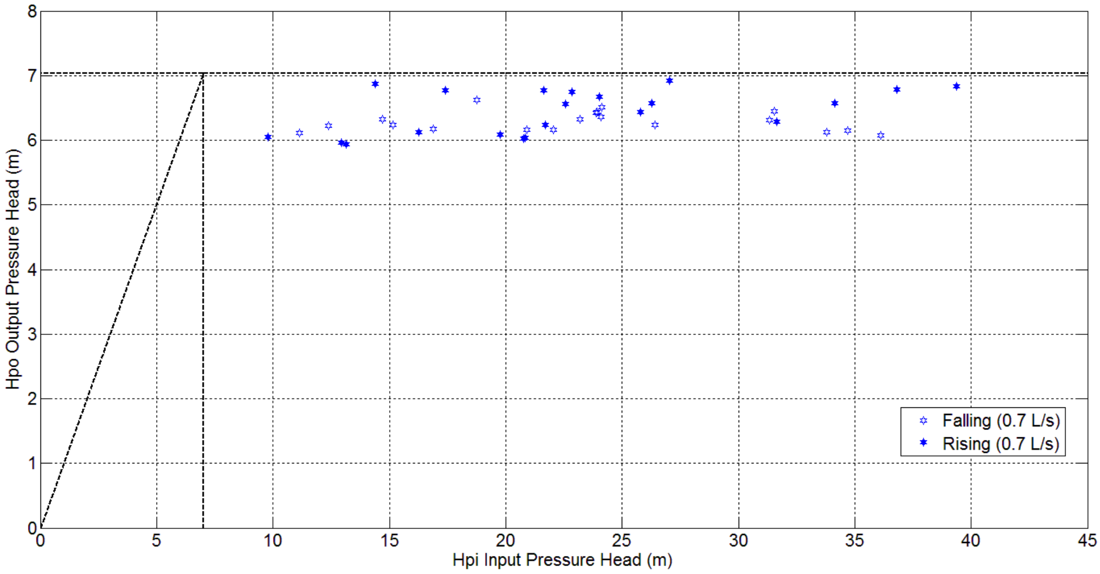

Figure 4.17 – NL10-1 automatic acquisition test with increased Hpi at 0.7 L/s

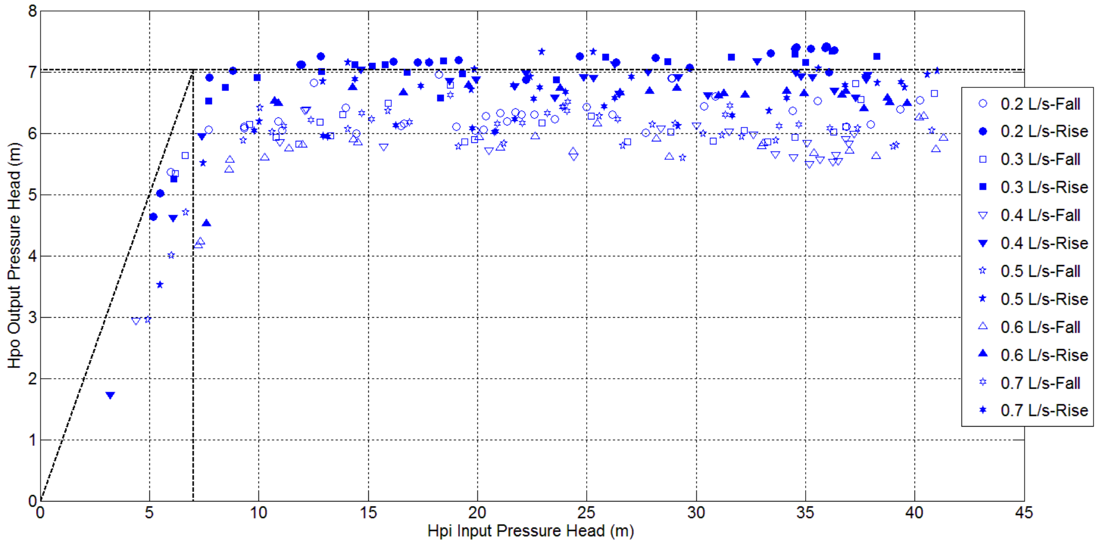

Figure 4.18 – NL10- automatic acquisition test with increased Hpi at all discharges

Figure 4.18 shows all the discharges for this stage of testing; this graph needs to be interpreted carefully as there is a lot of information portrayed on this graph. At higher input pressures there seems to be a higher variation of output pressure points. From inspection of the graph there also seems to be about a third of the rising pressure points above the pressure regulators set pressure rating.

The shape and size of this hysteresis plot is somewhat similar to the combined discharge plot figure Figure 4.10. At an increasing input pressure however the variation of output pressure increases. In figure Figure 4.10 it was said to have about a 1.3 meter head variation which equated to a percentage of 18.6%. For figure 4.18 for an input pressure of 15 meters head the varation is about 1.2 meters head (17.1%) which is simiular. At an input pressure of 35 meters head the varation is about 2 meters head (28.6%). Looking at the distrubtion between rising and falling points (the soild and non-soild points respectivly) it seems that varaiation of the falling points is slighty more than that of the rising points.

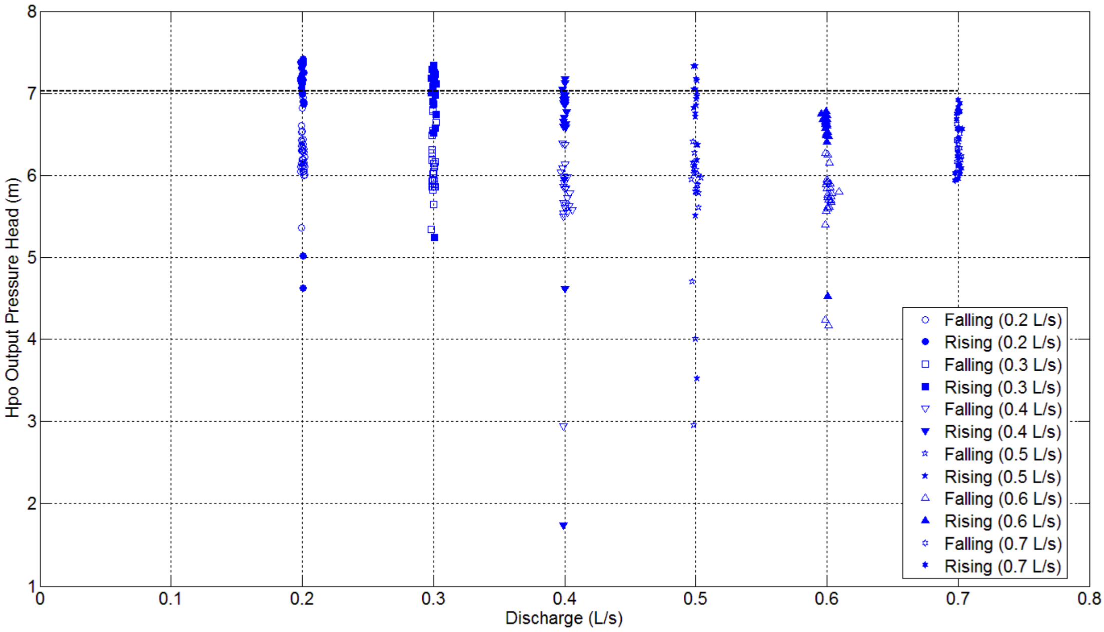

Figure 4.19 – NL10-1 automatic acquisition test with increased Hpi showing the distribution of discharges

Figure 4.19 reports the same information as figure Figure 4.18 however the x axis is replaced by the z axis. The figure reports and proves that while undertaking this series of tests the discharge was at a constant value.

4.5 Continuing Hysteresis Tests

A different approach was taken with this stage of testing. Following the methodology discussed in section **Error! Reference source not found.** figures Figure 4.20 – NL10-1 Continuing hysteresis test at Q = 0.2 L/s, Figure 4.21 and Figure 4.22 have been produced which represent aimed discharge at 0.2, 0.4 and 0.6 L/s respectively.

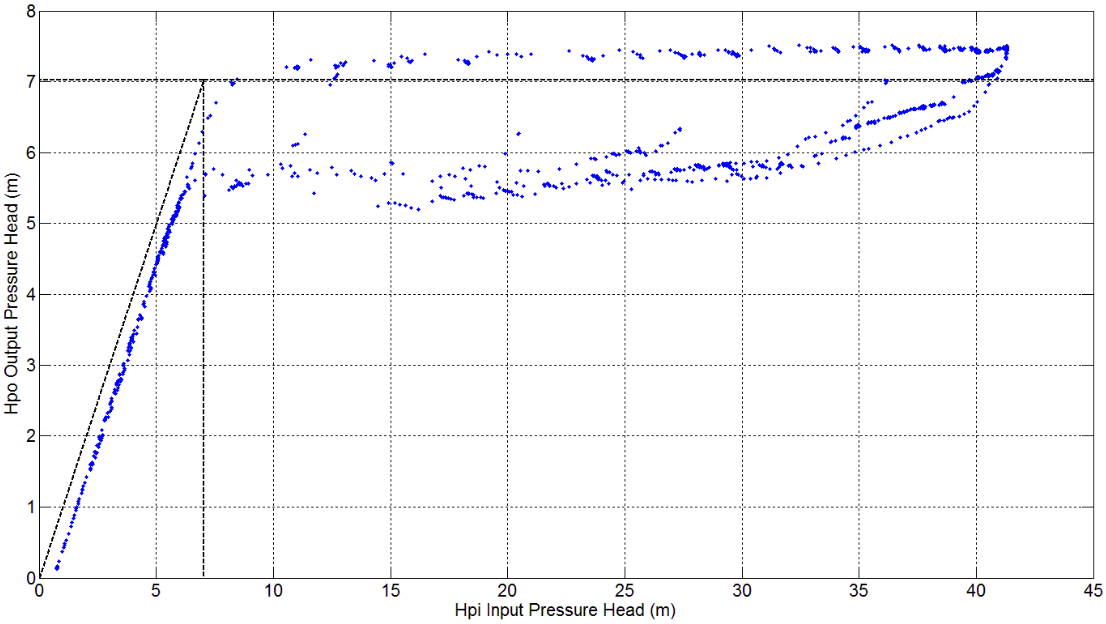

Figure 4.20 – NL10-1 Continuing hysteresis test at Q = 0.2 L/s @ +/- 8.15%

Figure 4.20 shows the first of these graphs, with a discharge at 0.2 L/s and a discharge variation of +/- 8.15%. The figure gives a characteristic shape. In Bernuth and Baird (1990), they report four line segments can represent the boundaries giving by the hysteresis curve. As with the singular point tests, as the input pressure increases it follows the 1:1 line at an offset below the line due to the headloss. Above the pressure rating of the pressure regulator when the variable headloss starts, as the input pressure continues to increase the output pressure also increases, 7.5 metres head is the highest output pressure received. It is at this point when the input pressure is at its maximum that the tube inside in the pressure regulator is at its closest point to the redistribution plug and where the highest regulation is achieved. After this, when the input pressure is decreased the output pressure moves down. While the output pressure is decreasing the tube is moving away from the redistribution plug. From figure Figure 4.20 it takes about 10 kPa of decreasing input pressure to reach the lowest limb of the hysteresis curve. After this the lower limb is fairly steady before the point is reached were the device stops regulating.

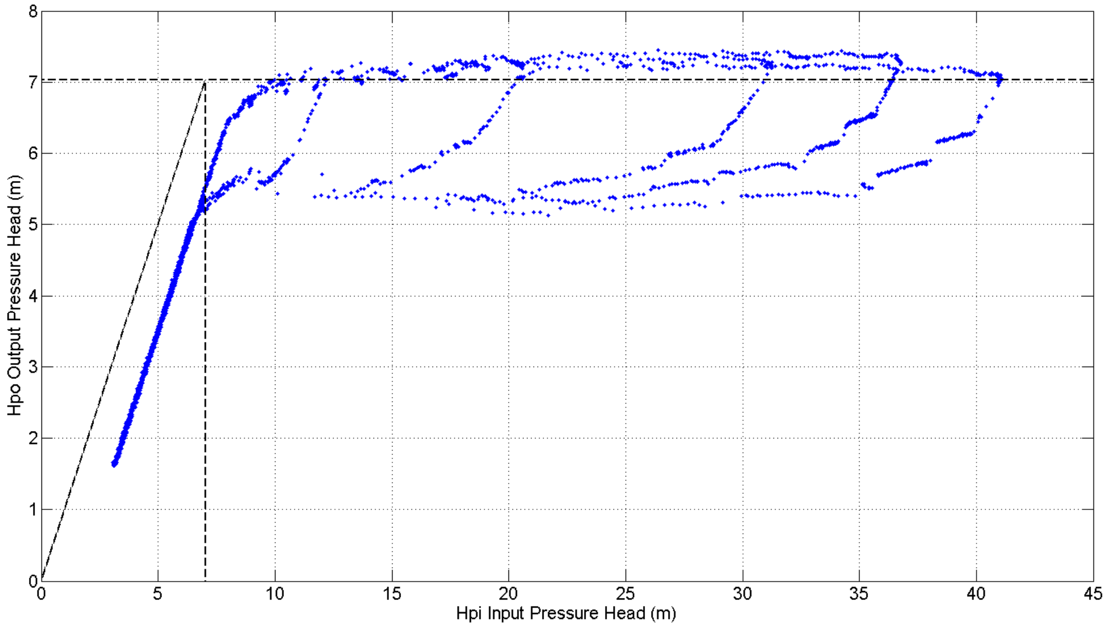

Figure 4.21 - NL10-1 Continuing hysteresis test at Q = 0.4 L/s @ +/- 8.16%

Figure 4.21 is the test results for a second discharge value, 0.4 L/s with a discharge variation of +/- 8.16%. The characteristic shape can again be seen in this figure, as in figure Figure 4.20. With this test, different input pressures were approached and then decreased from. For each pass the input pressure was always decreased back to the original and lowest point possible to keep the discharge required. As explain earlier, due to the experiment setup, the higher the discharge raised the lowest possible input and corresponding output pressure possible to reach. What is interesting to see in figure Figure 4.21 is that at higher input pressure, at the point when the input pressure is decreased, there is a different approach path taken to get to the lower limb. At the higher input pressures, the hysteresis curve does not move straight to the lower limb when the input pressure is decreased, there is a delayed effect. Contrasting to lower input pressures, when the input pressure is decreased, the curve shifts to the lower limb (output pressure decreases to little shift in input pressure). Most of the upper limb of this graph falls above the pressure regulator pressure set rating. While the lowest area of the lower limb sits about 1.9 meters head below the pressure set rating.

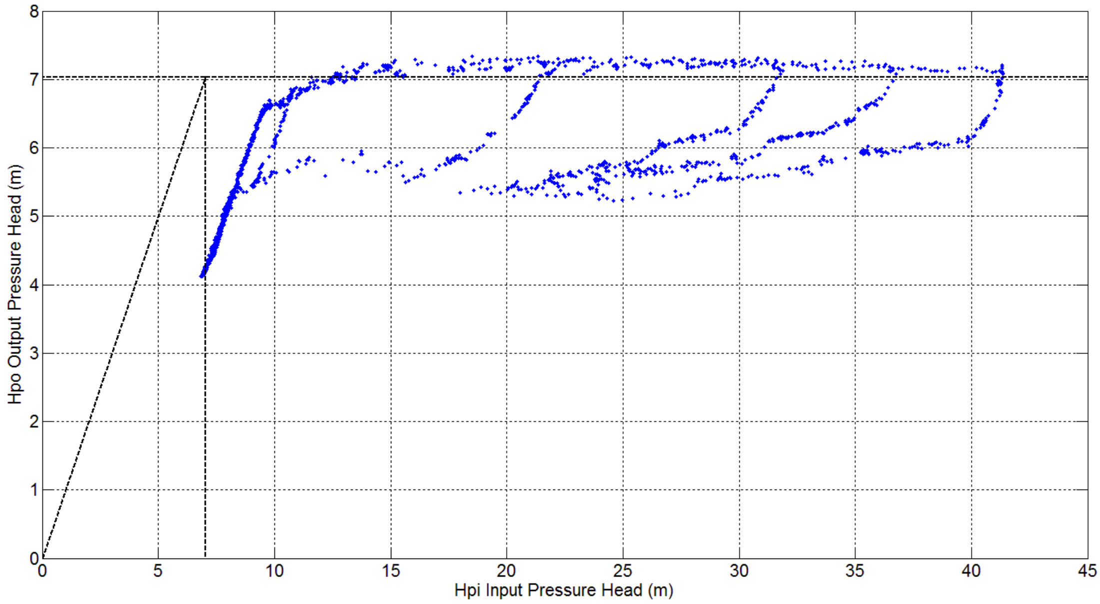

Figure 4.22 - NL10-1 Continuing hysteresis test at Q = 0.6 L/s @ +/- 7.93%

Figure 4.22 is the third graph which shows this hysteresis effect at a different discharge, 0.6 L/s which has a discharge variation of 7.93%. This figure is similar to figure Figure 4.21, in that is hold the same characteristic shape. Again at higher input pressures, for the hysteresis curve to move from the higher to lower limb, it takes a large change of input pressure head. The position of the higher and lower limb of the hysteresis curve is the same to figure Figure 4.21. The highest discharge used, 0.6 L/s was shifted the offset from the 1:1 line due to the increased headloss between the inlet and outlet pressure tapping points of the experiment. This headloss is due to the pipe friction and fitting minor losses.

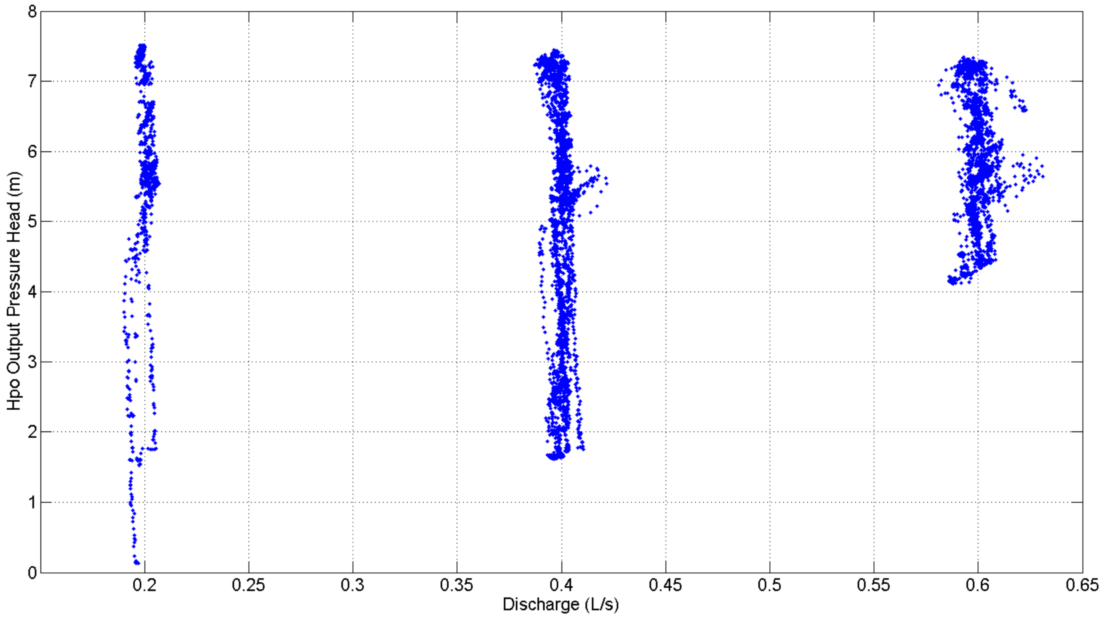

Figure 4.23 - NL10-1 Continuing hysteresis tests showing discharge variation

As explained earlier because this experiment involved a continual shift of the valves the discharge was not constant. However it was keep within a tight controlled band rate, figureFigure 4.23 show this tests discharge variation and the tight band of which they were kept. Table 4.3 below also shows some basis data statistics on this experiment for each of the aimed discharges, 0.2, 0.4 and 0.6 L/s.

Table 4.3 - Data statistics on continuing hysteresis tests

	Q = 0.2 L/s	Q = 0.4 L/s	Q = 0.6 L/s
Count	1291	2767	1802
Minimum	0.19011	0.38710	0.58102
Maximum	0.20697	0.42151	0.63111
Average	0.19999	0.399465	0.59953
Standard Deviation	0.00342	0.00404	0.00617

4.6 Creep Test

Section 3.7 outlines the methodology undertaken for this stage of tests. The creep tests investigates the movement of tube and thus the shift of regulation of the pressure regulator when in operation for a long period of time.

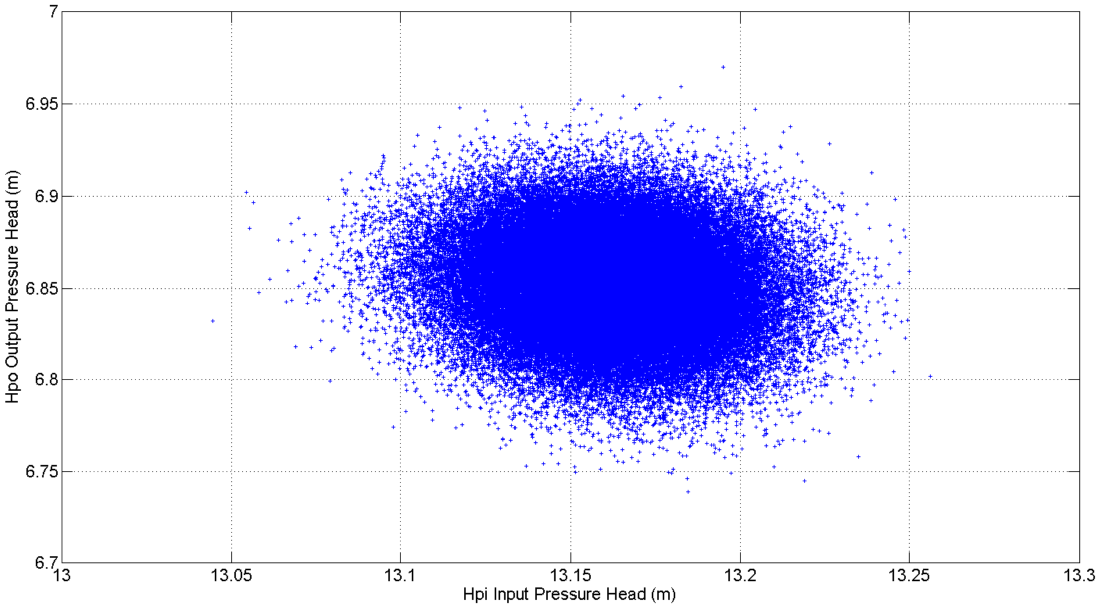

Figure 4.24 – Rising pressure 24 hour creep test

Figure 4.24 – Rising pressure 24 hour creep test shows a graph for this creep tests for a rising output pressure. The test was run for a 24 hour period and each point of data represents one second of this period of time. Similarly figureFigure 4.25 – Falling pressure 24 hour creep testshows the graph for a falling output pressure. This test was run straight after the test of the rising pressures and it was run for the same amount of time, 24 hours.

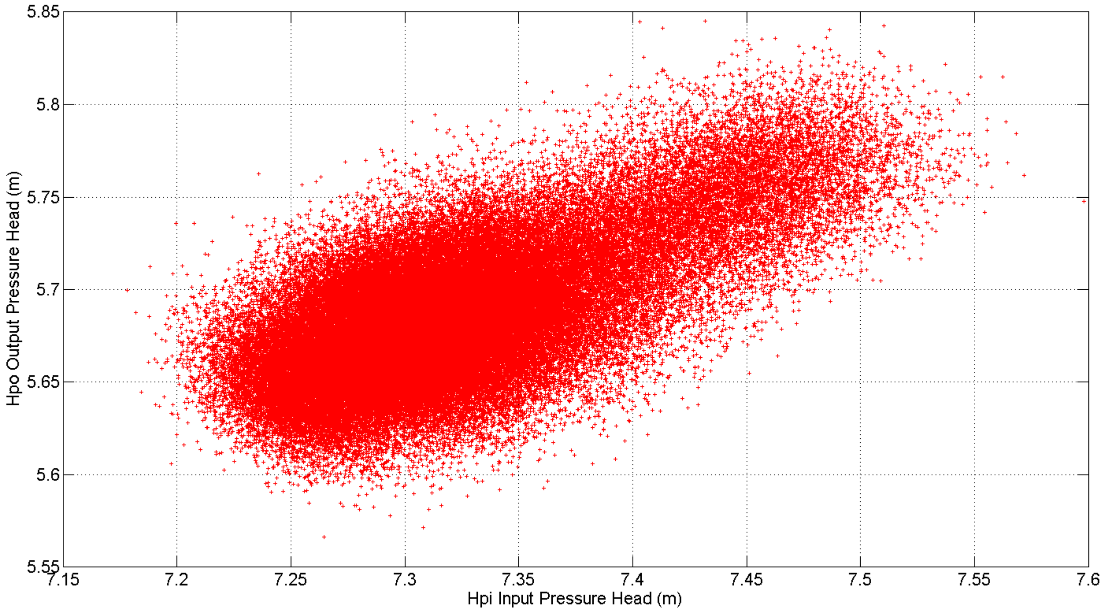

Figure 4.25 – Falling pressure 24 hour creep test

As discussed in section 3.7, the temperature was measured at particular intervals of the test. Table 4.4 shows this variation. It shows that the largest different of temperature was 1.5 °C over both the rising and falling parts of the test.

Table 4.4 – 24 hour creep test temperature measurements

Rising		Falling	
Time	Temp (°C)	Time	Temp (°C)
18:00	16.5	17:40	16.5
23:20	16	20:15	16
3:50	15.5	23:45	16
8:15	16	7:15	15.5
11:05	17	14:50	17
15:40	17	17:55	16.5
18:50	16.5		

Table 4.5 – Creep test minimum, maximum and variation values.

	Minimum	Maximum	Variation (%)
Rising Input Pressure	13.045	13.256	1.59
Rising Output Pressure	6.7388	6.9701	3.31
Falling Input Pressure	7.1783	7.5981	5.52
Falling Output Pressure	5.5665	5.8452	4.76

Following on from the temperature variation, the variation in the graphs are analysed. Table 4.5 reports these variations of the input and output pressures for both the rising and falling tests. It shows that move variation is reported with the falling test, than the rising tests.

4.7 Friction Investigation

This stage of testing, friction investigation, involves looking at the hysteresis difference between the upper and lower limbs which is caused by the friction of the tube moving through the O-ring. The methodology of the stage of testing is detailed in section 3.8.

Figure 4.26 shows a graph of the first of this test. It can be seen that the presentation of the figure is similar to previous figures, in terms of the broken lines representing the pressure regulators set pressure rating and the 1:1 line from the origin to the interception of the lines.

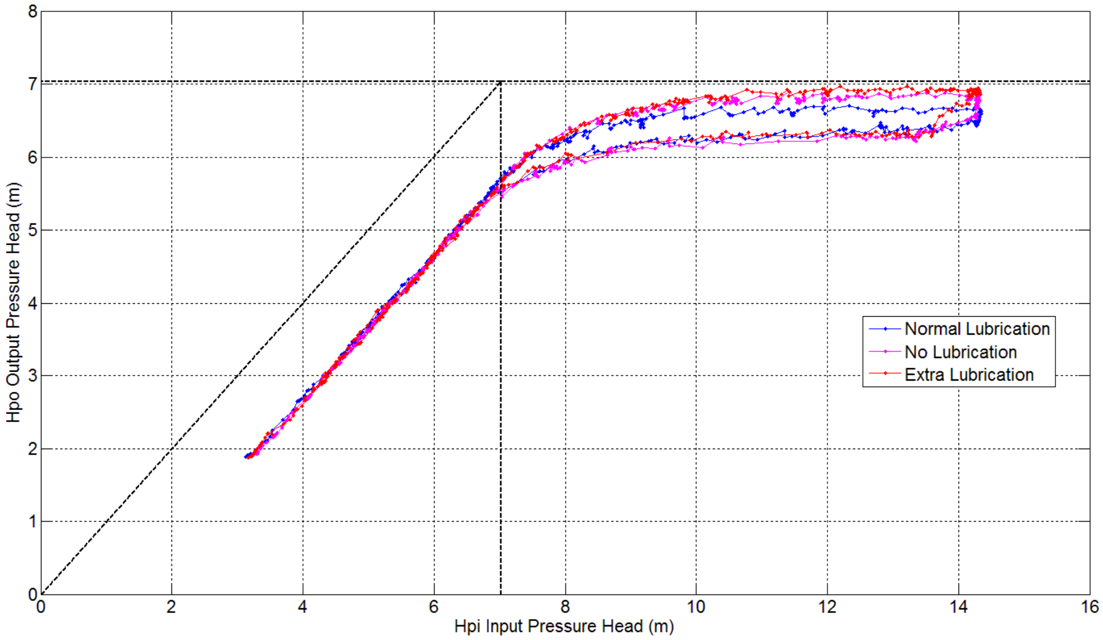

Figure 4.26 – NL10-2 Tube friction investigation

The Nelson pressure regulators when manufactured do have some lubrication, thus the device was tested normally without any alteration firstly, this is shown in the figure as normal lubrication. Once this was done, the device was dissembled and this lubrication was wiped away, the pressure regulator was then resembled very carefully and retested, this is shown in the figure as no lubrication. For the extra lubrication, the last of the three shown on the figure, a water based lubrication was used and applied to the tube, the device was then tested.

All three tests fit together as they approach regulation, under the 1:1 line. As the upper limb of the graph is approached the three tests separate out. While no points go above the pressure regulators set pressure rating the extra lubrication test is the closest to this line. Just underneath the extra lubrication test is the no lubrication test. The upper limb of the normal test is below the no lubrication. On the lower limb, all three tests follow the same path back to the constant approach line. Like with previous tests an understanding of the discharge variation is important and is shown for this test in figureFigure 4.27. This point plot shows all the discharges for the three tests. From this plot a 6.6% variation of discharge is shown.

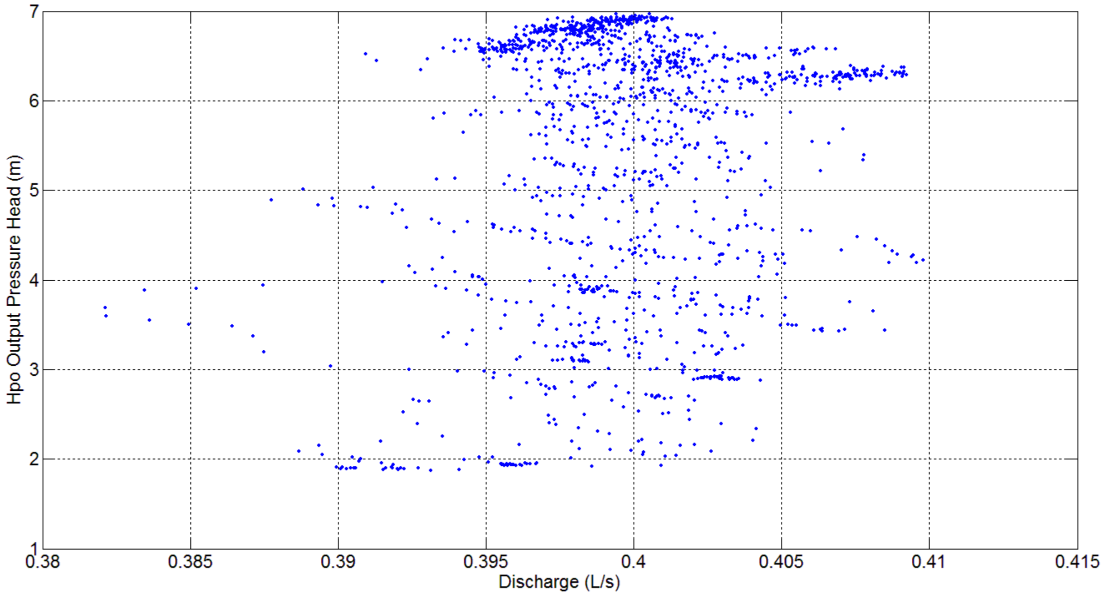

Figure 4.27 – NL10-2 Tube friction investigation showing discharge variation

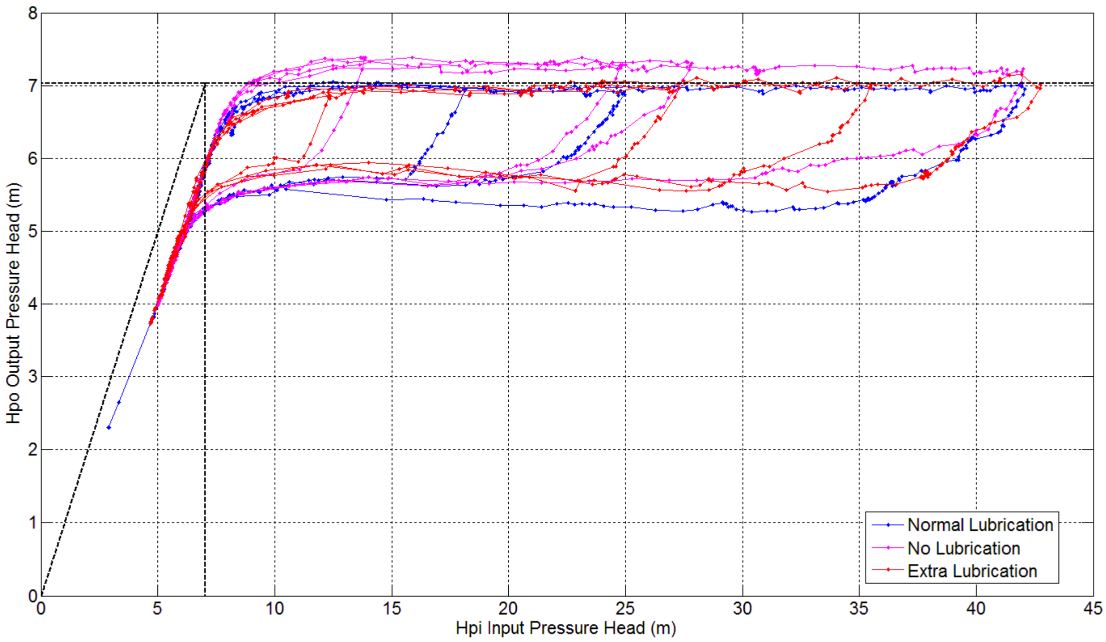

Figure 4.28 – NL10-3 Tube friction investigation

Figure 4.28 shows the second plot for the friction investigation. For this test extra input head was used. The upper limb of this graph shows the normal and extra lubrication to be at about the same output pressure, following the pressure regulators pressure set line for the increase input pressure. The no lubrication for the upper limb is above the pressure set line at about 0.2 metres output head. Like with the continuing hysteresis test different input pressures where the experiment shifted from rising to falling pressures. On the lower limb the normal lubrication test has the lowest output pressure. The extra and no lubrication tests follow the same path however at the lower input pressures the extra lubrication output pressure raises slightly. The test with the smallest distance between the upper and lower limbs is the extra lubrication test. Figure 4.29 shows the discharge variation for the three tests, normal, no and extra lubrication. The aimed discharge for this test was 0.3 L/s and the variation was 14.2%.

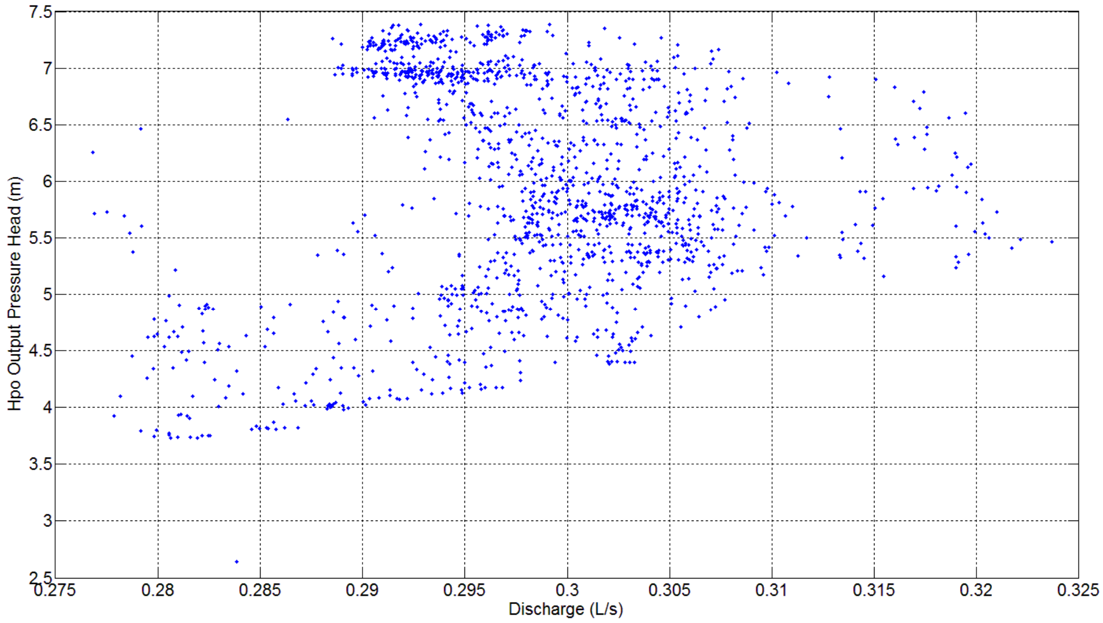

Figure 4.29 – NL10-3 tube friction investigation showing discharge variation

4.8 Movement of Tube inside Pressure Regulator

The regulation part of the pressure regulator is controlled by the tubes displacement. This stage of tests was investigated to study this displacement and the rate of displacement of the tube inside the pressure regulator. Section **Error! Reference source not found.** explains how the materials were used for this experiment and the methodology undertaken.

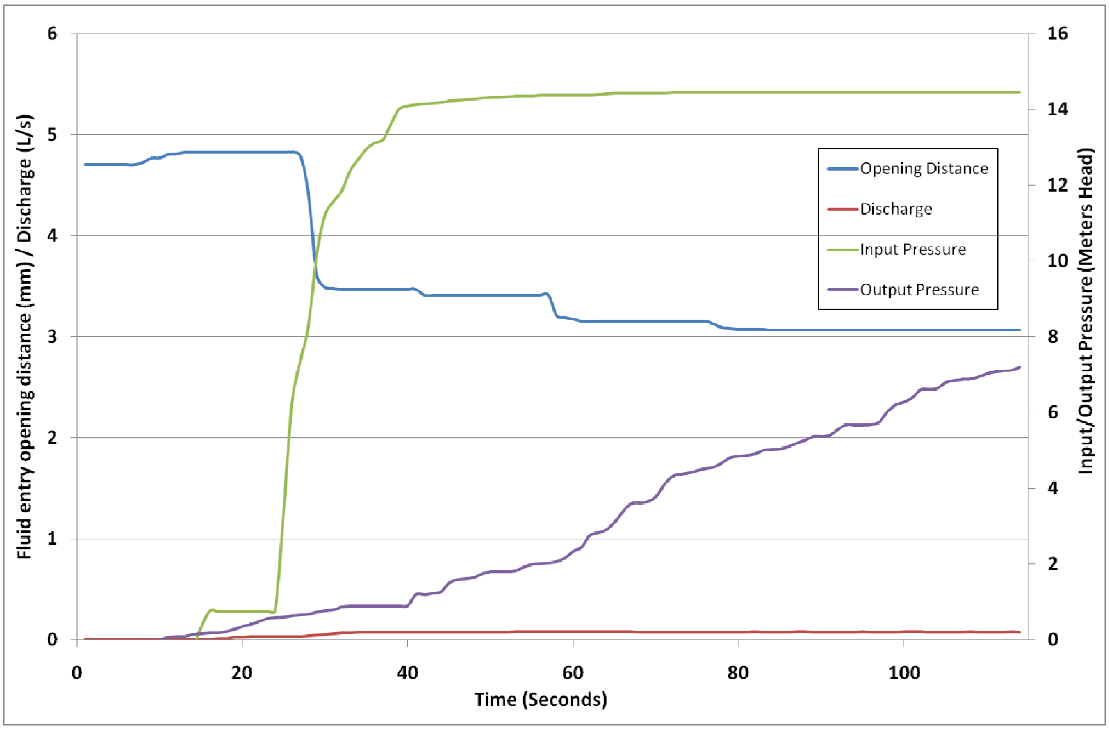

Figure 4.30 – NL10-TD Tube upward displacement investigation with 3TN #15 nozzle

Figure 4.30 shows the first of the graphs for this stage of testing. The graph shows four parameters. The input and output pressure are displayed and read from the secondary y axis, on the right hand side of the graph. Both the input and output pressures units are in metres head. The discharge is displayed on the primary y axis along with the opening distance.

The opening distance is the distance between the tube and the lip on the redistribution plug. Appendix B shows a schematic diagram of the pressure regulator which shows this distance. This distance by the circumference around the tube is the area which the fluid is allowed to enter into the tube for its regulation and where the variable headloss occurs. The x axis on figure Figure 4.30 shows the time which test was carried out for.

The discharge shows an exponential increase as the valve is turned on, this is what is expected to be seen for the discharge. For the discharge to be included on the figure the display is very small as the experimental setup restricted large discharges to be tested. A 3TN #15 nozzle was used for this test, replicating a small discharge.

As the valve was turned on and the input pressure increased, figure Figure 4.30 shows the time taken to get to full pressure to be about 8-10 seconds. It is expected once the input pressure was above the pressure regulators set output pressure the regulation would begin and the output pressure would level out. However the output pressure was seen to increase at a fairly steady and constant rate until the test stopped, it finished at about 7.2 metres head.

At the start of this test the tube was in its furthest position from the lip of the redistribution plug of 4.7 mm. The tubes displacement was measured which moved closer to this lip and finished at 3.066 mm from the lip. The tube move towards the lip 1.634 mm. The rate of this displacement also is important. With reference to figure Figure 4.30 the tube as moved back slightly, which means the spring has had a force causing it to displace the tube. The tube then does not move from this position before it suddenly moves forward, which is where most of the displacement occurs. For another minute of testing, the tube continues to move forward at different increments before the end of the test. The sudden movement forward of the tube occurs when the input pressure is increased the most, which what would be expected to be seen.

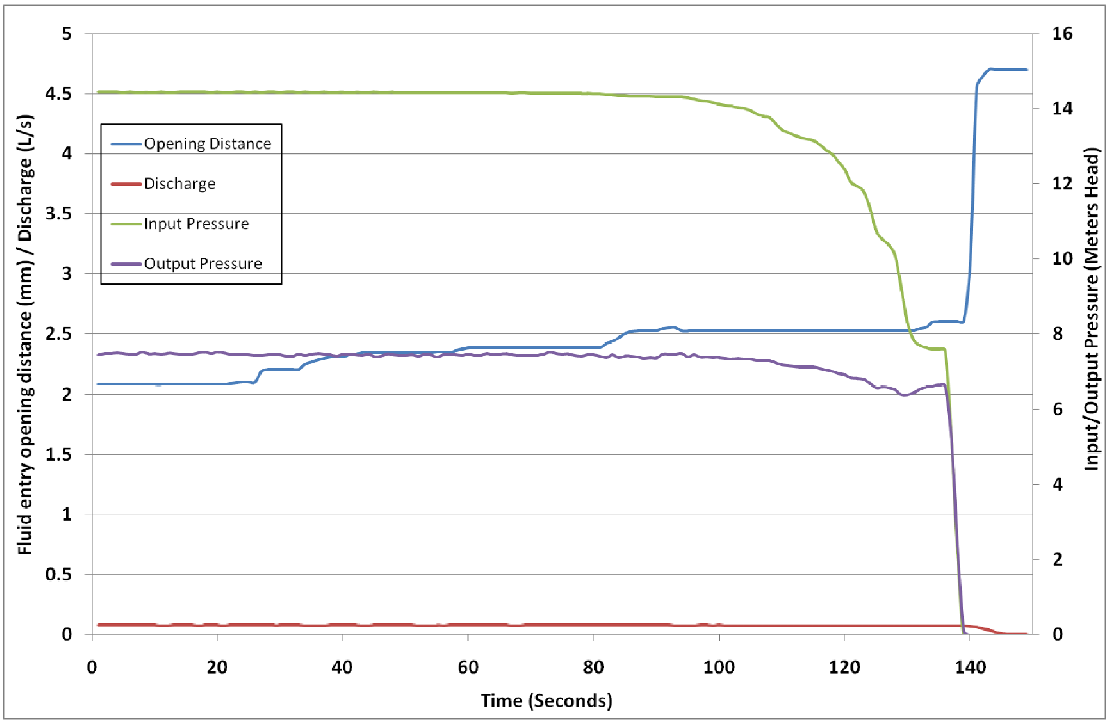

Figure 4.31 - NL10-TD Tube downward displacement investigation with 3TN #15 nozzle

Figure 4.31 shows a graph for the closing of the valve with the same nozzle, 3TN #15. The same presentation of the graph is seen as figure Figure 4.30, with the pressures on the secondary y axis and the opening distance and discharge displayed on the primary y axis. Time is on the x axis.

This test starts with the valve fully on and the discharge at its maximum point. As the tests is continued and the valve turned off, the discharge is exponential decreased. As the valve is fully turned on the pressure regulator is regulating the pressure, this is seen as the output pressure stays constant. However when the input pressure is decreasing and above the pressure regulators set constant output pressure the output pressure is seen to decrease slightly.

The tubes movement for this test saw no major change, apart from a few small incremental movements, the major movement away from the lip was at the point when the valve was about 90% shut and the input and output pressure dropped. The tube then displaced back to its origin of 4.7 mm away from the lip.

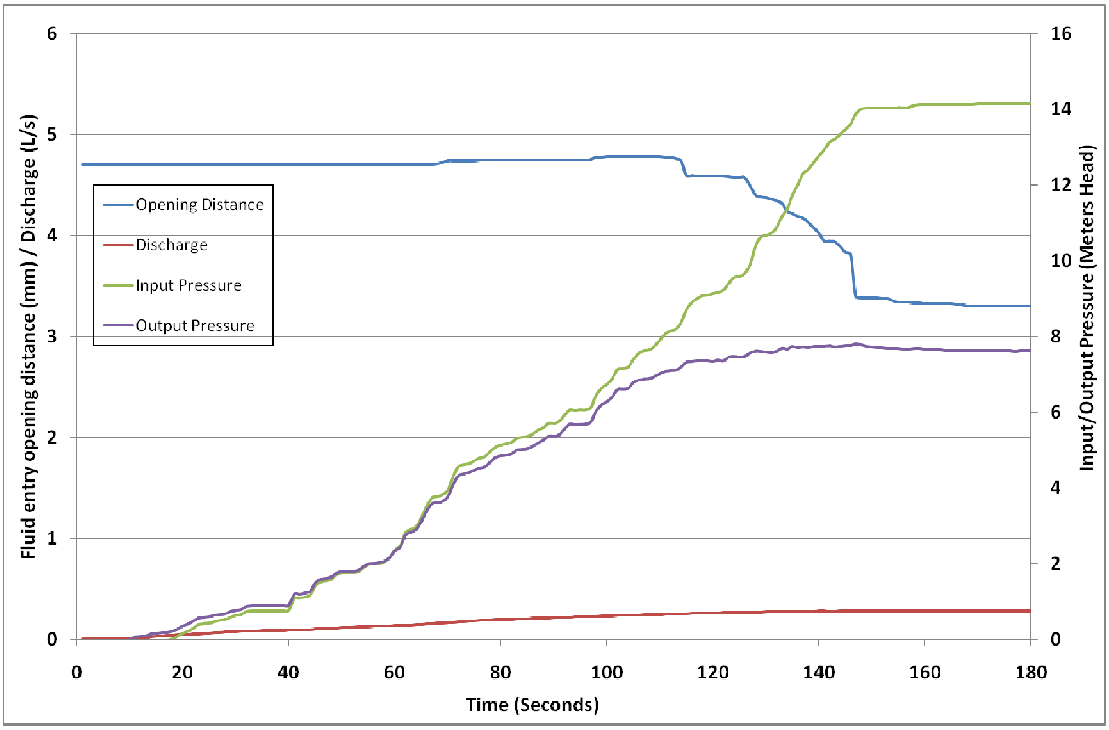

Figure 4.32 - NL10-TD Tube upward displacement investigation with 3TN #28 nozzle

Figure 4.32 shows the first of the second part for this test using a larger sized nozzle. Due to the limitations of the testing rig a medium sized nozzle was used which gave a maximum discharge of 0.28 L/s. In this figure, with the valve fully shut and opened slowly the discharge is seen to have a more characteristic curve as the valve is turned on. The pressure difference between the input and output pressures are more to be expected in figure Figure 4.32. On the approach with the input and output pressure rising, the difference between the lines is increasing, this is due to the increased velocity and the increased headloss between the input and output fittings. The output pressure then levels off at the regulation pressure, while the input pressure continues to increase. Again however the output pressure getting to regulating is gradual and it is not as quick as expected.

The tubes movement again begins by slightly moving backward away from the lip. At nearly 2 minutes into the test the tube takes a few incremental steps forward. There is a small sudden movement forward before the tube stops it movement.

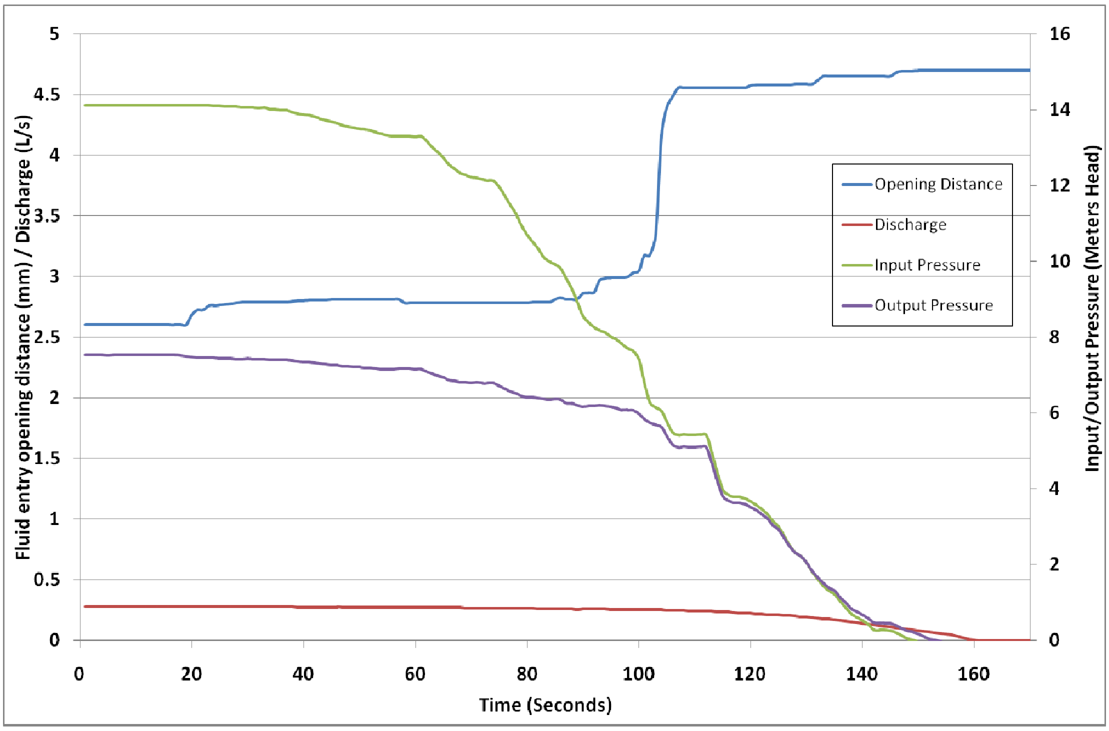

Figure 4.33 - NL10-TD Tube downward displacement investigation with 3TN #28 nozzle

Figure 4.33 shows the last of the graphs for this test. The tube is displaced down and the 3TN #28 nozzle is used. The exponential shape of the discharge can be seen again. With the valve fully open and the pressure regulator functioning the large difference between the input and output pressures can be seen. As the input pressure is decreased, so too does the output pressure, before it theoretical should, as the input pressure is still above the set rating pressure of the pressure regulator. When the input pressure does get to this point the difference closes and the pressure decrease. The displacement of the tube is seen again as a generalised S-curve; where it slowly moves back from the lip, shifts back suddenly and then steadies off. Again the point where the tube moves its most is when the valve is about 90% shut off and the pressure drop back to zero.

4.9 Statistical Analysis

4.9.1 Introduction

Following variation differences seen in the performance of the pressure regulator. A statistical analysis is performed to understand the variation and to also calculate to sample size of pressure regulators which are needed to adequately characterise manufacturers' variation in their manufacturing of pressure regulators. Section 4.9 outlines the methodology which has been used for this statistical analysis. An ANOVA (analysis of variation) has been performed for two discharges. The normal model theory has been applied to calculate the sample size of the number of pressure regulators which need to be tested.

4.9.2 The ANOVA test

Nelson Nozzle 3TN #28

The null hypotheses is stated the all the means of the five tests of each pressure regulator are equal.

$$H_0 : \mu_1 = \mu_2 = \mu_3 \qquad \textbf{4.1}$$

The treatment sum of squares is calculated;

$$SSTR = n_1(\bar{\mathrm{x}}_1 - \bar{\mathrm{x}})^2 + n_2(\bar{\mathrm{x}}_2 - \bar{\mathrm{x}})^2 + \cdots + n_k(\bar{\mathrm{x}}_\mathrm{k} - \bar{\mathrm{x}})^2 \qquad \textbf{4.2}$$

The number of tests for each pressure regulator was 5, thus n_k = 5, $\bar{\mathrm{x}}$ is the pressure regulators set pressure rating in metres head = 7.04321, $\bar{\mathrm{x}}_1$ is the mean of the 5 tests for each pressure regulator.

$$SSTR = 1.0375 \qquad \textbf{4.3}$$

$$MSTR = \frac{SSTR}{k-1} \qquad \textbf{4.4}$$

MSTR was calculated from equation 4.4, where k = the number of pressure regulators tested = 16.

$$MSTR = 0.069166 \qquad \textbf{4.5}$$

The error sum of squares is calculated

$$SSE = (n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \cdots + (n_k - 1)s_k^2 \qquad \textbf{4.6}$$

Again n is the number of tests performed = 5, s_k = the sample variance. SSE was calculated from equation 4.4

$$SSE = 0.2755 \qquad \textbf{4.7}$$

The error mean square is calculated by equation 4.8.

$$MSE = \frac{SSE}{n-k} \qquad \textbf{4.8}$$

$$MSE = \ 0.0043 \qquad \textbf{4.9}$$

The f-distribution is calculated by equation 4.8.

$$df\ (k-1, n-1) \qquad \textbf{4.8}$$

For a 5% significance level (α), the value of F-statistic is looked up. Appendix K shows the values of F for a 5% significance level.

$$df = (15{,}64) \approx (15{,}60) = \ 1.84 \qquad \textbf{4.9}$$

The test statistic is found by equation 4.10

$$test\ statistic = \frac{MSTR}{MSE} \qquad 4.10$$

$$test\ statistic = \ 16.085 \qquad 4.11$$

As the test statistic falls in the reject region, the null hypothesis is rejected. The means of the five tests of the 16 pressure regulators tested are not equal.

Nelson Nozzle 3TN #50

The null hypotheses is stated the all the means of the five tests of each pressure regulator are equal.

$$H_0 : \mu_1 = \mu_2 = \mu_3 \qquad 4.12$$

The treatment sum of squares is calculated;

$$SSTR = 0.8665 \qquad 4.13$$

$$MSTR = 0.0619 \qquad 4.14$$

$$SSE = 0.1286 \qquad 4.15$$

$$MSE = 0.0021 \qquad 4.16$$

For a 5% significance level (α), the value of F-statistic is looked up. Appendix K shows the values of F for a 5% significance level.

$$df = (14{,}60) \approx (15{,}60) = \ 1.84 \qquad 4.17$$

$$test\ statistic = \frac{MSTR}{MSE} \qquad 4.18$$

$$test\ statistic = \ 28.879 \qquad 4.19$$

As the test statistic falls in the reject region, the null hypothesis is rejected. The means of the five tests of the 16 pressure regulators tested are not equal.

4.9.3 Determination of Sample Size

The normal model was used to calculate the sample size for the number of pressure regulators which needed to be tested. Equation 4.20 was used for this process.

$$n = (\frac{\sigma}{\frac{\bar{y} - \mu}{z}})^2 \qquad \textbf{4.20}$$

where σ is the standard deviation, ȳ is the theoretical mean, μ is the mean, z is the z-score and n is the sample size.

Nelson Nozzle 3TN #28

$$n = (\frac{0.1288}{\frac{7.04321 - 7.01617}{1.96}})^2 = 87.16 \ = 88 \qquad \textbf{4.21}$$

88 pressure regulators are needed to be tested, as 16 devices have already been tested, 72 more tests need to be carried out.

Nelson Nozzle 3TN #50

$$n = (\frac{0.1065}{\frac{7.04321 - 5.2065}{1.96}})^2 = 0.0129 = 1 \qquad \textbf{4.22}$$

From the calculation is equation 4.22 the number of devices needed to be tested is rounded up to 1. This calculation is unreasonable; this is due to the mean of the tests carried out. At the higher discharge the output pressure is lower and the difference between the pressure regulators set pressure rating and the mean of the tests of the 16 Nelson pressure regulators is large due to the higher discharge, from a larger nozzle size used.

Chapter 5 DISCUSSION

5.1 Introduction

This chapter provides a discussion on the results and analysis provided in the previous chapter. Each series of tests will be discussed, the first being the tests set out to replicate the results from the literature.

5.2 Result Replication from von Bernuth and Baird (1990)

The first stages of testing were to try and replicate the results from von Bernuth and Baird (1990). In replicating the results from this literature a similar test rig was constructed, however they were some major differences. To obtain a constant discharge for the test Bernuth and Baird used a discharge controlled regulator (with a set pressure of 68.9 kPa) and a precision orifice. This discharge control regulator was a previously tested pressure regulator. Figure 2.2 shows the schematic used by von Bernuth and Baird (1990).

The test rig which was constructed to replicate the results, consisted of valves placed both sides of the pressure regulator being tested and each one manipulated, a nozzle was used to control the discharge from the experiment. Two pressure regulators were used in this manual test. The first was a Valley 6 PSI pressure set pressure regulator with a ¾ female to ¾ female connection fitting and the second was a Nelson 10 PSI pressure set pressure regulator with a ¾ female to ¾ female connection fittings.

This early testing in replicating the results from von Bernuth and Baird (1990) clearly established the importance of using the upstream and downstream valves and how their use, influenced the discharge and input and output pressure in the testing rig. Table 4.1 shows this influence. In contrast to von Bernuth and Baird (1990) testing rig, where one valve was used and a second discharge controlled regulator was used. There is no real discharge control with their experimental methodology. To obtain multiple points around the hysteresis curve for stage one testing is time consuming because of the slight movement of the valves required to achieve a constant discharge. Levers were connected to these valves; however they were short levers which had limited control over the valves.

From the result replication test from von Bernuth and Baird it was thought to keep the same hydraulic setup of the testing rig. However better control over the levers was needed to get to the accuracy of the discharges values. To do this longer extension levers were designed and made which gave the movement of the valve from a smaller increment change of the lever.

It was found that many points were needed to get enough data around the hysteresis curve to understand what was happening. More points were tried to be sourced for subsequence tests.

5.2.1 Automatic Data Acquisition Test Results

After the literature replication tests were analysed the testrig was further developed to allow for automation data acquisition. The second major change also was the introduction of long levers controlling the movement over the two valves. This allowed getting minute movements of the valves and thus achieving higher precision on the discharge of the experiment. Seven different discharge values were tested of the one pressure regulator. A Nelson 10 PSI pressure set pressure regulator, the same device used in the literature replication tests.

Generally these tests saw the upper and lower bounds of the hysteresis curve. However there was scatter of the values, particularly with the rising points of the tests. In contrast it seems that the falling points do not deviate much on the output pressure axis. The difference between this series of tests and the tests by Bernuth and Baird (1990), there is not a clear differentiation with this tests, however with Bernuth and Baird (1990) there is a clear difference, which makes the line fitting to their data and analysis easier.

The water supply for this experiment was from the high header tank which gave much lower input heads for the different discharges when compared to Bernuth and Baird (1990). It is believed that due to the force equilibrium in the pressure regulators is why the scatter is experienced for the rising input pressure. Appendix B shows a schematic diagram for a Nelson 10 PSI pressure regulator, the same one tested for this test, however appendixAppendix B shows a different connection fitting. When in operation the force of the spring is pushing the tube down. Counteracting this force is the pressure of water behind the rubber skirt, which acts as a force up. Together these make up the two main forces which result in the regulation action of the pressure regulator. When a rising pressure is being tested, the tube is in a forward movement towards the redistribution plug, when a falling pressure is being tested the tube is in a backward movement away from the redistribution plug. There is a third force induced while the tube is moving, and this is the frictional force when the tube moves through the O-ring.

It is though due to the low input heads which have been tested in this stage of testing, automatic data acquisition, the force equilibrium which is needed for the tube to be moved for regulation, particularly the force behind the rubber skirt which is pressurised by the input pressure is not great enough to overcome the normal forces required and the frictional force which is why scatter is seen for the rising pressures in the test stage figures.

For the falling figures because the tube is moving away from the redistribution plug, by the force of the spring, as the force under the rubber skirt is reduced the falling output pressure points are generally positioned on the same output pressure.

When pressure regulators are installed on large mobile irrigation machines and in operation their input pressures are going to much higher, typically in the order of 200 – 400 kPa. Due to this higher input pressures are needed in the experimental testing rig to understand what these devices do at higher input pressures and what the performance of their regulation is at these higher input pressures.

5.2.2 Automation Testing with Higher Input Pressures

The same methodology was taken with this stage of testing as with stage previous to this. It was wanted to saw the effect with high input pressures on the singular point graph and to see if it followed the same trend as without the introduction of the pump. To understand the effect the high input pressures would have on the pressure regulators, such as they would be operation on large mobile irrigation machines. Six different discharges were tested for the automation testing with higher input pressures; these are 0.2 L/s through to 0.7 L/s at 0.1 L/s increments.

It was found with this test that the regulation of the pressure regulator does function at higher input pressures, the performance of this regulation needs to be looked at. Large degrees of scatter were found with this test, particularly with the falling output pressure points. This is conversely different to what was found in the previous stage tests, as the scatter was generally present for the rising output pressure points. It is believed that this is again due to the force equilibrium. With the higher input pressures, this gave the pressure regulator higher forces behind the rubber skirt. These higher forces gave a better and more defined counteraction on the force induced by the spring; the results from this moved the tube in a more definitive displacement. This is why the rising points do not have much scatter in this test, because the higher input pressure induced a large force which gave a better force equilibrium.

The falling points have more scatter directly for the reason given above, which keep the rising points from have no scatter. The larger forces behind the rubber skirt do not resolve completely with the spring to move the tube away from the redistribution plug. When the frictional force is brought into this equation the scatter is made worse due to the rubbing of the tube on the O-ring.

What is seen also with this stage of testing is as the discharge increase the rising output pressures decrease. The same effect can be said for the falling output pressure points, however the shift is not to the same degree. As the discharge increases then, the hysteresis pattern migrates downwards.

In figureFigure 4.17 the discharge of 0.7 L/s is reported, the points of this discharge do not have a distinguishable different between the rising and falling points. The Nelson manufacturer's literature on this product report that the flow range for the Nelson 10 PSI pressure regulator is 0.0315 to 0.6309 L/s. This means that the highest discharge tested falls outside this range.

Bernuth and Baird (1990) did not test high range discharges, so the effect this has on pressure regulator remains unknown. Australian irrigators have installed large mobile irrigation machines which have a system capacity to irrigate with higher discharges. A higher discharge results in the velocity through the pressure regulator being increased. This speeds up the function of pressure regulator, because the fluid is being passed through the device at a quicker rate and the pressure response through the device is quicker because of the increase velocity through the tube.

The water inside the tube when in operation has a friction loss, due to the fluid being forced against the plastic tube. At a high discharge, the increased velocity creates another force in the tube. As the water is displaced around the redistribution plug and into the tube it pulls the tube down, away from the redistribution plug. This force acts in the same direction as the spring, and in opposite direction to the force under the rubber skirt and the friction force through the O-ring.

For this test to really be definitive more tests need to be repeated, on this pressure regulator but also different pressure regulators of the same model and type.

This stage of testing as with the previous stage looked at obtaining multiple rising and falling output pressure points around the hysteresis curve. Each point was not obtained in chronological order, thus a stage of testing was looked at where is was true and the tube was on a continual movement.

5.3 Continuing Hysteresis Tests

These tests saw the first major changes in the way the experiment testrig was used in the tests. Instead of getting multiple points at a constant discharge, the valves were continual altered in sequence. Three different discharges were tested these being 0.2, 0.4 and 0.6 L/s. Section **Error! Reference source not found.** describes the methodology taken with this test. Section 4.5 presents the figure and analysis the data for the continuing hysteresis tests.

In interpretation of the results of the hysteresis tests, thought needs to put back to the physical components of the pressure regulator. The continuing hysteresis tests involved continually moving the valves allowing the input pressure to be increased and decreased. The effect this has on the pressure regulators is that the tube is moving towards the redistribution plug and away from the redistribution plug for the regulation of the input pressure which was continually changing. An increasing input pressure means that once the pressure gets above the pressure regulators set pressure rating the device needs to start regulating so the tube moves forwards. The distance it moves and the rate of movement depends on the nature of the input pressure being fed into the device. This is due to the pressure behind the tube and counteracting the spring to arrive at the correct position for the tube to be from the correct pressure regulation.

When this theory is applied back to figuresFigure 4.20, Figure 4.21 and Figure 4.22 and in their interpretation, we can see this. In figure Figure 4.21 at higher input pressure, when they are decreased, there are patterns where the tube on its new positioning downwards is lagged. It will not move or move slightly then suddenly move. At lower input pressure it seems to move with less resistance. It is believed this is due to the lower forces acting on the tubes movement at the lower input pressures.

Each test of the different discharges gives a characteristic curve. With mostly all of the upper limb values above the pressure regulators pressure set rating. This upper limb is also slightly curved upwards. With the middle valued input pressures giving higher output pressure then the two lower and higher input pressures which give a comparatively smaller output pressure. On the lower limb of the hysteresis curve this effect can also be seen to some extent. Middle input pressure on the lower limb of the curve give out the lowest output pressure and higher input pressure on the lower limb give out the higher output pressures. However at about 15 meters head input pressure the output pressure increases about 0.5 meters head and settles back down to its value before it spiked. This effect is seen more in figure Figure 4.22 with a discharge of 0.6 L/s, but is also seen in the lower two discharges. The cause of this is due to the tube suddenly moving while the input pressure is decreased at a constant rate. It is seen more so at a higher discharge because of the extra volume of water passing though the device and from this the extra physical forces when the pressure regulator is in operation.

The continuing hysteresis tests are different to the singular points tests in such that the valves were in constant movement. This meant that the discharge could not be recorded as a constant value, they is variation. Control could however be placed on the amount of variation of the discharge throughout the test. A narrow band rate was selected and the discharge was not allowed to go above or below that value. This band rate was selected to be 10% of the discharge being examined. Figure 4.23 shows this discharge variation for the continuing hysteresis tests. Table 4.3 - Data statistics on continuing hysteresis tests also shows some basis data statistics on the discharge variation. For all three tests discharges the variation is about 8% under the set 10% selected.

5.4 Creep Tests

LMIM when in operation will typically run for hours at a time irrigating the field. When pressure regulators are installed on LMIM, they too will be in constant operation for hours at a time. As a development from the singular point tests it was hypothesised that after long term operation the pressure regulator will shift its tube position which in turn would move either decrease or increase the output pressure. Both a rising and falling pressure was considered and tested for 24 hours.

Figure 4.24 displays a point plot of the input and output pressures from the pressure regulator over the 24 hour period. Each point represents one second of the test. From the figure it can be seen that there is some variation. This variation needs to be taken into context and with reference to the axis. Table 4.5 shows the test's minimum and maximum values as well as the calculated variation. From this table and from figures Figure 4.24 and Figure 4.25 it can be seen that there is more variation over the 24 hour period from the falling pressure than the rising pressure. The variation comparison between the rising and falling pressure states that the higher variation for the rising test was for the output pressure but for the falling pressure there was a higher variation for the input pressure.

The temperature of the water exiting the experiment was measured every few hours to see the variation. A temperature change of the water will alter the density and viscosity of the water, which influences the friction and minor losses in the experiment. The rising test was done first and the falling test completed the day after. The temperature difference for both tests was 1.5 °C.

Only one test was done for this creep investigation and no real definite answer can be placed on this test because of the limited testing. From this test though the major movement from the upper to the lower limb of the hysteresis curve did not happen but there is variation when pressure regulators are in operation for a long period of time.

5.5 Friction Investigation

The hysteresis effect of the pressure regulator is caused by the movement of the tube through the O-ring. As with any two surface which are in contact there is a friction produced by sliding of the two materials. This stage of testing investigated this friction and to see if using lubrication lowered this friction and in turn lowered the hysteresis.

Two different pressure regulators were used in this investigation, one without extra input head and one with extra input head. NL10-2 is a Nelson 10 PSI set pressure regulator with connection fittings of 19 mm female for both the inlet and outlet and was the first device tested. The same testing methodology was used as with the continuing hysteresis tests. For this test the high header tank was used as the supply into the experiment. Figure 4.26 shows the first of the two tests. The Nelson pressure regulators when manufactured do have some lubrication, thus the device was tested normally without any alteration firstly, this is shown in the figure as normal lubrication. Once this was done, the device was dissembled and this lubrication was wiped away, the pressure regulator was then resembled very carefully and retested; this is shown in the figure as no lubrication. For the extra lubrication, the last of the three shown on the figure, a water based lubrication was used and applied to the tube, the device was then tested.

All three tests fit together as they approach regulation, under the 1:1 line. As the upper limb of the graph is approached the three tests separate out. While no points go above the pressure regulators set pressure rating the extra lubrication test is the closest to this line. Just underneath the extra lubrication test is the no lubrication test. The upper limb of the normal test is below the no lubrication. On the lower limb, all three tests follow the same path back to the constant approach line. Like with previous tests an understanding of the discharge variation is important and is shown for this test in figure Figure 4.27. This point plot shows all the discharges for the three tests. From this plot a 6.6% variation of discharge is shown.

Figure 4.28 shows the second plot for the friction investigation. For this test extra input head was used. The upper limb of this graph shows the normal and extra lubrication to be at about the same output pressure, following the pressure regulators pressure set line for the increase input pressure. The no lubrication for the upper limb is above the pressure set line at about 0.2 metres output head. Like with the continuing hysteresis test different input pressures where the experiment shifted from rising to falling pressures. On the lower limb the normal lubrication test has the lowest output pressure. The extra and no lubrication tests follow the same path however at the lower input pressures the extra lubrication output pressure raises slightly. The test with the smallest distance between the upper and lower limbs is the extra lubrication test. Figure 4.29 shows the discharge variation for the three tests, normal, no and extra lubrication. The aimed discharge for this test was 0.3 L/s and the variation was 14.2%.

While no concrete comparisons can be made from the two tests, because they were from two different pressure regulators and two different discharges. However it was observed that for the no lubrication test it was more jerked between points, than the extra or no lubrication. This is believed to be due to no lubrication and such the increased friction of the tube sliding against the o-ring.

Another interesting point to make of the size difference of the hysteresis between pressure regulators NL10-2 and NL10-3, while different input heads were experienced for each of the two tests there is a noticeable change in hysteresis. Pressure regulator NL10-2 had about 0.8 meters output head at its maximum input pressure and pressure regulator NL10-3 1.8 metres output head for the same input head. It is considered that the reason for this is due to the increased input pressure influences the force equilibrium inside the pressure regulator. The input pressure which when travels down the length of the tube and into the void space which gets pressurised, this pressure creates the force against the spring which with a few other forces such as gravity and friction displaces the tube. Appendix B illustrates this effect. It is thought that this increased input head changes the dynamics of how the pressured void space relates its force on the spring and that the overall equilibrium will be overdone, thus resulting in the increased hysteresis.

However because only one test has been performed no real conclusion can be made about this theory and further testing should be performed.

5.6 Displacement of Tube inside Pressure Regulator

This series of test investigated a fourth parameter along with the discharge, input and output pressures, the tubes displacement were measured. Section 3.9 outlines the methodology undertaken for this series of tests. Section 4.8 reports the results received for this series of tests.

The movement of the tube and the resultant distance between the inlet of the tube and the lip on the underside of the redistribution plug makes up the variable headloss, which is the basic function of the pressure regulator. In tracking the displacement of the tube and relating it back to the other parameters, discharge, input pressure and output pressure a relationship can be formed of the pressure regulators function. While mathematical determining this relationship is beyond this dissertation, the theory about how it can be gone about it discussed.

If a force equilibrium is performed on the pressure regulator, analysing the forces which shift the tube when the pressure regulator is functioning. The rate of the displacement can be calculated by differentiating the displacement with respect to time, this will be the velocity of the tube. If the velocity of the tube is also differentiated with respect to time, this will be calculated as the acceleration of the tube. Using Newtons second law detailed in equation 5.1, the acceleration of the tube together with the mass of the tube can be equated back to the other forces present when the pressure regulator is functioning, to obtain the mathematical model between the tubes movement and the regulating headloss.

$$F = ma \qquad \textbf{5.1}$$

where F = force (Newtons), m = mass (kg) and a = acceleration (m/s^2)

From section 4.8, figures Figure 4.30 and Figure 4.32 show the figures for the tubes movement up, moving towards the lip. The displacement and the rate of displacement was different then what was seen for the downward movement of the tube, where its movement was more sudden and the tube travelled further. It is believed the string glued onto the tube with the bolt as a weight which transferred the displacement onto the dial gauge, dragged the tube. The weight of the bolt was to great and it interfered in the function of the tube free movement. For this experiment to be repeated a lower weighted object is needed to get the correct balance between not interfering in the movement of the tube by not dragging it and creating an extra drag force but also for the weight to take the slack out of the line and transfer the displacement to the dial gauge.

5.7 Statistical Analysis

5.7.1 ANOVA

Pressure regulators are produced via modern manufacturing techniques and procedures, which introduces variation into their performance from the manufacturing process. In understanding this variation a statistical analysis is performed to test their deviation. Described in section 3.10 is the testing methodology performed for the statistical analysis. 16 Nelson 10 PSI pressure regulators were tested, with three difference connection fittings, 19 mm female to female, 19 mm female to 19 mm 3TN square and barbed to 3TN square. Section 4.9 outlines the results for this statistical analysis. Two statistical analysis procedures were undertaken, an ANOVA test and a sample size calculation. The ANOVA test found that for both nozzle sizes tested, the 3TN #28 and 3TN #50 the means of each pressure regulators were not equal.

This test assumes the means are normally distributed under the normal model. The parameter of interest is the output pressure from the pressure regulator; this was the parameter of which the test was undertaking. With the test saying the means are not equal, the question needs to raised, why?

Each component of the pressure regulator is manufactured separately and then assembled to make up the device of the pressure regulator. The manufacturing processes has particular tolerances on separate components and if the process exceeds this tolerance then a recalibration of the machine manufacturing the component needs to take place.

The spring inside each pressure regulator is made from wire, which is coiled by a machine. The function of this spring inside the pressure regulator is to provide a force to counteract other forces and to move the tube to its desired position for pressure regulation. For the spring to do this the length of the spring is critical, to long and it provides a larger force, to short and the force is not great enough. The Nelson manufacturer's literature reports a 6% variation. While this was not part the study, it is advised that future work should investigate the spring variation between pressure regulators, as it is this component which gives the most variation for the small change is manufacture specifications of the product.

5.7.2 Sample Size

In understanding the manufacturing variation the number of devices or sample size which need to be tested are to be calculated. For this calculation the normal model has been used. Section 4.9 shows the results for this calculation. The point of discussion is the large difference between the sample sizes of the test for the 3TN #28 and #50 nozzles, 88 and 1 respectively. The reason that for the #50 test the number is so unreasonable is due to the high discharge associated with this nozzle. The discharge was above what was recommended from the manufacture, which decreased the output pressure considerably. The difference between the theoretical and real means is a comparatively large difference.

The calculation for the 3TN #28 nozzle should then be used. With 16 devices already tested, 72 more Nelson 10 PSI pressure regulators need to be tested in order to understand the manufacture variation.

This sample size calculation is based on the normal model, which assumes statistical the devices are distributed evenly. In the ANOVA test, this was proved not to be the case a further statistical analysis needs to be undertaken to determine to true number of devices which needs to be tested, if not under the normal model.

5.8 The Methodology and Model

The major aim of this dissertation has to develop a suitable testing methodology. This discussion had been broken up to the different approaches taken for the testing methodologies each one discussed.

In terms of the best methodology to test the pressure regulators which give repeatable, robust results the continuing movement test fits this criterion. However the tube is being continual shifted due to the rising and falling input pressure by the two valves begin altered. It is believed that the automatic acquisition test is the most robust test, as each point is a new movement of the tube is some arbitrary point. More data points are needed for these tests then what was taken in the automatic acquisition test to fully understand the performance at the set discharge.

Both these series of tests are time consuming and tedious. Losing focus is easy with these tests due to the high concentration needed to move the levers in small increments. A further downside the time required to test one pressure regulator.

Another test rig needs to be designed which has the potential to test multiple devices at once accurately. Thought also needs to be devoted to how these devices operate in the field. Pressure regulators on large mobile irrigation machines are going to have varying discharges with respect to time and with respect to positioning on the machine. Tests need on be conducted in the field to understand the variations experienced. This also would allow multiply pressure regulators to be tested at the one time.

The variation of the output pressure which was seen with this project, on average about 1 metre head raises questions about how well these devices perform in the field and how well they regulator the pressure on large mobile irrigation machines to give a uniform irrigation. While there is no doubt, they would be needed in areas of large elevation difference where the input pressure is changing; is there a need for pressure regulators when there is no input pressure change.

Chapter 6 CONCLUSIONS

Different testing methodologies were undertaking with this dissertation. Depending on the methodology approach taken influences the result of the test. Each test result needs to be interpreted with reference to the methodology undertaken. This is the most significant conclusion of the experimental results.

It was found that the discharge range stated by the pressure regulators manufacturer needs to be followed, particularly for higher discharges. At higher discharges above the specifications recommended by the manufacturer the performance of the pressure regulators in terms of a definable upper and lower limb of the hysteresis curve decreases. The location of the output pressure is unknown; however it is under the set pressure rating of the pressure regulator.

The effect different discharges have on performance of the pressure regulator was investigated. It was discovered at an increased discharge the upper limb of the hysteresis curve decreases in output pressure. It is recommended that using a mid-range discharge of 0.3 - 0.4 L/s would be the optimum operational range for the pressure regulators as the upper limb would be above the pressure set rating for the pressure regulator. Conversely, when beginning an irrigation with a large mobile irrigation machine which has pressure regulators installed it is recommended to have the delivery valve shut off and when the pump is up to the correct speed, to open the delivery valve, thus increasing the input pressure and discharge to the machine. Once the correct input pressure is reached no further adjustments to the valve is recommended. This would make sure the output pressure of the pressure regulator is on the upper limb of the hysteresis curve.

This project set out to develop a methodology to test pressure regulators. Much more work is required to achieve the required outcome of this area to obtain a mathematical model for better modelling and design of pressurised irrigation systems when used with pressure regulators. The testing methodology needs to be taken further and tried with different models of pressure regulator and with difference pressure sets. Presently there are a number of different pressure regulators, with different pressure sets, different connection fittings and configured is different ways. While the testing of one type of pressure regulator is a starting point by defining the methodology much more testing is required to fully understand the variation associated with these devices.

Chapter 7 RECOMMENDATIONS FOR FUTURE WORK

7.1 Introduction

The work that has been conducted for this project highlights the importance for a number of areas which needs to be investigated further. This future development will help in fully understanding the performance of pressure regulators for the correct modelling of the devices in future pressurised irrigation simulation and computational programs.

7.2 Recommendations

This dissertation has large focused on different methodologies for testing pressure regulators. For the majority of the test one pressure regulator was used at one pressure rating, however with the proposed methodology more pressure regulators need to be tested. Not only do more device need to be tested by also different pressure sets to see if one performs more ideally then another. It is expected that the different pressure sets would perform differently due to the variation in the forces involved from the difference sized springs and resultant forces.

The water supply for this experiment was a clean cool supply free from any containment. When these devices are installed on large mobile irrigation machines the water supply will contain containments, which may take the form of grains of sand to water pollutants. The effect this water would have on the performance of the pressure regulators needs to be investigated.

Testing the pressure regulators in the field an understanding can also made about their field performance when operating on large mobile irrigation machines and if the laboratory test match up.

A further statistical analysis needs to be undertaken to understand the pressure regulators manufacturing variation. This dissertation assumed the devices fit under a normal model, this was proved to be incorrect. Further investigation is necessary to understand the number of devices which need to be tested to understand manufacturing variation.

The pressure regulator functions because of the components which make up the device. This dissertation has not investigated in detail, the functionality of particular components of the pressure regulator such as the spring, O-ring and tube and studies their mechanical behaviour. This study has mainly focused on the hydraulic workings of the device, however to fully understand and mathematically model the pressure regulator, the physical, mechanical and hydraulic behaviour of the pressure regulator need to be discussed.

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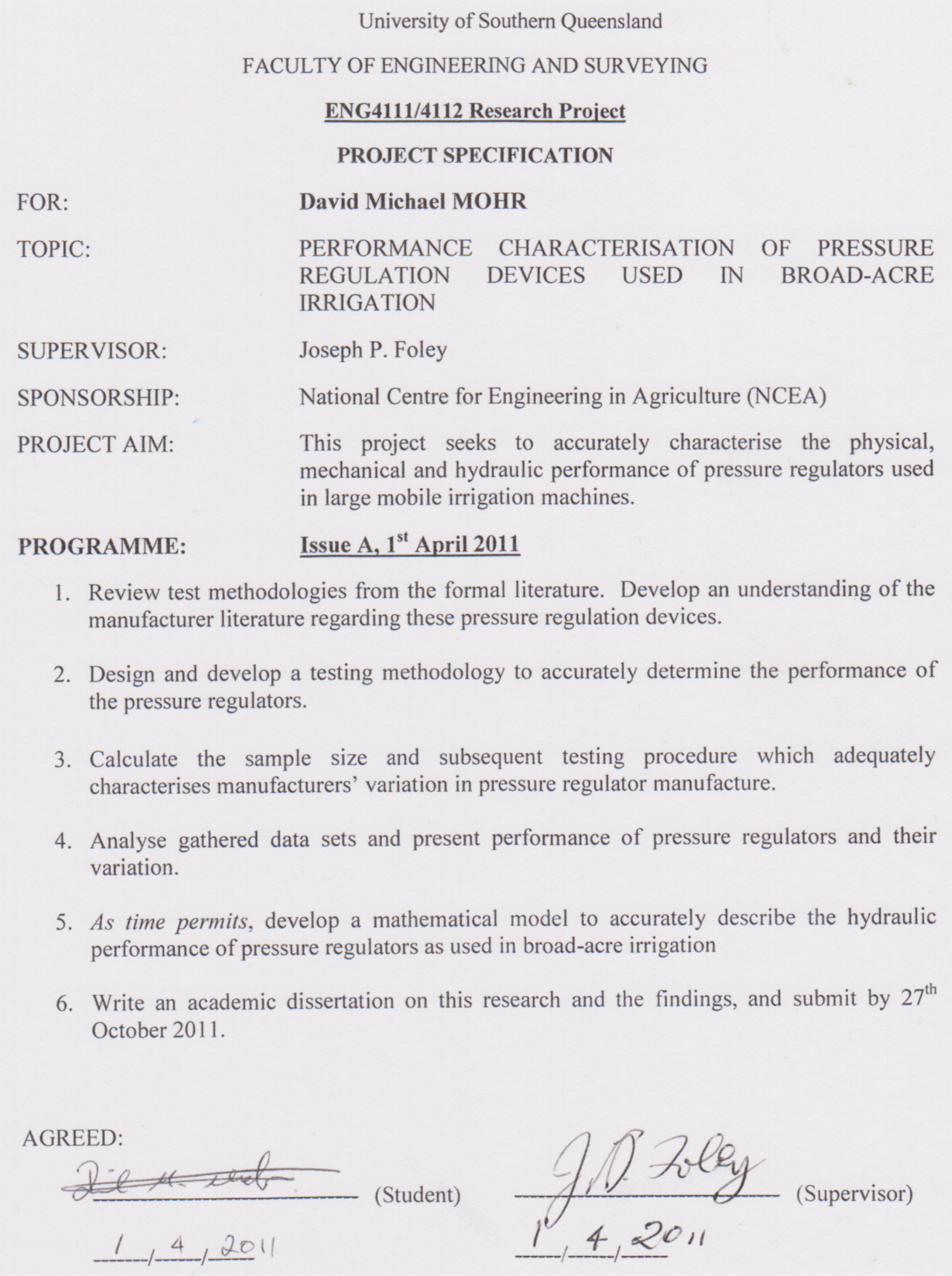
Figure 2.14 - http://www.wkbradford.com/posters/normmodA_lg.jpg

APPENDICES

Appendix A Project Specification



University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project

PROJECT SPECIFICATION

FOR: **David Michael MOHR**

TOPIC: PERFORMANCE CHARACTERISATION OF PRESSURE REGULATION DEVICES USED IN BROAD-ACRE IRRIGATION

SUPERVISOR: Joseph P. Foley

SPONSORSHIP: National Centre for Engineering in Agriculture (NCEA)

PROJECT AIM: This project seeks to accurately characterise the physical, mechanical and hydraulic performance of pressure regulators used in large mobile irrigation machines.

PROGRAMME: **Issue A, 1st April 2011**

1. Review test methodologies from the formal literature. Develop an understanding of the manufacturer literature regarding these pressure regulation devices.
2. Design and develop a testing methodology to accurately determine the performance of the pressure regulators.
3. Calculate the sample size and subsequent testing procedure which adequately characterises manufacturers' variation in pressure regulator manufacture.
4. Analyse gathered data sets and present performance of pressure regulators and their variation.
5. *As time permits*, develop a mathematical model to accurately describe the hydraulic performance of pressure regulators as used in broad-acre irrigation
6. Write an academic dissertation on this research and the findings, and submit by 27th October 2011.

AGREED:

(Student)

1/4/2011

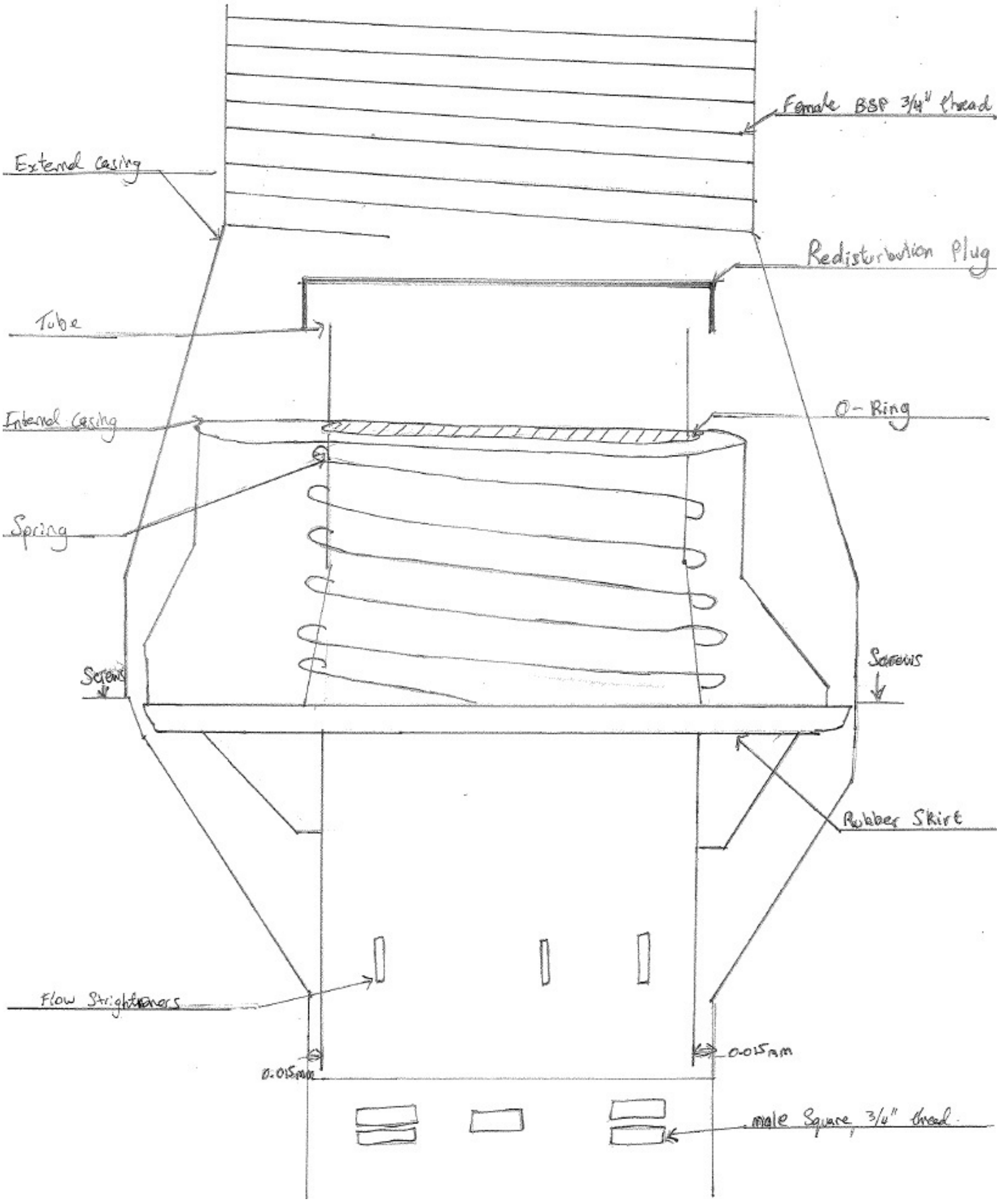
J.P. Foley (Supervisor)

1/4/2011

Appendix B Internal view of Nelson 10 PSI set pressure, pressure regulator with ¾ threaded female to ¾ square fitting

Internal View of NL10/F5 Pressure Regulator

Not to Scale



Appendix C **Table Z – Areas under the standard Normal curve**

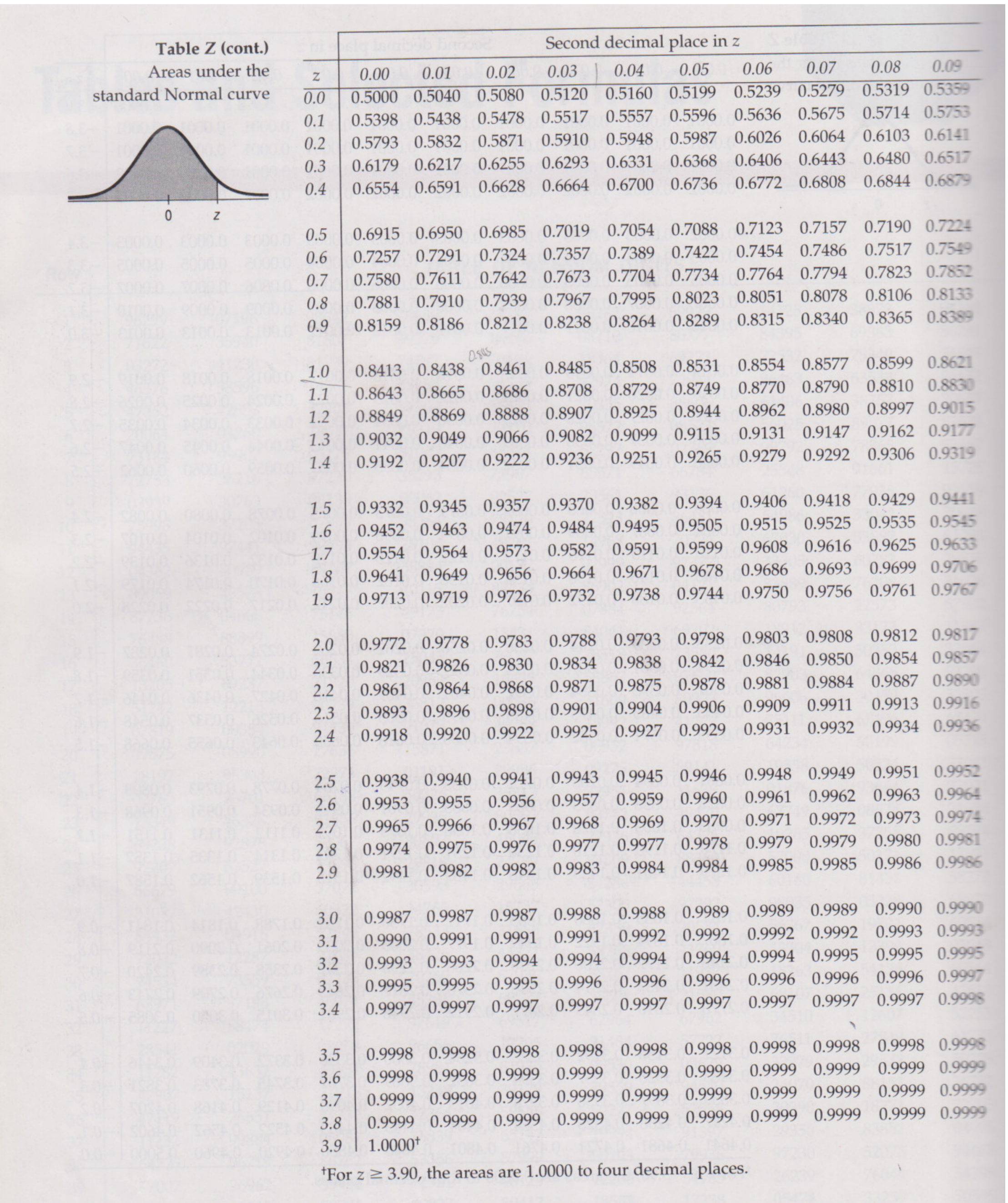
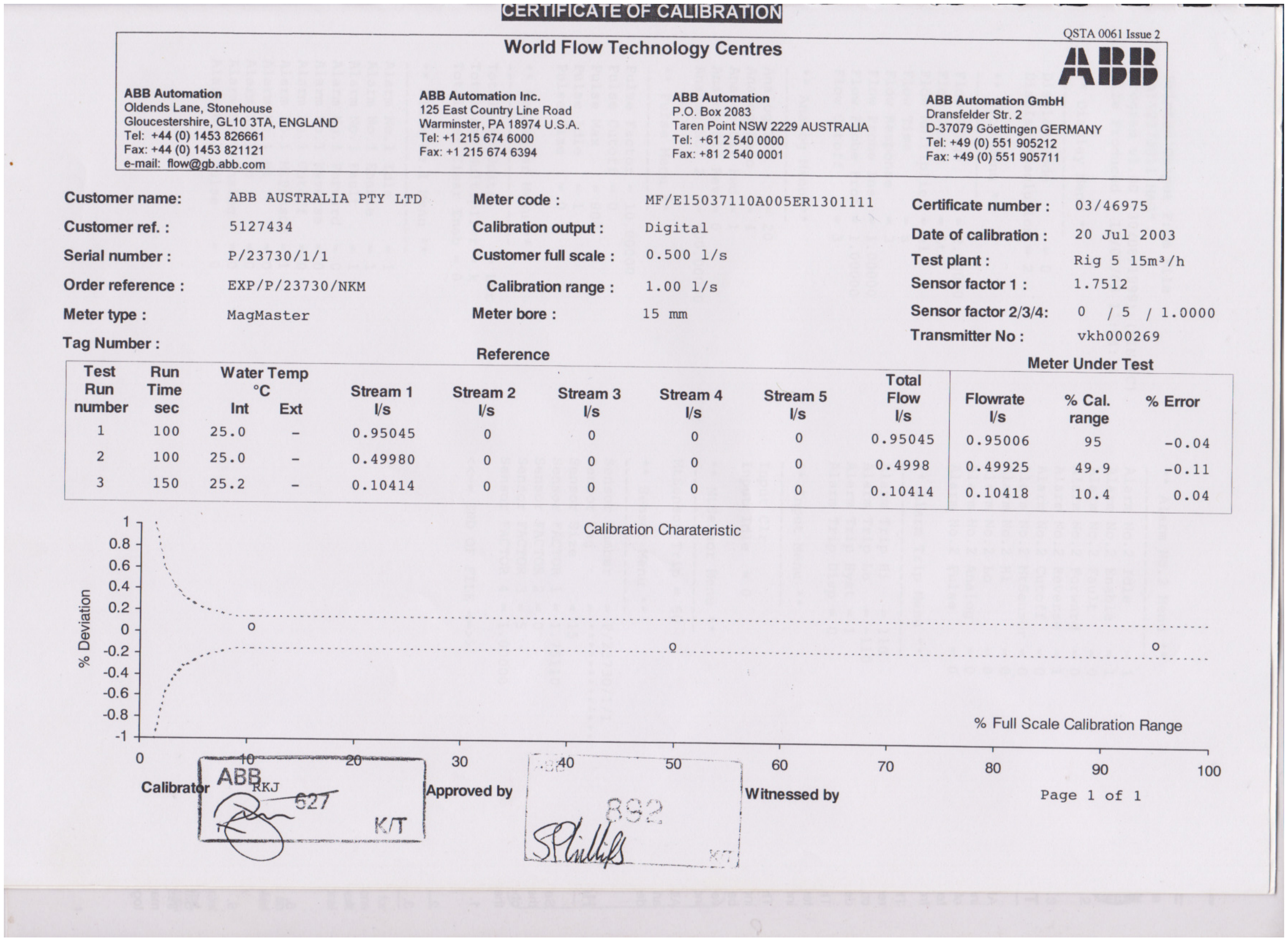


Table Z (cont.)
Areas under the
standard Normal curve

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
	Second decimal place in z									
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.845 0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.1	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.2	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.3	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.4	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998
3.5	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998
3.6	0.9998	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
3.7	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
3.8	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
3.9	1.0000†									

†For z ≥ 3.90, the areas are 1.0000 to four decimal places.

Appendix D Certificate of Calibration (flowmeter)



CERTIFICATE OF CALIBRATION

QSTA 0061 Issue 2

World Flow Technology Centres

ABB

ABB Automation
Oldends Lane, Stonehouse
Gloucestershire, GL10 3TA, ENGLAND
Tel: +44 (0) 1453 826661
Fax: +44 (0) 1453 821121
e-mail: flow@gb.abb.com

ABB Automation Inc.
125 East Country Line Road
Warminster, PA 18974 U.S.A.
Tel: +1 215 674 6000
Fax: +1 215 674 6394

ABB Automation
P.O. Box 2083
Taren Point NSW 2229 AUSTRALIA
Tel: +61 2 540 0000
Fax: +81 2 540 0001

ABB Automation GmbH
Dransfelder Str. 2
D-37079 Göettingen GERMANY
Tel: +49 (0) 551 905212
Fax: +49 (0) 551 905711

Customer name: ABB AUSTRALIA PTY LTD
Customer ref. : 5127434
Serial number : P/23730/1/1
Order reference : EXP/P/23730/NKM
Meter type : MagMaster
Tag Number :

Meter code : MF/E15037110A005ER1301111
Calibration output : Digital
Customer full scale : 0.500 l/s
Calibration range : 1.00 l/s
Meter bore : 15 mm

Certificate number : 03/46975
Date of calibration : 20 Jul 2003
Test plant : Rig 5 15m³/h
Sensor factor 1 : 1.7512
Sensor factor 2/3/4: 0 / 5 / 1.0000
Transmitter No : vkh000269

		Reference								Meter Under Test		
Test Run number	Run Time sec	Water Temp °C Int	Water Temp °C Ext	Stream 1 l/s	Stream 2 l/s	Stream 3 l/s	Stream 4 l/s	Stream 5 l/s	Total Flow l/s	Flowrate l/s	% Cal. range	% Error
1	100	25.0	-	0.95045	0	0	0	0	0.95045	0.95006	95	-0.04
2	100	25.0	-	0.49980	0	0	0	0	0.4998	0.49925	49.9	-0.11
3	150	25.2	-	0.10414	0	0	0	0	0.10414	0.10418	10.4	0.04

Calibration Charateristic

Calibrator ABB RKJ 627 K/T

Approved by

892
SPhillips
K/T

Witnessed by

Page 1 of 1

Appendix E Level Run to Low and High Header tanks for pressure calibration

Survey One

	Backsight	Foresight	Int	Rise	Fall	RL (AHD)	Comment
	1.444					693.809	DW - On door sill
	1.665	1.467			0.023	693.786	P1
	1.605	1.661	1.652 (Cross at flange)	0.004		**693.79**	**Cross on floor**
	1.499	1.608			0.003	693.787	P1
		1.476		0.023		NA	DW - On door sill
Σ	6.213	6.212		0.027	0.026		

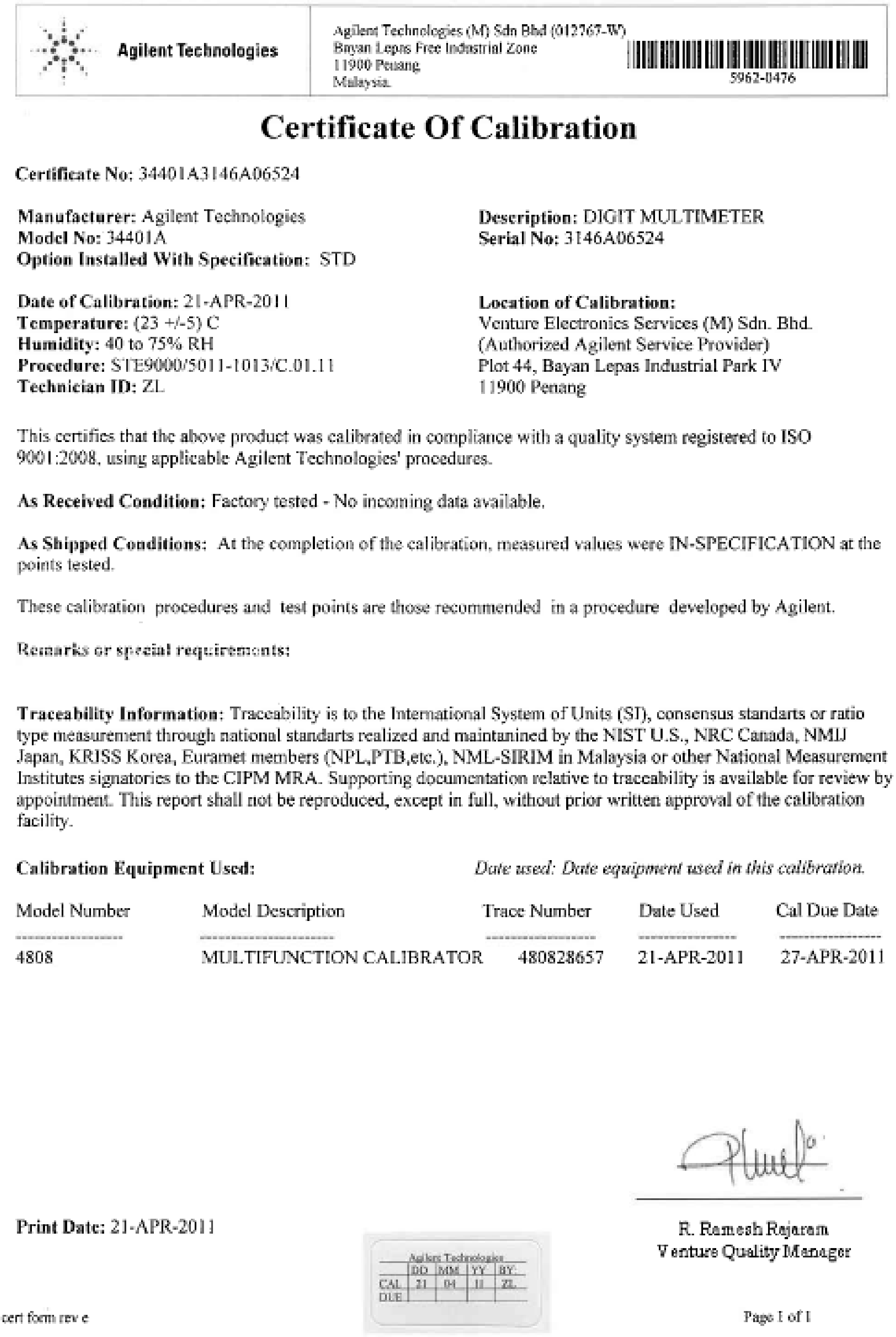
Survey Two

	Backsight	Foresight	Int	Rise	Fall	RL (AHD)	Comment
	3.328					697.654	Level floor 2-stairwall-arrow
	0.786	0.802		2.526		**700.18**	**Lower Header Tank-long edge**
		3.313			2.527	697.653	Level floor 2-stairwall-arrow
Σ	4.114	4.115		2.526	2.527	NA	

Survey Three

	Backsight	Foresight	Int	Rise	Fall	RL (AHD)	Comment
	1.534					704.934	Point 'Duff' Level 4 Z block
	1.955	0.679		0.855		705.789	P2
	1.647	0.128		1.827		707.616	P3
	1.874	0.662		0.985		708.601	P4
	0.536	0.504		1.37		**709.971**	**High Header Tank-long edge**
	0.323	1.906			1.37	708.601	P4
	0.157	1.308			0.985	707.616	P3
	0.584	1.983			1.826	705.79	P2
		1.439			0.855	704.935	Point 'Duff' Level 4 Z block
Σ	8.61	8.609		5.037	5.036	NA	

Appendix F Certificate of Calibration (Digital Multimeter used for Pressure Transducer Calibration)



Agilent Technologies

Agilent Technologies (M) Sdn Bhd (012767-W)
Bayan Lepas Free Industrial Zone
11900 Penang
Malaysia.

5962-0476

Certificate Of Calibration

Certificate No: 34401A3146A06524

Manufacturer: Agilent Technologies
Model No: 34401A
Option Installed With Specification: STD

Description: DIGIT MULTIMETER
Serial No: 3146A06524

Date of Calibration: 21-APR-2011
Temperature: (23 +/-5) C
Humidity: 40 to 75% RH
Procedure: STE9000/5011-1013/C.01.11
Technician ID: ZL

Location of Calibration:
Venture Electronics Services (M) Sdn. Bhd.
(Authorized Agilent Service Provider)
Plot 44, Bayan Lepas Industrial Park IV
11900 Penang

This certifies that the above product was calibrated in compliance with a quality system registered to ISO 9001:2008, using applicable Agilent Technologies' procedures.

As Received Condition: Factory tested - No incoming data available.

As Shipped Conditions: At the completion of the calibration, measured values were IN-SPECIFICATION at the points tested.

These calibration procedures and test points are those recommended in a procedure developed by Agilent.

Remarks or special requirements:

Traceability Information: Traceability is to the International System of Units (SI), consensus standarts or ratio type measurement through national standarts realized and maintanined by the NIST U.S., NRC Canada, NMIJ Japan, KRISS Korea, Euramet members (NPL,PTB,etc.), NML-SIRIM in Malaysia or other National Measurement Institutes signatories to the CIPM MRA. Supporting documentation relative to traceability is available for review by appointment. This report shall not be reproduced, except in full, without prior written approval of the calibration facility.

Calibration Equipment Used: *Date used: Date equipment used in this calibration.*

Model Number	Model Description	Trace Number	Date Used	Cal Due Date
4808	MULTIFUNCTION CALIBRATOR	480828657	21-APR-2011	27-APR-2011

Print Date: 21-APR-2011

R. Ramesh Rajaram
Venture Quality Manager

Agilent Technologies

	DD	MM	YY	BY:
CAL	21	04	11	ZL
DUE				

cert form rev e

Page 1 of 1

Appendix G Labview output for Stage Two-Automatic data acquisition tests for discharges of 0.3 and 0.5 L/s

Output for 0.3 L/s

```
%PT Offset: Add 0.415m head of water to Inlet and Outlet Pressure Data

%Flow Data in L/s

%Pressure Data in kPa

%Nozzle: Nelson 3TN 36/128"

%PR: NL10-1

%Static Head: 144.6 kPa

%Water Temp_start: 20.5'C (Water Temp measured at start and end of test)

%Water Temp_end:21.5

%%%%%%%%%FALLING%%%%%%%%%%%%%%%%%%%%%%%%%
7/12/2010

2:05:45 PM

Flow,Inlet Pressure,Outlet Pressure

0.300099,109.162895,56.875874

0.299608,109.151558,56.840225

7/12/2010

2:07:00 PM

Flow,Inlet Pressure,Outlet Pressure

0.300430,121.271790,56.847923

0.300470,121.422882,56.893288

7/12/2010

2:08:30 PM

Flow,Inlet Pressure,Outlet Pressure

0.299874,92.227745,54.961166

0.299751,91.959190,55.073368

7/12/2010

2:10:31 PM
```

```
Flow,Inlet Pressure,Outlet Pressure
0.299893,63.464939,52.609406
7/12/2010
2:10:36 PM
Flow,Inlet Pressure,Outlet Pressure
0.299989,63.368134,52.642216
0.299591,63.508282,52.594418
7/12/2010
2:12:05 PM
Flow,Inlet Pressure,Outlet Pressure
0.300441,38.028992,32.010265
0.300481,38.063015,32.079124
7/12/2010
2:16:09 PM
Flow,Inlet Pressure,Outlet Pressure
0.300328,112.204498,56.395069
7/12/2010
2:17:36 PM
Flow,Inlet Pressure,Outlet Pressure
0.299841,103.765060,57.059364
0.299845,103.805969,57.257839
7/12/2010
2:17:43 PM
Flow,Inlet Pressure,Outlet Pressure
0.300317,103.867950,57.237183
0.299644,103.980148,57.144020
7/12/2010
```

```
2:18:59 PM
Flow,Inlet Pressure,Outlet Pressure
0.299265,83.174263,57.131058
0.299140,83.151985,57.168728
7/12/2010
2:20:17 PM
Flow,Inlet Pressure,Outlet Pressure
0.299813,78.036903,55.982315
0.300067,78.135338,56.003784
7/12/2010
2:20:26 PM
Flow,Inlet Pressure,Outlet Pressure
0.299417,78.234573,56.043884
7/12/2010
2:21:37 PM
Flow,Inlet Pressure,Outlet Pressure
0.300874,71.221802,54.095558
7/12/2010
2:21:43 PM
Flow,Inlet Pressure,Outlet Pressure
0.299757,71.156181,54.056271
0.300603,71.359924,54.016171
7/12/2010
2:23:19 PM
Flow,Inlet Pressure,Outlet Pressure
0.299973,121.532249,58.519188
0.300626,121.524956,58.587238
```

```
%%%%%%%%%%%%%%RISING%%%%%%%%%%%%%%%%%%%%
7/12/2010
3:09:48 PM
Flow,Inlet Pressure,Outlet Pressure
0.300411,121.422073,65.102180
0.300422,121.510780,64.972160
7/12/2010
3:10:20 PM
Flow,Inlet Pressure,Outlet Pressure
0.299787,118.362640,64.887505
7/12/2010
3:11:33 PM
Flow,Inlet Pressure,Outlet Pressure
0.300283,111.498886,64.824318
7/12/2010
3:12:41 PM
Flow,Inlet Pressure,Outlet Pressure
0.300157,98.707481,64.631508
7/12/2010
3:13:24 PM
Flow,Inlet Pressure,Outlet Pressure
0.299750,85.762589,63.457245
7/12/2010
3:14:14 PM
Flow,Inlet Pressure,Outlet Pressure
0.299462,71.475769,61.352566
7/12/2010
```

```
3:14:16 PM
Flow,Inlet Pressure,Outlet Pressure
0.299411,71.258659,61.380516
7/12/2010
3:15:20 PM
Flow,Inlet Pressure,Outlet Pressure
0.300605,61.266693,54.992355
7/12/2010
3:16:14 PM
Flow,Inlet Pressure,Outlet Pressure
0.299821,48.035099,42.576557
7/12/2010
3:17:20 PM
Flow,Inlet Pressure,Outlet Pressure
0.300609,44.251869,38.970745
```

Output for 0.5 L/s

```
%PT Offset: Add 0.415m head of water to Inlet and Outlet Pressure Data
%Flow Data in L/s
%Pressure Data in kPa
%Nozzle: Nelson 3TN 48/128"
%PR: NL10-1
%Static Head: 144.6 kPa
%Water Temp_start: 20.0'C (Water Temp measured at start and end of test)
%Water Temp_end: 21.5'C
%%%%%%%%%%%%FALLING%%%%%%%%%%%%%
8/12/2010
11:37:38 AM
Flow,Inlet Pressure,Outlet Pressure
0.499983,57.534496,40.564236
0.499899,57.865021,40.364544
8/12/2010
11:41:03 AM
Flow,Inlet Pressure,Outlet Pressure
0.500038,49.300900,32.653088
8/12/2010
11:44:42 AM
Flow,Inlet Pressure,Outlet Pressure
0.500994,55.296959,37.907475
8/12/2010
11:46:45 AM
Flow,Inlet Pressure,Outlet Pressure
0.500072,51.880707,34.978516
```

```
8/12/2010
11:48:17 AM
Flow,Inlet Pressure,Outlet Pressure
0.500300,55.910622,38.423111
0.500518,56.125301,38.529236
8/12/2010
11:49:22 AM
Flow,Inlet Pressure,Outlet Pressure
0.500588,62.419083,44.623306
0.499876,62.552345,44.551613
8/12/2010
11:50:06 AM
Flow,Inlet Pressure,Outlet Pressure
0.500336,65.820755,47.685535
8/12/2010
11:51:34 AM
Flow,Inlet Pressure,Outlet Pressure
0.499843,69.774124,50.658245
8/12/2010
11:52:26 AM
Flow,Inlet Pressure,Outlet Pressure
0.499486,73.780960,51.884758
8/12/2010
11:53:22 AM
Flow,Inlet Pressure,Outlet Pressure
0.500769,77.517212,52.232704
8/12/2010
```

```
11:55:06 AM
Flow,Inlet Pressure,Outlet Pressure
0.500434,84.762093,54.025486
%%%%%%%%%%%%RISING%%%%%%%%%%%%%%%%%%%%%
8/12/2010
11:57:22 AM
Flow,Inlet Pressure,Outlet Pressure
0.499225,83.898506,60.081497
0.499713,84.424683,60.025192
8/12/2010
11:57:26 AM
Flow,Inlet Pressure,Outlet Pressure
0.500278,84.281693,60.034912
0.499560,83.807373,60.384075
8/12/2010
11:58:21 AM
Flow,Inlet Pressure,Outlet Pressure
0.499544,83.347633,60.346405
0.499318,83.399879,60.163319
8/12/2010
12:00:29 PM
Flow,Inlet Pressure,Outlet Pressure
0.500786,81.791801,59.258823
8/12/2010
12:02:15 PM
Flow,Inlet Pressure,Outlet Pressure
0.499751,80.764168,59.315937
```

```
0.499527,80.559204,59.334568
8/12/2010
12:03:31 PM
Flow,Inlet Pressure,Outlet Pressure
0.499598,77.964401,58.216610
0.499316,77.783340,58.145321
8/12/2010
12:04:31 PM
Flow,Inlet Pressure,Outlet Pressure
0.499690,72.385124,53.311775
8/12/2010
12:05:06 PM
Flow,Inlet Pressure,Outlet Pressure
0.499580,65.296616,46.888382
8/12/2010
12:06:13 PM
Flow,Inlet Pressure,Outlet Pressure
0.501185,56.785141,38.746346
8/12/2010
12:06:34 PM
Flow,Inlet Pressure,Outlet Pressure
0.499838,51.375198,33.819244
0.500199,51.150391,33.975189
8/12/2010
12:07:16 PM
Flow,Inlet Pressure,Outlet Pressure
0.500705,48.338486,30.706795
```

```
8/12/2010

12:07:58 PM

Flow,Inlet Pressure,Outlet Pressure

0.500574,48.434486,31.117928

0.500325,48.284615,30.997219

8/12/2010

12:09:22 PM

Flow,Inlet Pressure,Outlet Pressure

0.500188,47.663258,30.058706
```

Appendix H Matlab code for Stage two – Automatic data acquisition data processing

```
%David Mohr

%0050086160

%ENG4111/ENG4112 Research Project

%Performance Characterization of Pressure Regulation Devices used

%in Broad-acre Irrigation


%Stage Two Script - Automatic data acquisition


%This script inputs the raw textfile produced from the software and
puts

%the flow (L/s), input pressure (kPa) and output pressure (kPa) into

%matlab. Each group is taken individually and kept separate. The
pressure

%transducer offsets are also added in this script and the pressures

%converted from kPa to metres head.


%Clears the associated variables, matlab command window, and closes all

%figures respectively.


clear

clc

close all


%A datafile from the 'Labview' software is inputted into matlab via
matlabs

%textread function. From the output Labview textfile each time the
software

%outputs a time, date and file structure was stamped to each read. The

%textread function takes these stamps and converts this to a value of 0
in

%matlab. This is going to be a standard format. The values of flow,
input
```

```
%and output pressure from the textfile are taken and grouped.


%Value of gravitational acceleration is calculated and used for matlab

%analysis (units = m/s^-2)


g = 9.789278;


%All textfiles on folder are ordered to be brought into script and
named in

%an appropriate way for further analysis.


textfiles = dir('*.txt');

var = 1;

txtnum = length(textfiles);

while var <=txtnum

 a = double(textfiles(var).name);

fid = fopen(textfiles(var).name);


%From the called textfile, the matlab function textscan is used to read
the

%file in an appropriate format. Labview outputs the textfile in a
particular

%format and this matlab script has been written to work with that

%particular format and take out the necessary information.


file = textscan(fid, '%f %f %f', 'commentStyle', '%', 'delimiter',...

    '/ : , ','treatasempty', {'AM', 'PM',...

    'Flow,Inlet Pressure,Outlet Pressure'});


fclose(fid);
```

```
r = length(a)-4;

s = a(12:r);

t = double('Data_PP_');

u = [t s];

name = char(u);


raw_data = cell2mat(file);




b = length(raw_data);

d = 6;


%This loop takes the data extracted from the textfile, and selects and

%writes to a new variable the appropriate information needed and
discards

%the information or gaps through the extracted data.


i = 1; % raw data counter

j = 0; % resolved data counter (Flow, Pressure In, Pressure Out)

k = 1; % used for storage in cases with 2 lines of data.


while i <=b

    if raw_data(i,3) > 2000

        i = i + 4;


        k = 1;

        j = j + 1;

        if i > b

            break
```

```
        end
    end
    flow_raw(j,k) = raw_data(i,1);
    pressure_in_raw(j,k) = raw_data(i,2);
    pressure_out_raw(j,k) = raw_data(i,3);
    k = k + 1;
    i = i + 1;
end

  data_pp = [flow_raw, pressure_in_raw, pressure_out_raw];

  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%

   c = length (data_pp);
    i = 1;
while i <= c
    if  data_pp(i,2) == 0;
    elseif data_pp(i,2) ~= 0;
        data_pp(i,13) = (data_pp(i,2)-data_pp(i,1));
    end
    i = i+1;
end
i = 1;
while i <= c
    if data_pp(i,13) > 0;
        data_pp(i,2) = 0;
        data_pp(i,4) = 0;
        data_pp(i,6) = 0;
    elseif data_pp(i,13) < 0;
```

```
        data_pp(i,2) = data_pp(i,1);

        data_pp(i,4) = data_pp(i,3);

        data_pp(i,6) = data_pp(i,5);

    end

    i = i+1;

end


data_pp = [data_pp(:,1),data_pp(:,3),data_pp(:,5)];


%Pressure Calibration Conversation


data_pp(:,2) = ((data_pp(:,2))*5)/400;

data_pp(:,3) = ((data_pp(:,3))*5)/250;


data_pp(:,2) = (80.10726842*data_pp(:,2)) - 1.00480866;

data_pp(:,3) = (52.89185068*data_pp(:,3)) - 6.033053362;


  A =[name,' = data_pp'];

  eval(A);

   clc

 clear raw_data raw_data flow_raw pressure_in_raw pressure_out_raw
data_pp


 var = var + 1;


end




%Water Temps
```

```
Temp_05_fall = 19.5;

Temp_05_rise = 19.5;


Temp_10_fall = 20.0;

Temp_10_rise = 20.0;


Temp_15_fall = 21.0;

Temp_15_rise = 21.0;


Temp_20_fall = 18.5;

Temp_20_rise = 18.5;


Temp_25_fall = 20.6;

Temp_25_rise = 20.6;


Temp_30_fall = 21.0;

Temp_30_rise = 21.0;


Temp_50_fall = 21.5;

Temp_50_rise = 21.5;


%Corresponding Densities;


Density_05_fall = (-0.004*(Temp_05_fall^2)+(0.001*Temp_05_fall)+1000);

Density_05_rise = (-0.004*(Temp_05_rise^2)+(0.001*Temp_05_rise)+1000);


Density_10_fall = (-0.004*(Temp_10_fall^2)+(0.001*Temp_10_fall)+1000);

Density_10_rise = (-0.004*(Temp_10_rise^2)+(0.001*Temp_10_rise)+1000);
```

```
Density_15_fall = (-0.004*(Temp_15_fall^2)+(0.001*Temp_15_fall)+1000);

Density_15_rise = (-0.004*(Temp_15_rise^2)+(0.001*Temp_15_rise)+1000);


Density_20_fall = (-0.004*(Temp_20_fall^2)+(0.001*Temp_20_fall)+1000);

Density_20_rise = (-0.004*(Temp_20_rise^2)+(0.001*Temp_20_rise)+1000);


Density_25_fall = (-0.004*(Temp_25_fall^2)+(0.001*Temp_25_fall)+1000);

Density_25_rise = (-0.004*(Temp_25_rise^2)+(0.001*Temp_25_rise)+1000);


Density_30_fall = (-0.004*(Temp_30_fall^2)+(0.001*Temp_30_fall)+1000);

Density_30_rise = (-0.004*(Temp_30_rise^2)+(0.001*Temp_30_rise)+1000);


Density_50_fall = (-0.004*(Temp_50_fall^2)+(0.001*Temp_50_fall)+1000);

Density_50_rise = (-0.004*(Temp_50_rise^2)+(0.001*Temp_50_rise)+1000);


%Converting pressure to heads and adding pressure transducer elevation

%offsets (415mm)


PT_offset = 0.415;


Pressure_in_05_F = ((Data_PP_05_Fall(:,2).*1000)./(g*Density_05_fall) +
PT_offset);

Pressure_in_05_R = ((Data_PP_05_Rise(:,2).*1000)./(g*Density_05_rise) +
PT_offset);

Pressure_out_05_F = ((Data_PP_05_Fall(:,3).*1000)./(g*Density_05_fall)
+ PT_offset);

Pressure_out_05_R = ((Data_PP_05_Rise(:,3).*1000)./(g*Density_05_rise)
+ PT_offset);
```

```
Pressure_in_10_F = ((Data_PP_10_Fall(:,2).*1000)./(g*Density_10_fall) +
PT_offset);

Pressure_in_10_R = ((Data_PP_10_Rise(:,2).*1000)./(g*Density_10_rise) +
PT_offset);

Pressure_out_10_F = ((Data_PP_10_Fall(:,3).*1000)./(g*Density_10_fall)
+ PT_offset);

Pressure_out_10_R = ((Data_PP_10_Rise(:,3).*1000)./(g*Density_10_rise)
+ PT_offset);



Pressure_in_15_F = ((Data_PP_15_Fall(:,2).*1000)./(g*Density_15_fall) +
PT_offset);

Pressure_in_15_R = ((Data_PP_15_Rise(:,2).*1000)./(g*Density_15_rise) +
PT_offset);

Pressure_out_15_F = ((Data_PP_15_Fall(:,3).*1000)./(g*Density_15_fall)
+ PT_offset);

Pressure_out_15_R = ((Data_PP_15_Rise(:,3).*1000)./(g*Density_15_rise)
+ PT_offset);



Pressure_in_20_F = ((Data_PP_20_Fall(:,2).*1000)./(g*Density_20_fall) +
PT_offset);

Pressure_in_20_R = ((Data_PP_20_Rise(:,2).*1000)./(g*Density_20_rise) +
PT_offset);

Pressure_out_20_F = ((Data_PP_20_Fall(:,3).*1000)./(g*Density_20_fall)
+ PT_offset);

Pressure_out_20_R = ((Data_PP_20_Rise(:,3).*1000)./(g*Density_20_rise)
+ PT_offset);



Pressure_in_25_F = ((Data_PP_25_Fall(:,2).*1000)./(g*Density_25_fall) +
PT_offset);

Pressure_in_25_R = ((Data_PP_25_Rise(:,2).*1000)./(g*Density_25_rise) +
PT_offset);

Pressure_out_25_F = ((Data_PP_25_Fall(:,3).*1000)./(g*Density_25_fall)
+ PT_offset);

Pressure_out_25_R = ((Data_PP_25_Rise(:,3).*1000)./(g*Density_25_rise)
+ PT_offset);
```

```
Pressure_in_30_F = ((Data_PP_30_Fall(:,2).*1000)./(g*Density_30_fall) +
PT_offset);

Pressure_in_30_R = ((Data_PP_30_Rise(:,2).*1000)./(g*Density_30_rise) +
PT_offset);

Pressure_out_30_F = ((Data_PP_30_Fall(:,3).*1000)./(g*Density_30_fall)
+ PT_offset);

Pressure_out_30_R = ((Data_PP_30_Rise(:,3).*1000)./(g*Density_30_rise)
+ PT_offset);



Pressure_in_50_F = ((Data_PP_50_Fall(:,2).*1000)./(g*Density_50_fall) +
PT_offset);

Pressure_in_50_R = ((Data_PP_50_Rise(:,2).*1000)./(g*Density_50_rise) +
PT_offset);

Pressure_out_50_F = ((Data_PP_50_Fall(:,3).*1000)./(g*Density_50_fall)
+ PT_offset);

Pressure_out_50_R = ((Data_PP_50_Rise(:,3).*1000)./(g*Density_50_rise)
+ PT_offset);



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Plotting%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%

 %Conversion



%PSI to kPa

 %1 - 6.894757

  %PSI to metres head

  % 1 - 0.70282945

  %10 PSI = 7.02829 m head

  a = [0,7.04321];

 b = [0,7.04321];

 c = [7.04321,0];

 d = [7.04321,7.04320];

 e = [7.04321, 15];

 f = [0,0.6];
```

```
  plot( Pressure_in_05_F(:,1), Pressure_out_05_F(:,1), 'red +',
Pressure_in_05_R(:,1), Pressure_out_05_R(:,1), 'bl +', a, b, 'k --',
c, d, 'k --', d, c, 'k --', e, d, 'k --');

xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

title('Flow - 0.05 L/s')

legend('0.05 L/s-Fall', '0.05 L/s-Rise')

grid on

figure

plot( Pressure_in_10_F(:,1), Pressure_out_10_F(:,1), 'red +',
Pressure_in_10_R(:,1), Pressure_out_10_R(:,1), 'bl +', a, b, 'k --',
c, d, 'k --', d, c, 'k --', e, d, 'k --');

xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

title('Flow - 0.10 L/s')

legend('0.10 L/s-Fall', '0.10 L/s-Rise')

grid on

figure

plot( Pressure_in_15_F(:,1), Pressure_out_15_F(:,1), 'red +',
Pressure_in_15_R(:,1), Pressure_out_15_R(:,1), 'bl +', a, b, 'k --',
c, d, 'k --', d, c, 'k --', e, d, 'k --');

xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

title('Flow - 0.15 L/s')

legend('0.15 L/s-Fall', '0.15 L/s-Rise')

grid on

figure

plot( Pressure_in_20_F(:,1), Pressure_out_20_F(:,1), 'red +',
Pressure_in_20_R(:,1), Pressure_out_20_R(:,1), 'bl +', a, b, 'k --',
c, d, 'k --', d, c, 'k --', e, d, 'k --');

xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

title('Flow - 0.20 L/s')
```

```
legend('0.20 L/s-Fall', '0.20 L/s-Rise')

grid on

figure

plot( Pressure_in_25_F(:,1), Pressure_out_25_F(:,1), 'red +',
Pressure_in_25_R(:,1), Pressure_out_25_R(:,1), 'bl +', a, b, 'k --',
c, d, 'k --', d, c, 'k --', e, d, 'k --');

xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

title('Flow - 0.25 L/s')

legend('0.25 L/s-Fall', '0.25 L/s-Rise')

grid on

figure

plot( Pressure_in_30_F(:,1), Pressure_out_30_F(:,1), 'red +',
Pressure_in_30_R(:,1), Pressure_out_30_R(:,1), 'bl +', a, b, 'k --',
c, d, 'k --', d, c, 'k --', e, d, 'k --');

xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

title('Flow - 0.30 L/s')

legend('0.30 L/s-Fall', '0.30 L/s-Rise')

grid on

 figure

plot( Pressure_in_50_F(:,1), Pressure_out_50_F(:,1), 'red +',
Pressure_in_50_R(:,1), Pressure_out_50_R(:,1), 'bl +', a, b, 'k --',
c, d, 'k --', d, c, 'k --', e, d, 'k --');

xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

title('Flow - 0.50 L/s')

legend('0.50 L/s-Fall', '0.50 L/s-Rise')

grid on

  % Rising Falling 2D Plot

 figure

plot(Pressure_in_05_F(:,1), Pressure_out_05_F(:,1), 'red +',...

    Pressure_in_05_R(:,1), Pressure_out_05_R(:,1), 'bl +',...
```

```
    Pressure_in_10_F(:,1), Pressure_out_10_F(:,1), 'red o',...

    Pressure_in_10_R(:,1), Pressure_out_10_R(:,1), 'bl o',...

    Pressure_in_15_F(:,1), Pressure_out_15_F(:,1), 'red *',...

    Pressure_in_15_R(:,1), Pressure_out_15_R(:,1), 'bl *',...

    Pressure_in_20_F(:,1), Pressure_out_20_F(:,1), 'red d',...

    Pressure_in_20_R(:,1), Pressure_out_20_R(:,1), 'bl d', ...

    Pressure_in_25_F(:,1), Pressure_out_25_F(:,1), 'red s',...

    Pressure_in_25_R(:,1), Pressure_out_25_R(:,1), 'bl s',...

    Pressure_in_30_F(:,1), Pressure_out_30_F(:,1), 'red >',...

    Pressure_in_30_R(:,1), Pressure_out_30_R(:,1), 'bl >',...

    Pressure_in_50_F(:,1), Pressure_out_50_F(:,1), 'red p',...

    Pressure_in_50_R(:,1), Pressure_out_50_R(:,1), 'bl p',...

    a, b, 'k --',   c, d, 'k --', d, c, 'k --', e, d, 'k --');


xlabel('Hpi Input Pressure Head (m)');

ylabel('Hpo Output Pressure Head (m)');

%title('All Discharges');

grid on

 legend('0.05 L/s-Fall', '0.05 L/s-Rise', '0.10 L/s-Fall',...

    '0.10 L/s-Rise','0.15 L/s-Fall', '0.15 L/s-Rise','0.20 L/s-
Fall',...

    '0.20 L/s-Rise','0.25 L/s-Fall', '0.25 L/s-Rise','0.30 L/s-
Fall',...

    '0.30 L/s-Rise', '0.50 L/s-Fall', '0.50 L/s-Rise',...

    'Location', 'SouthEast');




%%%%%%%%%%%%%Three Dimensional Plot%%%%%%%%%%%%%%%%%

  figure

 plot3 (Pressure_in_05_F(:,1),Data_PP_05_Fall(:,1) ,
Pressure_out_05_F(:,1), 'red +')
```

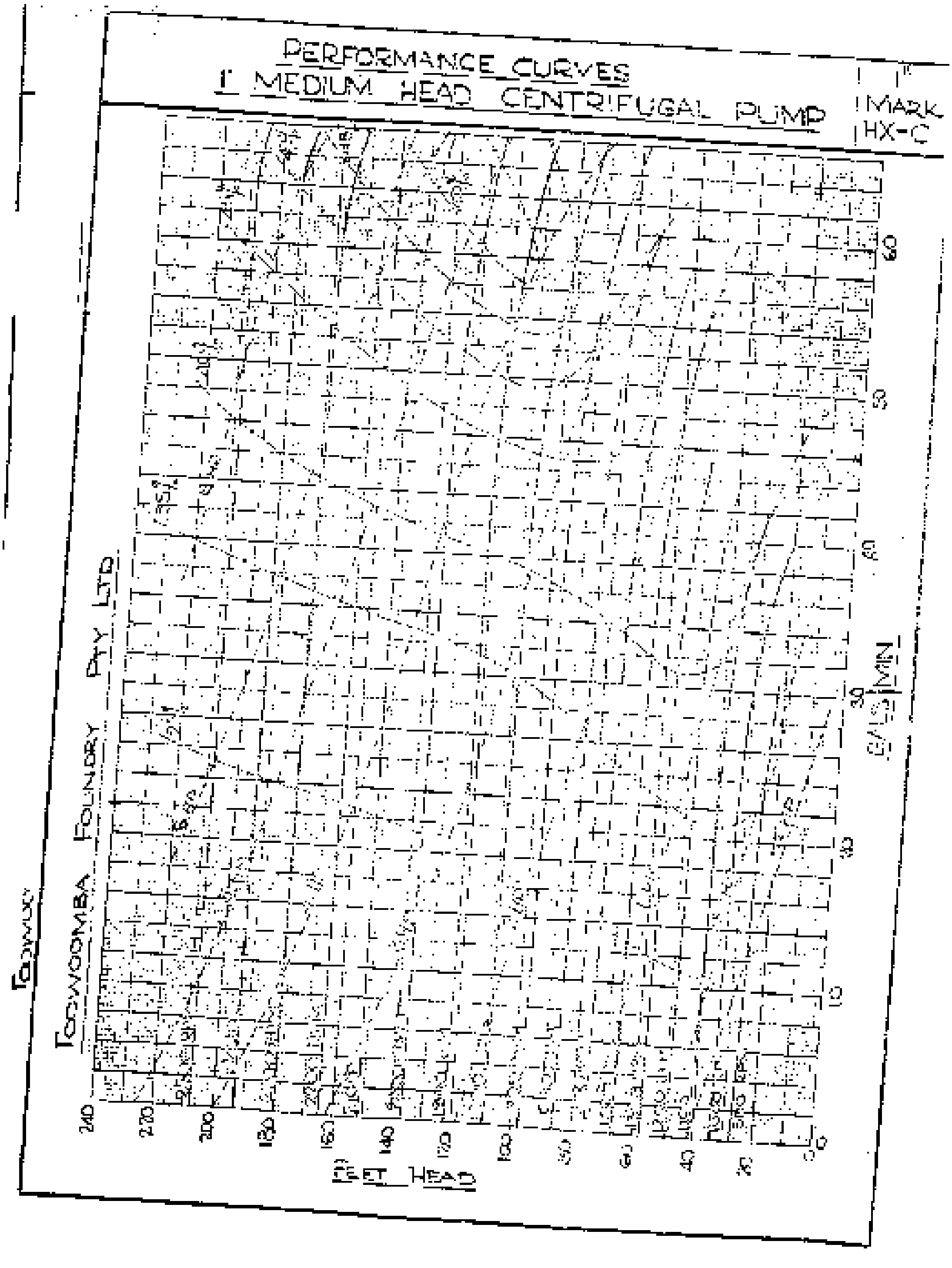
```
hold on

plot3 (Pressure_in_05_R(:,1),Data_PP_05_Rise(:,1) ,
Pressure_out_05_R(:,1), 'bl  +')

hold on

plot3 (Pressure_in_10_F(:,1),Data_PP_10_Fall(:,1) ,
Pressure_out_10_F(:,1), 'red x')

hold on

plot3 (Pressure_in_10_R(:,1),Data_PP_10_Rise(:,1) ,
Pressure_out_10_R(:,1), 'bl  x')

hold on

plot3 (Pressure_in_15_F(:,1),Data_PP_15_Fall(:,1) ,
Pressure_out_15_F(:,1), 'red o')

hold on

plot3 (Pressure_in_15_R(:,1),Data_PP_15_Rise(:,1) ,
Pressure_out_15_R(:,1), 'bl  o')

hold on

plot3 (Pressure_in_20_F(:,1),Data_PP_20_Fall(:,1) ,
Pressure_out_20_F(:,1), 'red s')

hold on

plot3 (Pressure_in_20_R(:,1),Data_PP_20_Rise(:,1) ,
Pressure_out_20_R(:,1), 'bl  s')

hold on

plot3 (Pressure_in_25_F(:,1),Data_PP_25_Fall(:,1) ,
Pressure_out_25_F(:,1), 'red *')

hold on

plot3 (Pressure_in_25_R(:,1),Data_PP_25_Rise(:,1) ,
Pressure_out_25_R(:,1), 'bl  *')

hold on

plot3 (Pressure_in_30_F(:,1),Data_PP_30_Fall(:,1) ,
Pressure_out_30_F(:,1), 'red d')

hold on

plot3 (Pressure_in_30_R(:,1),Data_PP_30_Rise(:,1) ,
Pressure_out_30_R(:,1), 'bl  d')

hold on
```

```
plot3 (Pressure_in_50_F(:,1),Data_PP_50_Fall(:,1) ,
Pressure_out_50_F(:,1), 'red o')

hold on

plot3 (Pressure_in_50_R(:,1),Data_PP_50_Rise(:,1) ,
Pressure_out_50_R(:,1), 'bl  o')

 grid on

 xlabel('Hpi Input Pressure Head (m)');

zlabel('Hpo Output Pressure Head (m)');

ylabel('Flow Rate (L/s)');

%title('All Discharges 3D plot');

grid on

 legend('0.05 L/s-Fall', '0.05 L/s-Rise', '0.10 L/s-Fall',...

    '0.10 L/s-Rise','0.15 L/s-Fall', '0.15 L/s-Rise','0.20 L/s-
Fall',...

    '0.20 L/s-Rise','0.25 L/s-Fall', '0.25 L/s-Rise','0.30 L/s-
Fall',...

    '0.30 L/s-Rise', '0.50 L/s-Fall', '0.50 L/s-Rise',...

    'Location', 'SouthEast');

 %legend('Falling (0.3 L/s)','Rising (0.3 L/s)','Falling (0.5 L/s)',
'Rising

%(0.5 L/s)');

  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 figure

 plot (Data_PP_05_Fall(:,1) , Pressure_out_05_F(:,1), 'red +')

hold on

plot (Data_PP_05_Rise(:,1) , Pressure_out_05_R(:,1), 'bl  +')

hold on

plot (Data_PP_10_Fall(:,1) , Pressure_out_10_F(:,1), 'red x')

hold on

plot (Data_PP_10_Rise(:,1) , Pressure_out_10_R(:,1), 'bl  x')

hold on

plot (Data_PP_15_Fall(:,1) , Pressure_out_15_F(:,1), 'red o')
```

```
hold on

plot (Data_PP_15_Rise(:,1) , Pressure_out_15_R(:,1), 'bl  o')

hold on

plot (Data_PP_20_Fall(:,1) , Pressure_out_20_F(:,1), 'red s')

hold on

plot (Data_PP_20_Rise(:,1) , Pressure_out_20_R(:,1), 'bl  s')

hold on

plot (Data_PP_25_Fall(:,1) , Pressure_out_25_F(:,1), 'red *')

hold on

plot (Data_PP_25_Rise(:,1) , Pressure_out_25_R(:,1), 'bl  *')

hold on

plot (Data_PP_30_Fall(:,1) , Pressure_out_30_F(:,1), 'red d')

hold on

plot (Data_PP_30_Rise(:,1) , Pressure_out_30_R(:,1), 'bl  d')

hold on

plot (Data_PP_50_Fall(:,1) , Pressure_out_50_F(:,1), 'red o')

hold on

plot (Data_PP_50_Rise(:,1) , Pressure_out_50_R(:,1), 'bl  o')

%plot (c, d, 'k --', f, d, 'k --');

plot (f, d, 'k --', 'LineWidth',2);

grid on


ylabel('Hpo Output Pressure Head (m)','FontSize',14);

xlabel('Flow Rate (L/s)','FontSize',14);

%title('All Discharges 3D plot');

grid on

 legend('0.05 L/s-Fall', '0.05 L/s-Rise', '0.10 L/s-Fall',...

    '0.10 L/s-Rise','0.15 L/s-Fall', '0.15 L/s-Rise','0.20 L/s-
Fall',...

    '0.20 L/s-Rise','0.25 L/s-Fall', '0.25 L/s-Rise','0.30 L/s-
Fall',...
```

```
    '0.30 L/s-Rise', '0.50 L/s-Fall', '0.50 L/s-Rise',...
    'Location', 'SouthEast');


%EOF
```

Appendix I Southern Cross Pump Curve HX-C Pump’s performance curve


PERFORMANCE CURVES
1" MEDIUM HEAD CENTRIFUGAL PUMP
MARK HX-C
TOOWOOMBA FOUNDRY PTY LTD
FEET HEAD
240
220
200
180
160
140
120
100
80
60
40
20
0
GALS/MIN
0
10
20
30
40
50
60

Appendix J Labview output for Stage Three-Automatic data acquisition tests with higher heads for discharges of 0.3 and 0.6 L/s

Output for 0.3 L/s

```
%PT Offset: Add 0.415m head of water to Inlet and Outlet Pressure Data
%Flow Data in L/s
%Pressure Data in kPa
%Nozzle: No Nozzle
%PR: NL10-1
%Water Temp Inital test 26.0 'C
%Water Temp End Test  'C
%%%%%%%%%%%%%FALLING%%%%%%%%%%%%%%%%%%%%%%%%
19/01/2011
9:58:47 AM
Flow,Inlet Pressure,Outlet Pressure
0.299459,360.420288,64.657028
0.299980,360.782593,64.75788919/01/2011
10:16:03 AM
Flow,Inlet Pressure,Outlet Pressure
0.301857,395.809265,63.216640
0.302337,396.309723,63.337753
19/01/2011
10:18:52 AM
Flow,Inlet Pressure,Outlet Pressure
0.299499,362.794983,62.266376
0.299140,363.005615,62.235188
19/01/2011
10:20:45 AM
Flow,Inlet Pressure,Outlet Pressure
0.300900,356.193970,58.195953
```

```
0.300948,355.074036,57.629280
19/01/2011
10:21:25 AM
Flow,Inlet Pressure,Outlet Pressure
0.299716,350.880096,57.412979
0.299953,351.520416,57.622799
19/01/2011
10:22:03 AM
Flow,Inlet Pressure,Outlet Pressure
0.300521,333.616364,56.607723
19/01/2011
10:22:45 AM
Flow,Inlet Pressure,Outlet Pressure
0.300508,321.338593,55.927227
19/01/2011
10:23:50 AM
Flow,Inlet Pressure,Outlet Pressure
0.300109,311.003845,57.688416
19/01/2011
10:24:27 AM
Flow,Inlet Pressure,Outlet Pressure
0.299169,297.082520,56.001759
0.299014,296.503113,55.648548
19/01/2011
10:25:14 AM
Flow,Inlet Pressure,Outlet Pressure
0.299993,278.201233,57.435257
```

```
0.299552,279.287476,57.873123
19/01/2011
10:25:58 AM
Flow,Inlet Pressure,Outlet Pressure
0.299448,258.726349,55.992847
19/01/2011
10:27:38 AM
Flow,Inlet Pressure,Outlet Pressure
0.298819,242.842651,59.791069
19/01/2011
10:28:46 AM
Flow,Inlet Pressure,Outlet Pressure
0.301526,220.650360,58.771946
0.300698,220.083282,58.485569
19/01/2011
10:29:55 AM
Flow,Inlet Pressure,Outlet Pressure
0.301197,186.246674,55.951530
0.301620,185.049637,55.953152
19/01/2011
10:31:28 AM
Flow,Inlet Pressure,Outlet Pressure
0.299207,102.129135,56.605293
19/01/2011
10:32:12 AM
Flow,Inlet Pressure,Outlet Pressure
0.299140,131.796249,60.085953
```

```
19/01/2011
10:33:06 AM
Flow,Inlet Pressure,Outlet Pressure
0.299526,112.342422,55.606827
0.299774,113.083839,56.254108
19/01/2011
10:34:37 AM
Flow,Inlet Pressure,Outlet Pressure
0.298830,152.301956,61.707397
0.298529,152.704437,61.993771
19/01/2011
10:35:26 AM
Flow,Inlet Pressure,Outlet Pressure
0.299311,179.973083,64.462601
19/01/2011
10:36:08 AM
Flow,Inlet Pressure,Outlet Pressure
0.300631,190.758728,56.233452
19/01/2011
10:37:22 AM
Flow,Inlet Pressure,Outlet Pressure
0.299495,126.505203,56.817947
0.299521,126.130608,57.179665
19/01/2011
10:37:53 AM
Flow,Inlet Pressure,Outlet Pressure
0.300244,61.474384,53.942448
```

```
19/01/2011

10:38:22 AM

Flow,Inlet Pressure,Outlet Pressure

0.298669,121.909576,58.906017

19/01/2011

10:39:19 AM

Flow,Inlet Pressure,Outlet Pressure

0.300153,90.471260,58.569012

19/01/2011

10:39:49 AM

Flow,Inlet Pressure,Outlet Pressure

0.298469,57.222267,51.161732

0.298859,57.243008,51.237885

%%%%%%%%%%%RISING%%%%%%%%%%%%

19/01/2011

9:29:57 AM

Flow,Inlet Pressure,Outlet Pressure

0.302131,79.617676,64.120728

0.302364,80.188644,64.603966

19/01/2011

9:30:54 AM

Flow,Inlet Pressure,Outlet Pressure

0.300714,56.623432,50.300175

0.300024,56.701851,50.181496

19/01/2011

9:33:32 AM

Flow,Inlet Pressure,Outlet Pressure
```

```
0.300220,71.999367,62.025772
0.300685,72.125099,61.922482
19/01/2011
9:34:24 AM
Flow,Inlet Pressure,Outlet Pressure
0.299535,93.576912,65.567192
0.300186,93.427200,65.063705
19/01/2011
9:35:08 AM
Flow,Inlet Pressure,Outlet Pressure
0.298354,122.407959,66.527580
19/01/2011
9:36:17 AM
Flow,Inlet Pressure,Outlet Pressure
0.300007,137.412628,67.595718
0.299397,138.260330,67.878853
19/01/2011
9:37:37 AM
Flow,Inlet Pressure,Outlet Pressure
0.299830,145.046539,67.269241
0.299229,145.217636,66.990562
19/01/2011
9:39:28 AM
Flow,Inlet Pressure,Outlet Pressure
0.301992,150.664871,67.505394
0.302348,150.158707,67.191071
19/01/2011
```

```
9:41:11 AM
Flow,Inlet Pressure,Outlet Pressure
0.301502,160.460846,66.434013
0.301276,160.828964,66.314926
19/01/2011
9:42:44 AM
Flow,Inlet Pressure,Outlet Pressure
0.298407,176.658066,68.146599
19/01/2011
9:43:54 AM
Flow,Inlet Pressure,Outlet Pressure
0.301376,175.387146,62.551132
19/01/2011
9:44:19 AM
Flow,Inlet Pressure,Outlet Pressure
0.301300,185.128052,66.207588
0.300339,185.107315,65.924454
19/01/2011
9:46:45 AM
Flow,Inlet Pressure,Outlet Pressure
0.299900,227.194885,65.262589
19/01/2011
9:47:22 AM
Flow,Inlet Pressure,Outlet Pressure
0.299892,248.917313,68.724617
19/01/2011
9:48:55 AM
```

```
Flow,Inlet Pressure,Outlet Pressure
0.299987,276.878448,68.046547
19/01/2011
9:50:38 AM
Flow,Inlet Pressure,Outlet Pressure
0.301389,305.087280,68.629829
19/01/2011
9:51:08 AM
Flow,Inlet Pressure,Outlet Pressure
0.298842,333.538605,69.175850
0.298485,334.144592,69.286026
19/01/2011
9:52:40 AM
Flow,Inlet Pressure,Outlet Pressure
0.300778,338.276917,67.850906
0.300279,337.613251,67.639870
19/01/2011
9:53:08 AM
Flow,Inlet Pressure,Outlet Pressure
0.300430,349.855438,69.602783
0.300951,350.250793,69.855942
19/01/2011
9:53:46 AM
Flow,Inlet Pressure,Outlet Pressure
0.300771,369.961823,68.746490
0.300809,369.644897,68.771606
```

Output for 0.6 L/s

```
%PT Offset: Add 0.415m head of water to Inlet and Outlet Pressure Data
%Flow Data in L/s
%Pressure Data in kPa
%Nozzle: No Nozzle
%PR: NL10-1
%Water Temp Inital test 23.0 'C
%Water Temp End Test 25.0 'C
%%%%%%%%%%%%FALLING%%%%%%%%%%%%%%
16/12/2010
8:16:23 AM
Flow,Inlet Pressure,Outlet Pressure
0.600000,319.580261,55.777763
0.600003,318.547821,55.883076
16/12/2010
8:17:44 AM
Flow,Inlet Pressure,Outlet Pressure
0.602484,271.770081,56.374413
0.602943,270.617126,55.926823
16/12/2010
8:19:01 AM
Flow,Inlet Pressure,Outlet Pressure
0.601781,245.468109,58.678783
0.602240,245.757812,58.424404
16/12/2010
8:19:47 AM
Flow,Inlet Pressure,Outlet Pressure
```

```
0.600144,217.824005,56.753139
16/12/2010
8:20:53 AM
Flow,Inlet Pressure,Outlet Pressure
0.600692,192.913666,56.656330
0.601287,192.998566,56.706558
16/12/2010
8:21:56 AM
Flow,Inlet Pressure,Outlet Pressure
0.599285,136.677689,56.273552
16/12/2010
8:22:31 AM
Flow,Inlet Pressure,Outlet Pressure
0.599014,81.209381,51.763645
16/12/2010
8:23:16 AM
Flow,Inlet Pressure,Outlet Pressure
0.598667,68.444595,40.966053
16/12/2010
8:24:27 AM
Flow,Inlet Pressure,Outlet Pressure
0.599267,81.610550,53.263573
16/12/2010
8:28:26 AM
Flow,Inlet Pressure,Outlet Pressure
0.599910,399.979797,56.551422
0.599974,399.914337,56.250465
```

```
16/12/2010
8:31:20 AM
Flow,Inlet Pressure,Outlet Pressure
0.600463,396.638794,54.823448
16/12/2010
8:33:36 AM
Flow,Inlet Pressure,Outlet Pressure
0.600568,389.032593,59.580845
16/12/2010
8:35:41 AM
Flow,Inlet Pressure,Outlet Pressure
0.600619,369.782928,53.767868
16/12/2010
8:36:49 AM
Flow,Inlet Pressure,Outlet Pressure
0.601225,358.014496,54.582844
0.602074,357.942566,54.651299
16/12/2010
8:37:37 AM
Flow,Inlet Pressure,Outlet Pressure
0.602865,342.188263,54.238544
16/12/2010
8:40:05 AM
Flow,Inlet Pressure,Outlet Pressure
0.603392,318.682648,55.251999
16/12/2010
8:41:45 AM
```

```
Flow,Inlet Pressure,Outlet Pressure
0.601904,277.623779,53.717236
16/12/2010
8:43:05 AM
Flow,Inlet Pressure,Outlet Pressure
0.603241,234.732300,54.459705
16/12/2010
8:44:18 AM
Flow,Inlet Pressure,Outlet Pressure
0.600379,202.068054,55.052303
16/12/2010
8:45:16 AM
Flow,Inlet Pressure,Outlet Pressure
0.602595,138.605118,55.856747
16/12/2010
8:45:37 AM
Flow,Inlet Pressure,Outlet Pressure
0.600346,97.270386,53.578709
16/12/2010
8:46:43 AM
Flow,Inlet Pressure,Outlet Pressure
0.609371,114.103943,55.466679
16/12/2010
8:48:01 AM
Flow,Inlet Pressure,Outlet Pressure
0.603035,108.009277,54.926331
16/12/2010
```

```
8:48:35 AM

Flow,Inlet Pressure,Outlet Pressure

0.601090,67.545692,40.377911

16/12/2010

8:51:15 AM

Flow,Inlet Pressure,Outlet Pressure

0.598705,391.251740,59.823071

%%%%%%%%%%%%%%%%%%%%%%RISING%%%%%%%%%%%%%%%%%%%%%%%%%%

16/12/2010

8:57:05 AM

Flow,Inlet Pressure,Outlet Pressure

0.599256,383.763397,61.786381

16/12/2010

8:57:40 AM

Flow,Inlet Pressure,Outlet Pressure

0.599398,375.866791,61.924911

16/12/2010

8:59:28 AM

Flow,Inlet Pressure,Outlet Pressure

0.599017,374.680725,62.527637

16/12/2010

9:00:40 AM

Flow,Inlet Pressure,Outlet Pressure

0.600191,364.478149,61.016369

16/12/2010

9:01:18 AM
```

```
Flow,Inlet Pressure,Outlet Pressure
0.598811,354.396088,63.030315
16/12/2010
9:02:45 AM
Flow,Inlet Pressure,Outlet Pressure
0.599294,337.568542,63.215832
16/12/2010
9:04:41 AM
Flow,Inlet Pressure,Outlet Pressure
0.600029,311.274109,63.027477
16/12/2010
9:05:22 AM
Flow,Inlet Pressure,Outlet Pressure
0.599781,299.593933,62.849659
0.598563,298.543335,62.736244
16/12/2010
9:05:52 AM
Flow,Inlet Pressure,Outlet Pressure
0.599108,280.987457,64.066452
16/12/2010
9:06:46 AM
Flow,Inlet Pressure,Outlet Pressure
0.599174,255.431396,63.392029
16/12/2010
9:08:20 AM
Flow,Inlet Pressure,Outlet Pressure
0.600053,228.974579,64.039719
```

```
16/12/2010
9:09:31 AM
Flow,Inlet Pressure,Outlet Pressure
0.599189,187.829971,64.484879
16/12/2010
9:10:10 AM
Flow,Inlet Pressure,Outlet Pressure
0.601112,103.313194,61.712662
16/12/2010
9:11:13 AM
Flow,Inlet Pressure,Outlet Pressure
0.595778,136.428818,64.167313
16/12/2010
9:11:35 AM
Flow,Inlet Pressure,Outlet Pressure
0.600568,71.136108,43.639423
16/12/2010
9:13:13 AM
Flow,Inlet Pressure,Outlet Pressure
0.600523,101.627510,62.115696
16/12/2010
9:14:12 AM
Flow,Inlet Pressure,Outlet Pressure
0.599048,159.005859,63.413094
16/12/2010
9:15:57 AM
Flow,Inlet Pressure,Outlet Pressure
```

```
0.596781,268.638458,63.596180
16/12/2010
9:17:18 AM
Flow,Inlet Pressure,Outlet Pressure
0.598988,301.804626,63.197601
0.597923,295.660553,59.954716
16/12/2010
9:17:49 AM
Flow,Inlet Pressure,Outlet Pressure
0.597962,329.889740,63.551220
16/12/2010
9:18:23 AM
Flow,Inlet Pressure,Outlet Pressure
0.600085,356.397461,63.596584
```

Appendix K Statistical Table – values of F for 5% significance level

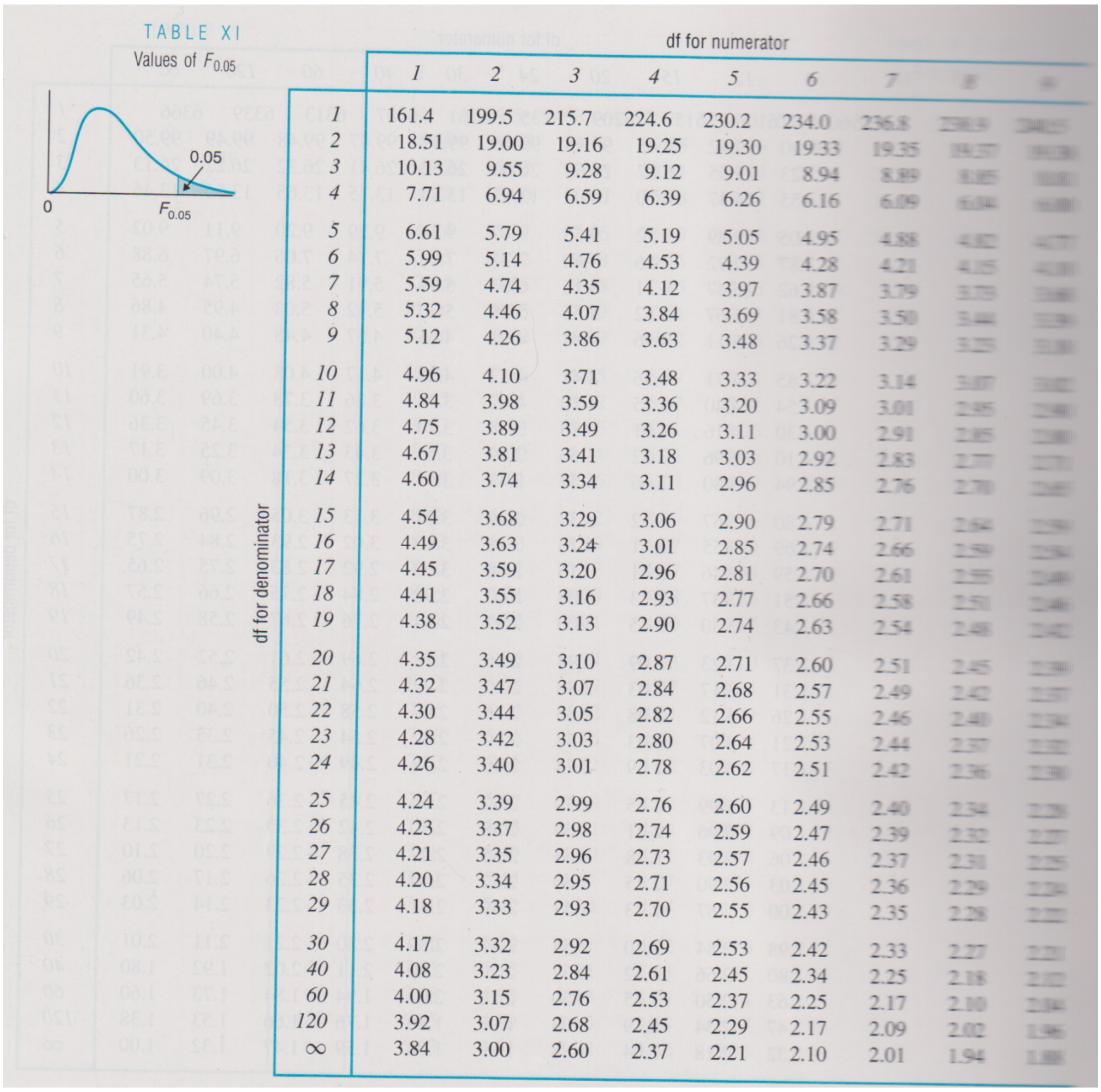


TABLE XI

Values of $F_{0.05}$

	df for numerator								
df for denominator	1	2	3	4	5	6	7	8	9
1	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42
20	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37
22	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30
25	4.24	3.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27
27	4.21	3.35	2.96	2.73	2.57	2.46	2.37	2.31	2.25
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21
40	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04
120	3.92	3.07	2.68	2.45	2.29	2.17	2.09	2.02	1.96
∞	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88

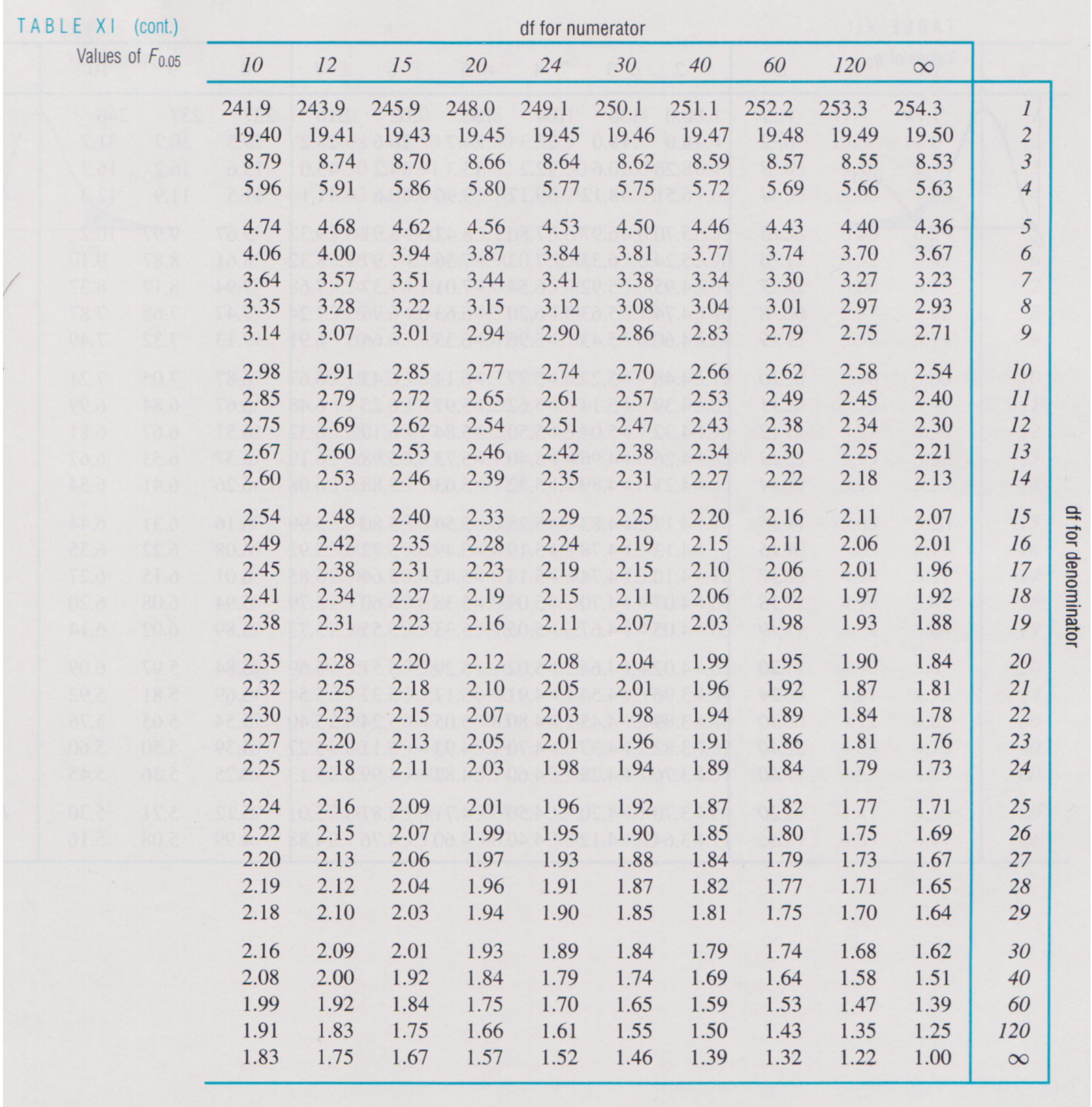


TABLE XI (cont.)

Values of $F_{0.05}$

df for numerator										
10	12	15	20	24	30	40	60	120	∞	df for denominator
241.9	243.9	245.9	248.0	249.1	250.1	251.1	252.2	253.3	254.3	1
19.40	19.41	19.43	19.45	19.45	19.46	19.47	19.48	19.49	19.50	2
8.79	8.74	8.70	8.66	8.64	8.62	8.59	8.57	8.55	8.53	3
5.96	5.91	5.86	5.80	5.77	5.75	5.72	5.69	5.66	5.63	4
4.74	4.68	4.62	4.56	4.53	4.50	4.46	4.43	4.40	4.36	5
4.06	4.00	3.94	3.87	3.84	3.81	3.77	3.74	3.70	3.67	6
3.64	3.57	3.51	3.44	3.41	3.38	3.34	3.30	3.27	3.23	7
3.35	3.28	3.22	3.15	3.12	3.08	3.04	3.01	2.97	2.93	8
3.14	3.07	3.01	2.94	2.90	2.86	2.83	2.79	2.75	2.71	9
2.98	2.91	2.85	2.77	2.74	2.70	2.66	2.62	2.58	2.54	10
2.85	2.79	2.72	2.65	2.61	2.57	2.53	2.49	2.45	2.40	11
2.75	2.69	2.62	2.54	2.51	2.47	2.43	2.38	2.34	2.30	12
2.67	2.60	2.53	2.46	2.42	2.38	2.34	2.30	2.25	2.21	13
2.60	2.53	2.46	2.39	2.35	2.31	2.27	2.22	2.18	2.13	14
2.54	2.48	2.40	2.33	2.29	2.25	2.20	2.16	2.11	2.07	15
2.49	2.42	2.35	2.28	2.24	2.19	2.15	2.11	2.06	2.01	16
2.45	2.38	2.31	2.23	2.19	2.15	2.10	2.06	2.01	1.96	17
2.41	2.34	2.27	2.19	2.15	2.11	2.06	2.02	1.97	1.92	18
2.38	2.31	2.23	2.16	2.11	2.07	2.03	1.98	1.93	1.88	19
2.35	2.28	2.20	2.12	2.08	2.04	1.99	1.95	1.90	1.84	20
2.32	2.25	2.18	2.10	2.05	2.01	1.96	1.92	1.87	1.81	21
2.30	2.23	2.15	2.07	2.03	1.98	1.94	1.89	1.84	1.78	22
2.27	2.20	2.13	2.05	2.01	1.96	1.91	1.86	1.81	1.76	23
2.25	2.18	2.11	2.03	1.98	1.94	1.89	1.84	1.79	1.73	24
2.24	2.16	2.09	2.01	1.96	1.92	1.87	1.82	1.77	1.71	25
2.22	2.15	2.07	1.99	1.95	1.90	1.85	1.80	1.75	1.69	26
2.20	2.13	2.06	1.97	1.93	1.88	1.84	1.79	1.73	1.67	27
2.19	2.12	2.04	1.96	1.91	1.87	1.82	1.77	1.71	1.65	28
2.18	2.10	2.03	1.94	1.90	1.85	1.81	1.75	1.70	1.64	29
2.16	2.09	2.01	1.93	1.89	1.84	1.79	1.74	1.68	1.62	30
2.08	2.00	1.92	1.84	1.79	1.74	1.69	1.64	1.58	1.51	40
1.99	1.92	1.84	1.75	1.70	1.65	1.59	1.53	1.47	1.39	60
1.91	1.83	1.75	1.66	1.61	1.55	1.50	1.43	1.35	1.25	120
1.83	1.75	1.67	1.57	1.52	1.46	1.39	1.32	1.22	1.00	∞