Design and Development of a Radial Vortex Flow Control Device

By

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Preface

Declaration / Acknowledgements

Declaration

I hereby certify that this material, which I now submit for assessment on the program of study leading to the award of Master of Engineering is entirely my own work, except where otherwise stated, and has not been submitted in whole or part to any other university.

Date: 20 / 06 / 2008

Signed …………………………………………

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Abstract

There has been a noticeable increase in flooding throughout Ireland in recent years, this is due to global climate change and increased urban development not allowing rainwater soak into the ground as it once did. This rainwater is then piped to the nearest watercourse or storm drain contributing to flooding during periods of heavy rainfall.

This project looks at the design, development and testing of a radial vortex flow control device which is use to limit the rate the rainwater leaves a particular site or development so as to help minimize downstream flooding.

A number of design concepts were developed along with a test rig to test the performance of the final design and investigate the influence of changing geometric variables had on the performance characteristics of the device. Two models were built to predict the geometric size of the unit under a given specification. An investigation was carried out to determine if computational fluid dynamics could be used to simulate the flow the vortex valve.

1.1 Introduction

Over the past ten to fifteen years the Irish landscape has changed radically with the Celtic Tiger transforming thousands of acres of green fields into developed sites for either residential, industrial or commercial use. A large percentage of these developments are adjacent to many of our villages, towns and cities changing their landscape dramatically.

Once a site is developed a huge amount of ground becomes impermeable preventing the rainwater soaking into the soil as would have happened pre development. Historically this water is collected in gullies and piped to the nearest water course or storm drain. The building boom coupled with global climate change has seen a huge amount of storm water runoff piped directly to the watercourse or storm drain which has caused conventional systems to become overloaded contributing to large scale flooding in many regional villages, towns and cities [1].

Local authorities now require a storm water management system be installed on each new development to limit the amount of storm water runoff, to that of a pre development rate as outlined in the greater Dublin strategic drainage survey [2]. This is achieved by slowing down or attenuating the water as it leaves the site and enters the storm drain or water course. A large tank (usually underground) stores the excess water during a rain storm while a flow control device limits the discharge to a pre development level.

The most effective and widely used flow control device is a vortex flow control device [3] which limits the discharge rate as a function of head i.e. height of water in the tank. One of the main reasons this type of flow control device is so popular is that the orifice opening is 3-6 times the cross sectional area of a conventional orifice plate. The unit has no moving parts and controls the flow through its geometrical relationships so therefore each unit is customized to site specific conditions based on flow rate and head height [3].

This project looks at the design and development of a radial vortex flow control device and aims to 1) Improve the method of installation 2) Investigate the geometrical relationships 3) Build a model that predicts the performance curve and geometric size for a given specification and 4) Investigate if Computational Fluid Dynamics (CFD) can be used to simulate flow through the vortex valve based on experimental results.

1.2 Flooding

Flooding has become a major problem in Ireland over the last number of years [1] with many towns and villages being flooded during periods of heavy rainfall. This flooding can be mainly attributed to two things;

- Increased urban development
- Global climate change

Irelands Celtic tiger economy has seen a considerable increase in the building industry and in particular urban development. This urban development has transformed green field sites into large residential, industrial and commercial facilities.

In the past, heavy rainstorms on these green field sites infiltrated into the ground as nature intended. But with increased urban development this process was interrupted, heavy rainstorms could no longer infiltrate into the ground because of impermeable materials such as concrete, tarmac, asphalt, roofs, etc.

Instead all the stormwater generated from these surfaces was piped to the nearest water course (river) or storm drain. This increased runoff coupled with global climate change has led to increased flooding due to conventional storm water drainage systems being overloaded. An example of such flooding can be seen below when the river Slaney in Enniscorthy burst it’s banks in 2003 after extremely heavy rainfall.

Figure 1.1 - Flooding in Enniscorthy, Co. Wexford (Courtesy of the OPW)

1.3 Sustainable Urban Drainage System (SuDS)

Sustainable Urban Drainage Systems (SuDS) is a direct response to the problem of flash flooding and is defined by the Construction Industry Research and Information Association (CIRIA) as “a sequence of management practices and control structures designed to drain surface water in a more sustainable fashion than some conventional techniques”. These techniques are as applicable to rural settings as they are to urban areas. [4]

Using SuDS techniques, water is either infiltrated or conveyed more slowly to water courses via ponds, swales, infiltration systems, attenuation tanks or other installations to try and closely mimic natural catchment drainage behaviour. Run off is frequently delayed in natural ponds or hollows. In addition to delaying the rate of runoff, there is more likelihood in the natural situation that pollutants will be filtered through soils or broken down by bacteria. By mimicking this, SuDS attenuates stormwater runoff and improves environmental performance [4].

There are eight main methods by which a Sustainable Urban Drainage System may be implemented [4].

- Permeable Pavements - Use of porous asphalt, porous paving or similar concepts to reduce imperviousness thus minimising runoff. Runoff infiltrates to a stone reservoir where some breakdown of pollutants occurs before controlled discharge to a drain or watercourse or direct infiltration.
- Filter Drains - A gravel filled trench, generally with a perforated pipe at the base which conveys runoff to a drain or watercourse. These provide attenuation and trap sediments.
- Infiltration Trenches/ Soak-away - Gravel or specially engineered trenches designed to store runoff while letting it infiltrate slowly to the ground. These provide treatment of runoff through filtration, absorption and microbial decomposition.
- Bio-Retention - These devices are depressions back filled with sand and soil and planted with native vegetation. They provide filtration, settlement and some infiltration. Typically under drained with remaining runoff piped back to the drainage system or watercourse.
- Swales - Grass lined channels designed to convey water to infiltration or a watercourse. Delays runoff and traps pollutants via infiltration for filtering effects of vegetation.

- Detention Basins - Dry vegetated depressions which impound stormwater during an event and gradually release it. Mostly for volume control but some pollutant removal is achieved via settlement of suspended solids and some infiltration.
- Retention Ponds - Permanent water bodies which store excess water for long periods allowing particle settlement and biological treatment. Very effective for pollutant removal but limited to larger developments. Have high habitat and aesthetic benefits.
- Attenuation Tanks – Underground storage tanks on site, either of concrete or modular plastic construction. These tanks store the excess runoff during a rainstorm event and release it into the local storm drain or water course at a controlled rate through the use of a flow control device.

A lot of the above methods are designed for above ground use, because of this a large area of land is required for their operation. Unfortunately urban development does not allow for such structures to be put in place in many situations and developers will not use such land hungry methods of SuDS. Because of this the most common approach is sub surface (underground) attenuation / infiltration tanks where the ground above the structure can be used for car parking, amenity area etc.

1.4 Infiltration / Soakaway

Infiltration devices are the first option which should be considered for stormwater disposal. Only if infiltration is not practical should runoff be disposed of to a watercourse or sewer. Infiltration allows runoff to be dealt with at source and mimics the natural process of groundwater recharge. Being buried, the systems often require little or no additional land take [3].

Infiltration systems are only effective in certain soil types and groundwater levels. They should only be installed if they will not put groundwater quality and ground stability at risk. Runoff which is likely to be heavily contaminated should not be disposed of by infiltration. Land use above and around the devices may need to be restricted to allow maintenance and prevent structural damage [3].

1.5 Storage and Attenuation

In situations where infiltration is not suitable due to ground conditions, attenuation storage will still allow the control of peak storm water. Storage allows surface water discharge from a developed site to mimic run off in its undeveloped state. A range of options are available and this choice will be influenced by a number of factors including drainage depth, ground water level, site topography, site usage (car park or building) and space available [3].

All systems require provision of some form of flow control device to mobilize the storage except where the run off restriction is not onerous or where discharge to natural ground to replenish the ground water table is feasible. In all cases the site condition and constraints, as well as discharge licenses stipulated by regulating body, must be properly understood before the preferred system can be specified [3].

All of the systems are relatively easy to maintain, although certain modular systems and in situ tanks could allow silt to enter and may be more difficult to clean than conventional piped systems. Some modular systems recommend putting a large silt collection device upstream of the storage facility to catch the silt before it reaches the tank.

1.6 Storm Water Flow Control Devices

There are a number of flow control devices that will regulate or control stormwater from a storage or attenuation system. The operation of a number of devices are detailed below with the advantages and disadvantages of each being outlined.

1.6.1 Orifice Plate

An orifice plate is the simplest type of flow control device which controls the rate of fluid flow. It states that "there is a relationship between the pressure of the fluid and the velocity of the fluid - velocity increases, the pressure decreases and vice versa". This principle is based on Bernoulli's equation and is one of the oldest types of flow control devices. An orifice plate is a thin plate with a hole in the middle. It is usually placed in a pipe in which fluid flows [5].

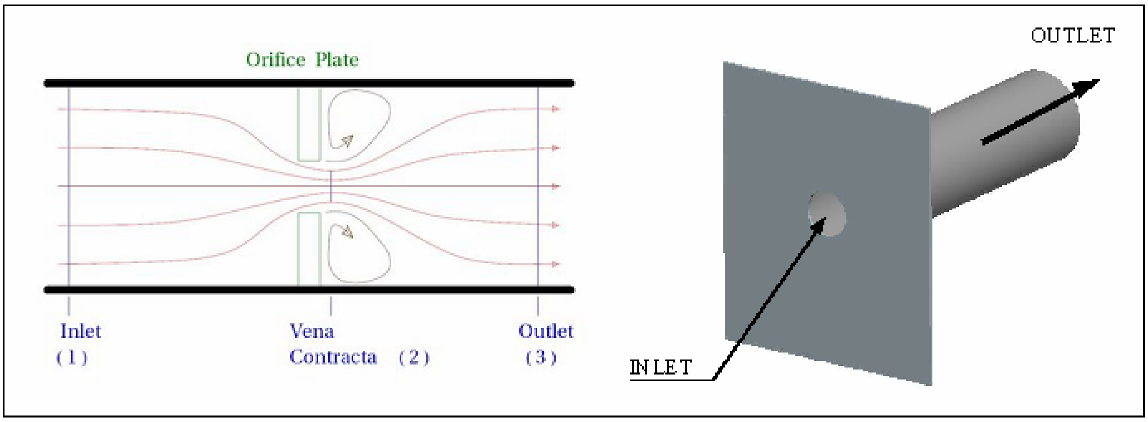

Figure 1.2 - Orifice Plate (Courtesy of Efunda)

As fluid flows through the pipe it has a certain velocity (which we want to measure) and a certain pressure (which is quite easily measured). When the fluid reaches the orifice plate, with the hole in the middle, the fluid is forced to converge and go through the small hole; the point of maximum convergence is actually just after the physical orifice, at the so-called "vena contracta" point (see figure 1.2). As it does so, the velocity and the pressure changes. By measuring the difference in fluid pressure between the normal pipe section and at the vena contracta, we can find the velocity of the fluid flow by applying Bernoulli's equation [5].

Advantages

- Inexpensive
- Simple calculation to determine orifice diameter

Disadvantages

- Prone to blockages due to small orifice diameter
- Increases storage requirements when compared with other flow control devices

1.6.2 Flow Valve

The flow valve was developed in the late 1970's in Sweden as a device for holding the outflow from a detention facility constant. The flow control device is essentially a central outlet pipe surrounded by a pressure chamber filled with air as shown in figure 1.3. The top part of the pressure chamber and its connection to the central outlet pipe are made of flexible rubber fabric; the rubber fabric is braced at the inlet and outlet of the centre pipe [6].

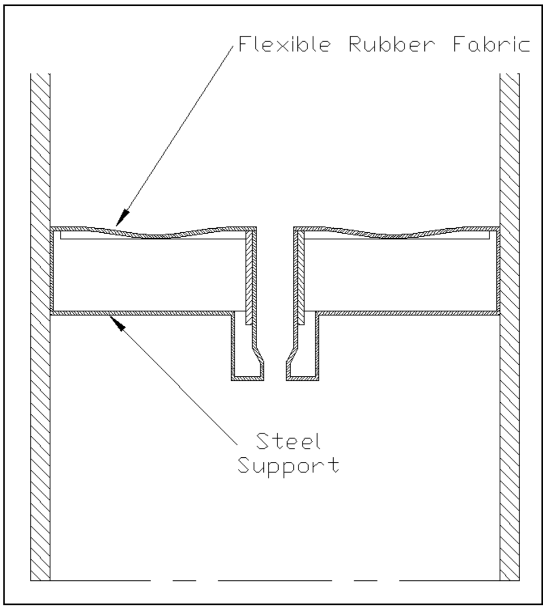

Figure 1.3 - Flow Valve

Water pressure on the upper portion of the rubber fabric is propagated through the pressure chamber displacing the fabric at the outlet section. Thus, the hydraulic capacity of the outlet is throttled by the change in cross sectional area. The resultant effect is that the discharge through the flow valve remains constant and independent of pressure [6].

Advantages

- Discharge independent of pressure

Disadvantages

- Prone to blockages due to small orifice diameter
- Expensive
- Not commonly used

1.6.3 Steinscruv Flow Regulator

The Steinscruv flow regulator was developed in Sweden in the mid-1970s for temporarily impounding flow in pipelines. The flow regulator consists of a stationary, anchored screw shaped plate that is turned through 270° and installed in a pipe, as shown in figure 1.4 below [6].

In the part of the plate which fits against the bottom of the pipeline, there is an opening to release a certain specified base flow. The opening is sized so that the flow that passes through the regulator is sufficient to maintain the self cleansing velocity of the pipeline.

Damming takes place when the inflow to the regulator exceeds the capacity of the base opening. The extent of this damming and the volume detained are dependent on the slope of the pipe. When the flow depth reaches the crown of the pipe, the flow capacity becomes practically equal to the unregulated capacity. It is possible to further regulate the flow by using several flow regulators in series [6].

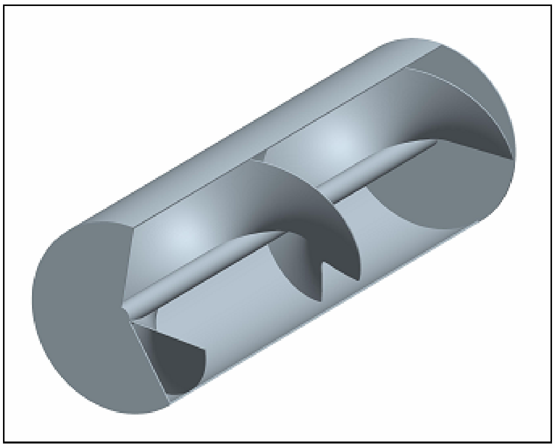

Figure 1.4 - Steinscruv Flow Regulator

Advantages

- At full bore the flow becomes almost equal to the unregulated capacity

Disadvantages

- Complex internal components
- Expensive
- Not commonly used

1.6.4 Hydro-Slide

The Hydro-slide regulator was commercially developed in Germany in the 1990's with a number of patents attached to its design. The device controls the flow by allowing the head of water in the detention facility to raise a float as shown in figure 1.5. This in turn opens an orifice the required amount to control the flow passing through [7].

Figure 1.5 - Hydro-Slide (Courtesy of Copa)

The Hydro-Slide does not affect the flow until it is approaching the set discharge limit, this allows fluid to be discharged to the watercourse for flows below the set point, hence slowing the build up of head in the detention tank and therefore maximizing the onsite detention volume.

The graph below in figure 1.6 shows the performance of the Hydro-slide compared with a vortex valve and orifice plate. The Hydro-slide operates efficiently but is very prone to blockage because of the small size of the orifice opening when compared with a vortex valve. In comparison the Hydro-slide is expensive because of its stainless steel casing and complex mechanical operation [7].

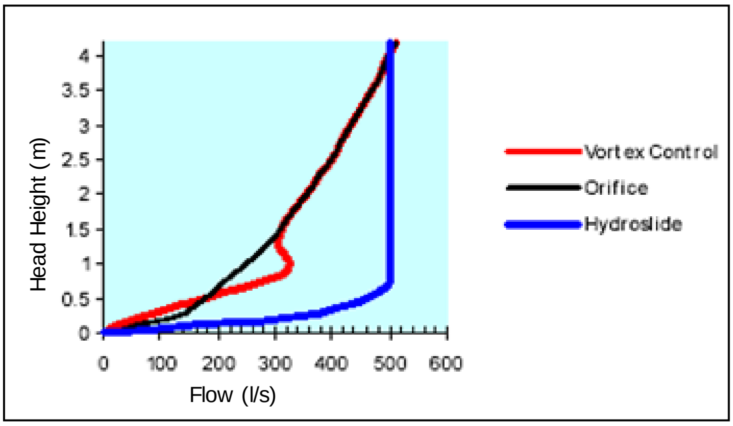

Figure 1.6 - Performance Curve (Courtesy of Copa)

Advantages

- Design flow rate reached at low head
- Very efficient for large head heights

Disadvantages

- Prone to blockages due to small orifice diameter
- Expensive
- Complex internal components

1.6.5 Vortex Flow Control Devices

Vortex Flow Control devices were developed in Denmark in the mid-1960's [8] to control outflow from a storage structure. At low flow rates fluid enters through the inlet and passes straight to the outlet with no restriction. As the inlet flow increases due to upstream hydraulic head, an air filled vortex is generated in the unit as shown in figure 1.7 below. This generates high peripheral velocities which restricts flow and creates a back pressure. The back pressure restricts flow to the desired rate at a given head height.

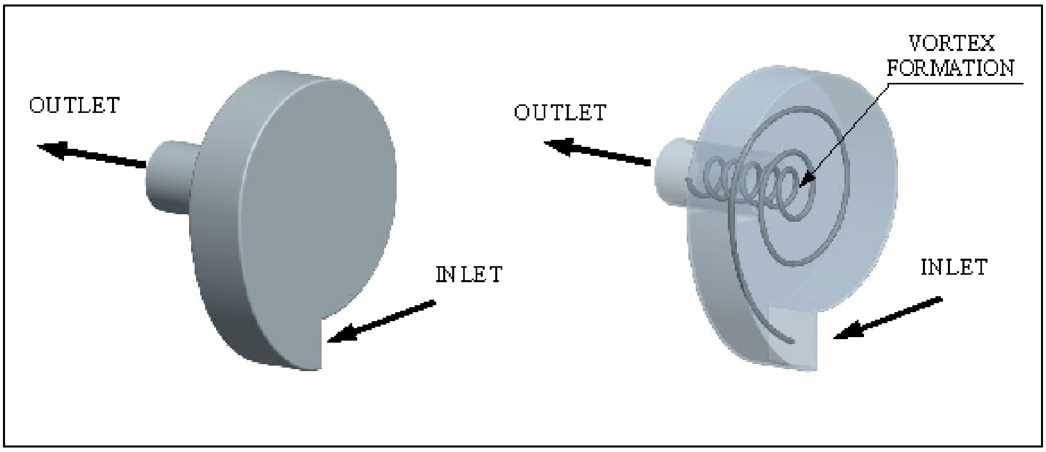

Figure 1.7 - Radial Vortex Valve

The vortex valve is self activating, requires no external power source and it has an orifice opening much larger than conventional flow control devices. This large opening coupled with high internal velocities minimise the risk of blockage. The complete absence of moving parts is also a big advantage with the possibility for mechanical failure minimised.

There are two main types of vortex flow control devices [9], the radial vortex valve and the conical vortex valve. Both valves work on the very same principle but have different geometries which give each there own benefits and advantages. The radial version is shown in figure 1.7 above and the conical version in figure 1.8 below. The radial version is mainly used for the control of stormwater from storage facilities. It is the more economical of the two to manufacture but requires a sump to operate. The conical type is used in combined sewer / stormwater systems and does not require a sump so can be easily retrofitted to existing facilities.

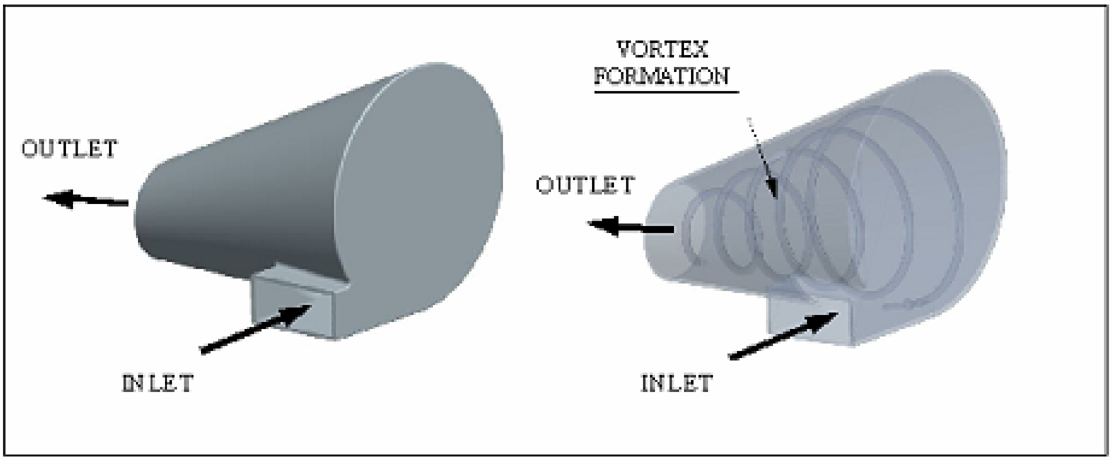

Figure 1.8 - Conical Vortex Valve

A number of variations of each type exist but the main geometry and principle of operation remain the same. It is possible to modify the performance of a valve by using additions extras such as an adjustable intake gate and / or a vortex suppressor pipe (draws additional air into the vortex).

Vortex flow control devices have a very unique head discharge characteristic. The head discharge curve is “S” shaped and is compared below in figure 1.9 to a conventional orifice plate.

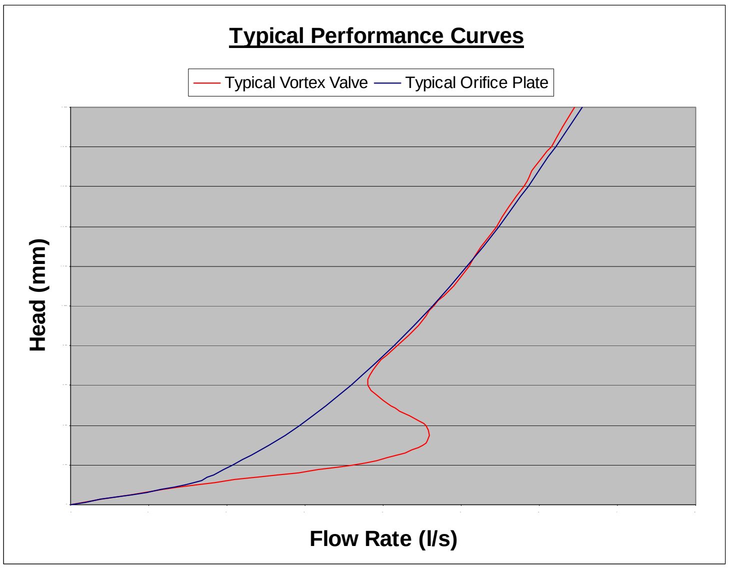

Figure 1.9 - Typical Performance Curve

Advantages

- Outlet orifice cross sectional area is 3-6 times that of an orifice plate so therefore the possibility of a blockage is minimised
- Unique S shaped discharge curve
- Self Activating and self cleansing
- Available in radial and conical geometry
- Reduces storage requirements of attenuation systems

Disadvantages

- Difficult to install in a standard storm water manhole
- Expensive due to their stainless steel construction
- Limited number of suppliers
- Widely used in industry

1.7 Commercial Vortex Flow Control Devices

There are four main manufacturers of vortex flow control devices around the world. One based in Britain, one in Canada, one in the USA and one in Sweeden

1.7.1 Hydro-Brake (Hydro-International)

The Hydro-Brake (fig.1.10) is the most commonly used vortex flow control valve with over 10,000 units installed worldwide. The units are manufactured by Hydro International LTD, an English company with regional offices in the USA and Ireland. The company was formed in 1980 to promote hydrodynamic vortex separation and vortex flow control technology around the world. The inventor of the Hydro-Brake was a Mr Bernard Smisson who designed the very first vortex overflow in England in the 1960s. Faced with space constraints while trying to construct a conventional side weir overflow, he developed a circular weir (fig. 1.10) overflow configuration which was later developed into a vortex flow control device [9].

Figure 1.10 - Hydro-brake (Courtesy of Hydro International)

1.7.2 Hydro-Vex

The Hydro-Vex is manufactured by a Canadian company John Meunier founded in 1948. They are a manufacturer of water and wastewater treatment equipment and solutions. They manufacture a wide range of vortex valves for stormwater and combined sewer applications including radial and conical units. The unit shown below in figure 1.11 is a radial vortex valve installed in a rectangular manhole [10].

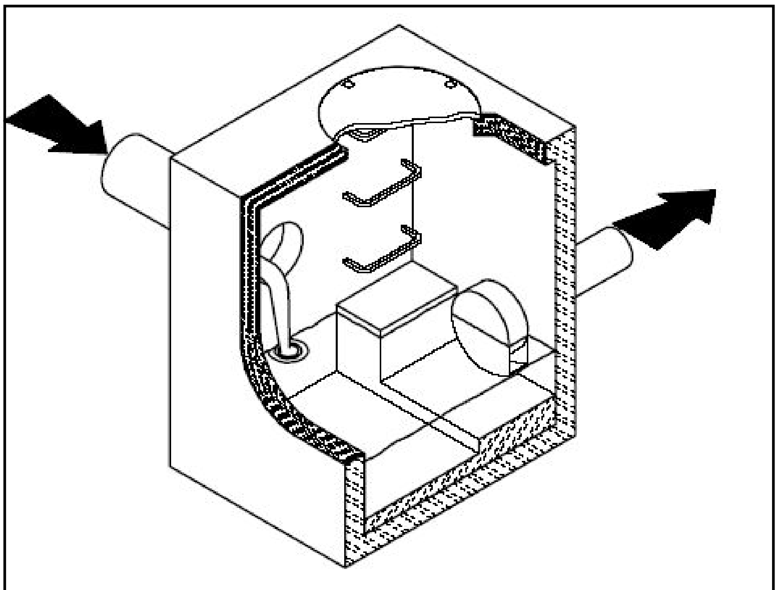

Figure 1.11 - Hydro-Vex (Courtesy of John Meunier)

1.7.3 Mosbaek Flow Control Devices

The Swedish company called Mosbaek was founded almost 35 years ago by inventor and engineer Joergen Mosbaek. Joergen Mosbaek was the first person in the world to have the idea of developing a device for sewage systems which only allowed a limited, close to constant flow to pass, regardless of water level. This invention (figure 1.12) he chose to call a 'water brake' or 'flow controller'. In the course of time he has further developed that first, initial design, and today the company offers a wide product range which covers virtually any need for flow control in sewage systems [8].

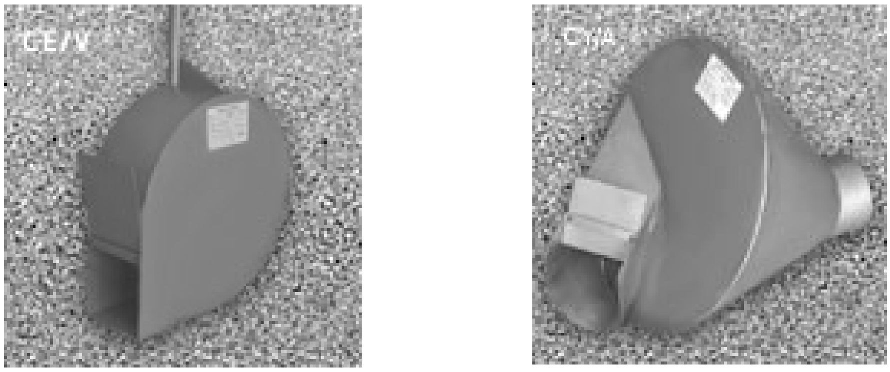

Figure 1.12 - Water Brake (Courtesy of Mosbaek)

1.7.4 hydro-brake (Vortechnics)

Vortechnics Inc. is an American company that specializes in stormwater quality treatment systems and vortex flow control devices. They have the name hydro-brake registered in the USA with Hydro-International having it registered in the U.K. and Europe. It works on the very same principle as the hydro-brake but does not have the pivoting bypass door in the back of the vortex chamber [11].

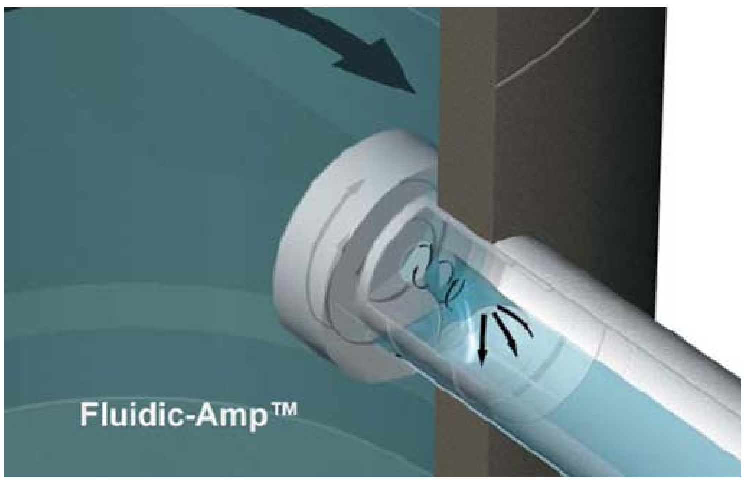

Fig. 1.13 - hydro-brake (Courtesy of Vortechnics)

1.8 The Vortex

The word vortex comes from the latin word *vertex, verticis (m.)* meaning "eddy" or "whirlwind". Some of the earliest research on vortex motion was published by Hermann von Helmholtz (1821-1894) in 1858, and by William Thomson, later Lord Kelvin (1824-1907), in 1869. The names of these two giants of classical physics are jointly associated with many of the principal concepts of vortex motion [12].

The exact definition of the word vortex is neither simple nor unique and is dependent upon the distinction being made between a particle rotating about its own axis or one revolving with many other particles around a common axis. For the purpose of this thesis a single particle rotating about its own axis will not be considered and the following definition of a vortex will apply [12].

> *A vortex is the rotating motion of a multitude of material particles around a common center.*

The path of individual particles does not have to be circular, but may also be asymmetrical as shown in figure 1.14. The vortex motions in figure 1.14 (a) and (b) are plane structure's with their paths the same in every plane normal to the axis of rotation but in nature and technology this is rarely the case and vortex motion is nearly always spatial where the path lines are not perpendicular to the axis of rotation but have a component parallel to it as in figure 1.14 (c). A spatial vortex does not need its path closed as with the concentric and asymmetrical vortex.

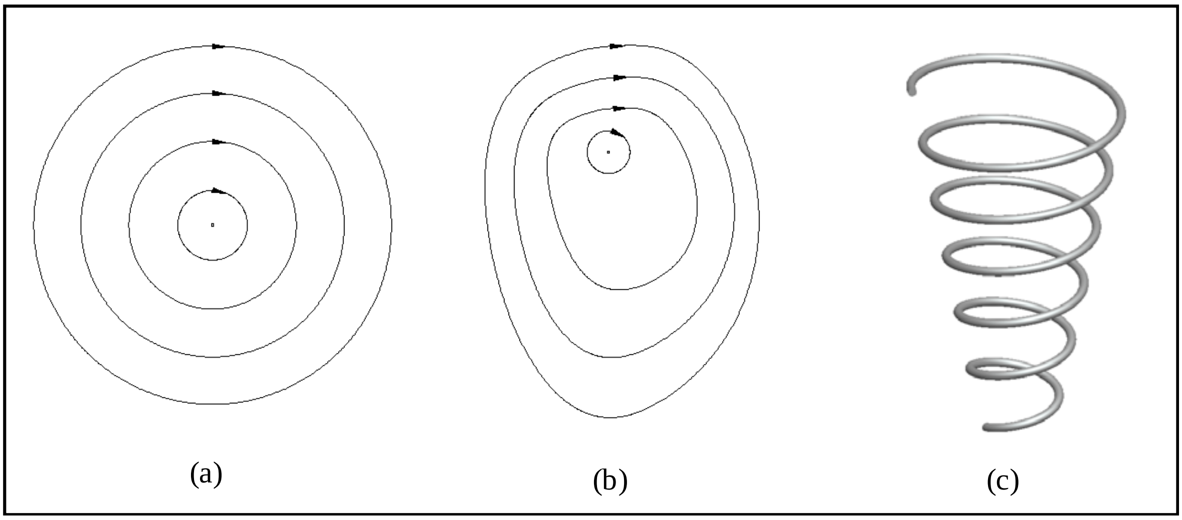

Figure. 1.14 – Concentric, Asymmetric and Spatial Vortex Motion

1.8.1 Vortex Motion

There are two main types of plane vortex motion, 1) the potential vortex which is sometimes called a free vortex and 2) solid body rotation which is often called a forced vortex. The simplest way to explain the difference between these two vortices is with an example:

A solid cylindrical rod is rotating at constant velocity in a fluid, after a short period of time (transient) the fluid velocity is highest and equal to that of the rod at the rods surface since the fluid adheres to the surface of the rod. With increasing distance from the centre of rotation the velocity decreases inversely proportional to the distance (see figure 1.15). Such fluid motion is called a potential vortex. A potential vortex is also irrotational which means that although the streamlines are circular the individual molecules of the vortex do not spin as they orbit the axis of the vortex. This can be demonstrated by observing a cross placed in a potential vortex, the cross rotates about the axis of the vortex but not around its own axis. Therefore the fluid has no vorticity except at the centre of rotation. A common everyday example of a potential or free vortex is a bathtub vortex which can be seen form when a bath of water is emptying [12].

Now consider a hollow tube filled with water rotating a constant velocity about the axis of the tube, again after a transient period the fluid will rotate like a solid body because of its adherence to the walls of the tube. The velocity of the fluid increases linearly with distance from the centre of rotation (see fig.1.15), and the angular velocity is constant everywhere in the fluid. This type of vortex motion is called solid body rotation or a forced vortex and is true only when the fluid motion is steady. A common everyday example of a forced vortex is when a cup of tea is being stirred [12].

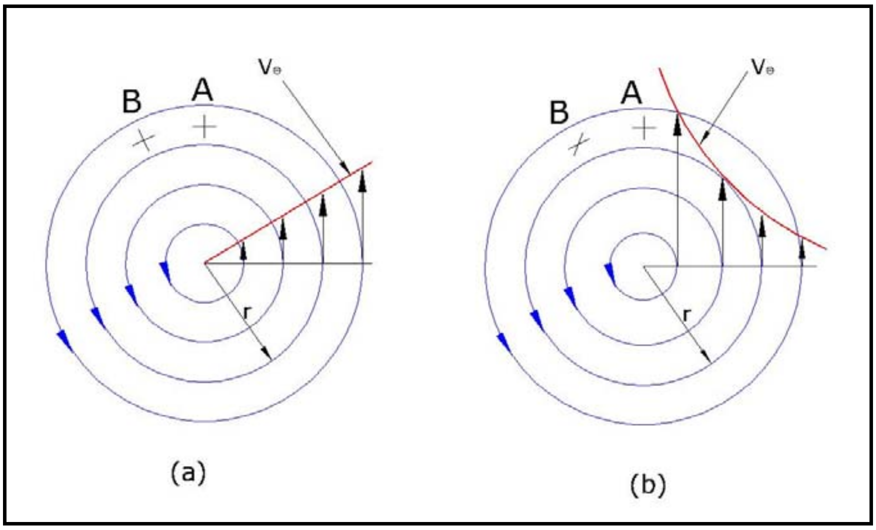

Figure 1.15 - (a) forced vortex and (b) free vortex

1.9 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods to solve the governing equations of fluid flow, namely the conservation laws relating to the transport of mass, momentum and energy. Computers are used to perform millions of calculations that are required to simulate the interaction of fluids and gases with surfaces used in engineering. However, even with simplified equations and high-speed supercomputers, only approximate solutions can be achieved in many cases. Validation of CFD results is an essential part of CFD for accurate modelling and simulations [13].

CFD has become an essential part of technological advancement in the following areas: aerospace, automotive, heat transfer, process engineering, hydrodynamics, wind power, air conditioning and ventilation, hydraulics, sediment transport, biomedical engineering and electronic cooling. The results of a simple steady state and complex transient analysis can be seen below.

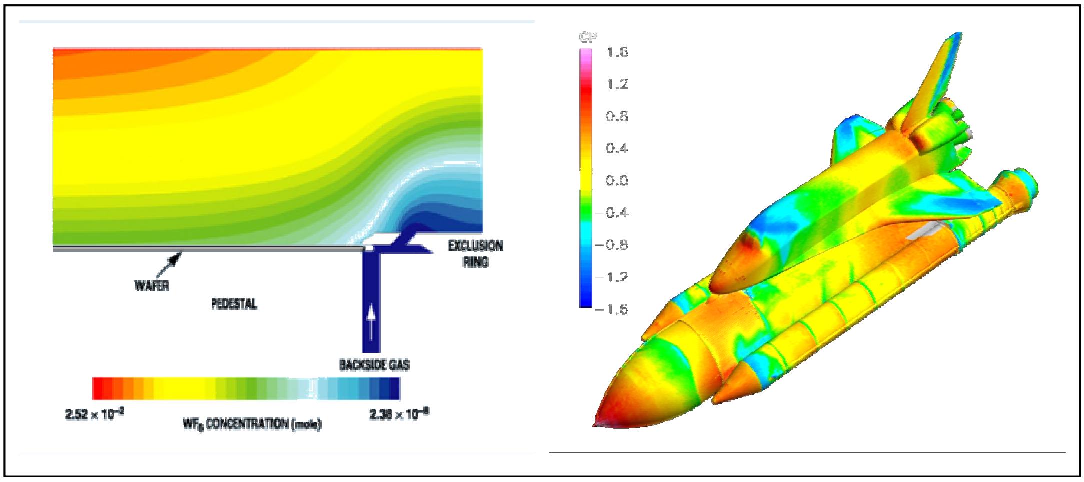

Figure 1.16 – CFD Analysis Examples

A commercial CFD software package called Ansys CFX was used to perform the simulations. Ansys CFX is one of the leading CFD software packages available on the market and simulations are normally performed by experienced engineering analysts specialising in fluid dynamics. This is due to the complexities involved in model setup and inaccuracies associated with poor assumptions. For these reasons along with the time dependent nature of the analysis the author received some guidance from IDAC Ireland in the setup of the problem using Ansys CFX software [14].

1.10 Aim and Objectives

The vortex flow control device is the most widely used method for controlling the discharge rate of storm water. There are only a handful of manufacturers, all of which keep the design principles closely guarded and are therefore unknown. Currently none of the designs allow for easy installation in a standard storm water manhole. For these reasons the following aims and objectives were set out.

1.10.1 Aims

- The main aim of this project is to design and develop a radial vortex flow control valve for controlling flow from storm water attenuation systems.

1.10.2 Objectives

- To design and develop a number of concepts for the vortex flow control device along with ways in which they can be easily installed.
- To select a concept and develop a detailed design
- To build working prototypes of the detailed design
- To design and develop a full scale test rig and test a prototype unit.
- To test a number of prototypes and find the influence each of the geometric variables has on the performance of the device.
- To select a geometric relationship between each of the variables that satisfies the following:
    1. An outlet cross sectional area 3-6 times that of an orifice plate
    2. An inlet cross sectional area similar to that of the outlet to minimize blockage
    3. A performance curve that will maximize the flow through the unit while keeping a large design flow range.
- To build a mathematical model to predict the geometric size of the vortex chamber and generate a head discharge curve when given a flow rate and head height specification.
- To investigate if computational fluid dynamics can be used to model the performance of the radial vortex valve based on experimental results.

2.0 Introduction

Vortex flow control devices by their very nature change in size and geometry depending upon the required flow rate and specified head height. The design approach was to carry out the product design specification and base the conceptual design on one particular size of radial vortex flow control device with the ability to scale up and down the size depending on the required specification. Three concepts were developed for ways to mount the vortex valve to the inside of a standard Ø1.2m storm water manhole. Two concepts were then developed for the shape of the vortex chamber.

2.1 Industry Standard

Currently all radial vortex valves in industry are manufactured from stainless steel and have been for many years [7-11]. All current radial vortex valves on the market also need to be mounted onto a flat surface so therefore modifications are required to the standard Ø1.2m storm water manhole found on most construction sites. This means that a custom rectangular manhole has to be constructed where the vortex valve is to be installed, alternatively a flat face can be shuttered on a circular manhole as shown blow in figure 2.1. The interface between the vortex valve and the manhole does not have a waterproof seal which may alter the performance claims of the manufacturer.

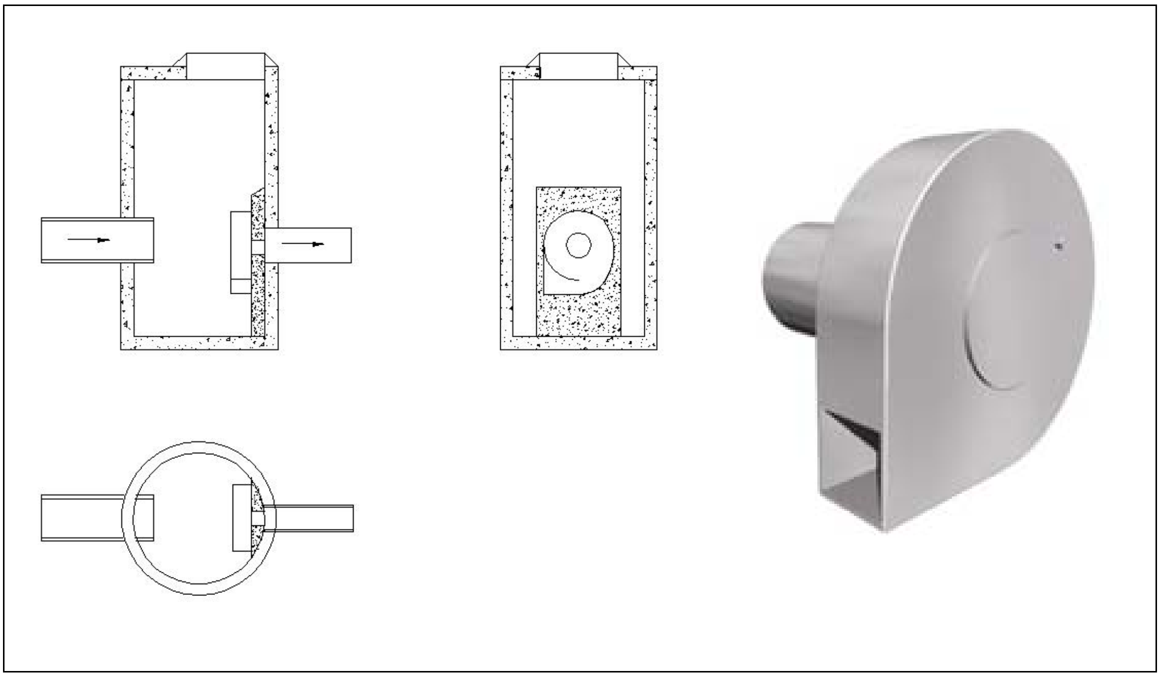

Figure 2.1 - Standard Radial Vortex Valve Mounting (Courtesy of Hydro International)

2.2 Product Design Specification

A product design specification was developed to outline all the design and performance requirements of the vortex valve, this includes identifying the problems associated with current vortex valves in the market place and setting objectives to alleviate these problems.

2.2.1 Performance

- The vortex valve must be easily installed into a Ø1.2m manhole ring.
- The vortex valve must be available for installation in a rectangular manhole.
- The vortex valve must provide a watertight seal between the manhole and the vortex valve.
- The vortex valve must integrate an emergency bypass of the vortex chamber in the event of a blockage due to some contaminant in the water e.g. large plastic bag.
- The vortex valve must allow service to the pipe downstream of the manhole.
- The vortex valve must be able to suit an outlet pipe size of up to 300mm.
- The vortex valve must have an expected service life of 50 years in line with the current specification for storm water pipe.
- The vortex valve must be durable enough the take any general handling and transportation that may occur on site.

2.2.2 Manufacturability

- The vortex valve is to be fabricated or moulded from a suitable type of plastic, this makes the unit a lot more economical to manufacture than those available in stainless steel.
- The plastic vortex valve must provide performance equal to or greater than that of a stainless steel unit.

2.2.3 Assembly

- The vortex valve is to be assembled using corrosion resistant materials
- The vortex valve will comply with design for assembly guidelines so the product is easily and economically assembled.

2.3 <u>Mounting - Concept 1</u>

Concept 1 is a vortex valve with a horizontal outlet pipe mounted to a square flange, the outlet pipe has a vertical tee that acts as an overflow pipe. The overflow pipe must be equal or greater in length than the head height or top water level. This means that if the head height ever goes above the design height the unit will automatically by-pass the valve and flow to the outlet pipe. This feature will never allow the vortex valve to flood up to ground level unless the overflow pipe also gets blocked.

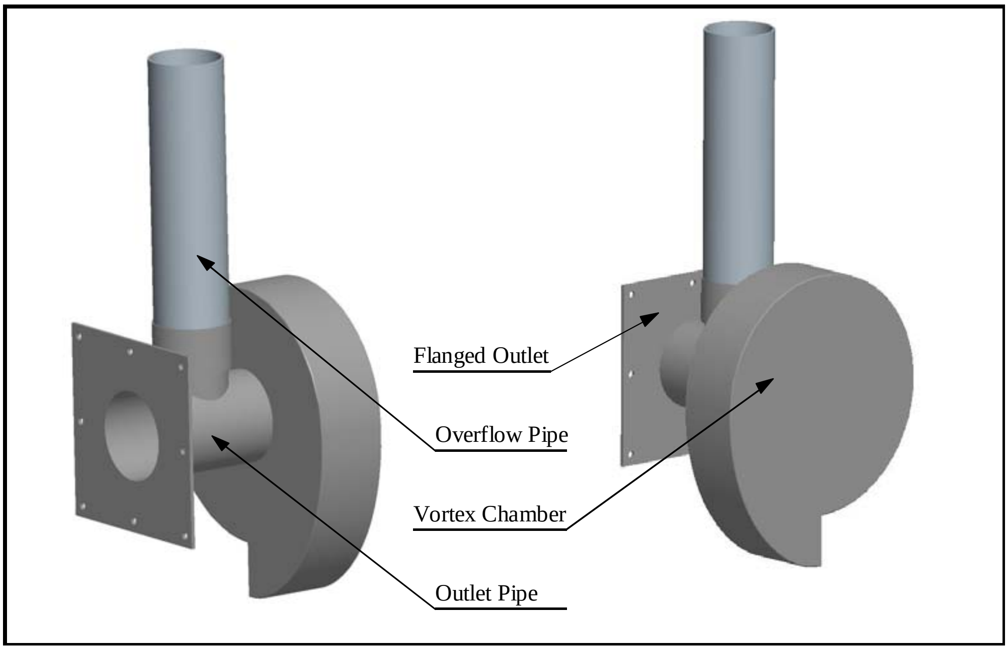

Figure 2.2 – Mounting Concept 1

2.3.1 <u>Installation</u>

Concept 1 may be installed in either a standard Ø1.2m manhole (see figure 2.3) or a rectangular manhole. For a rectangular manhole a straight outlet flange is required and for a circular manhole a curved outlet flange is required.

Installation of the unit is as follows:

- Align the flange to the outlet pipe on the inside face of the manhole
- Mark and drill the manhole to take the steel stud anchors
- Fix the flange to the manhole with the steel stud anchors
- Seal around the flange with silicone

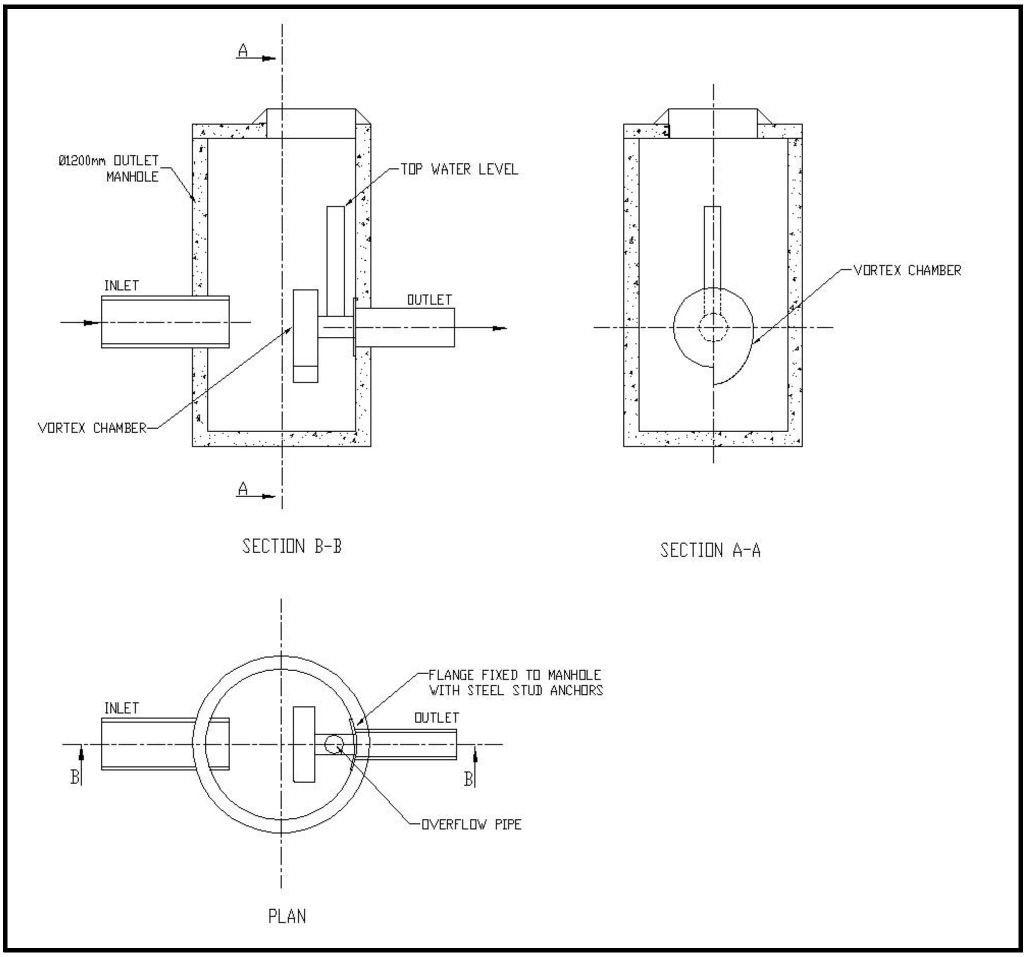

Figure 2.3 – Mounting Concept 1 Installation

2.4 Mounting - Concept 2

Mounting concept 2 was developed to allow the water source (e.g. attenuation tank) to fully drain in the event of a blockage at the intake to the vortex chamber. The main feature of this concept is its by-pass facility which can be operated via a wire rope from the top of the manhole. The wire rope is attached to a pivoting door on the side of the unit which can by-pass the vortex chamber and direct flow into the outlet pipe.

The mounting chamber is designed to bolt onto the inside of either a rectangular or circular manhole, the outlet pipe of the unit is joined to the outlet pipe of the manhole. Concrete is poured around the outlet pipe joint with the vortex chamber mounting acting as a concrete shutter, this provides a watertight seal between the manhole, mounting chamber and outlet pipe.

One advantage of using this design is that a number of standard size mounting chambers can be available off the shelf and selected according to the size of the vortex chamber. This minimises both design and assembly time per unit leading to a more cost effective product.

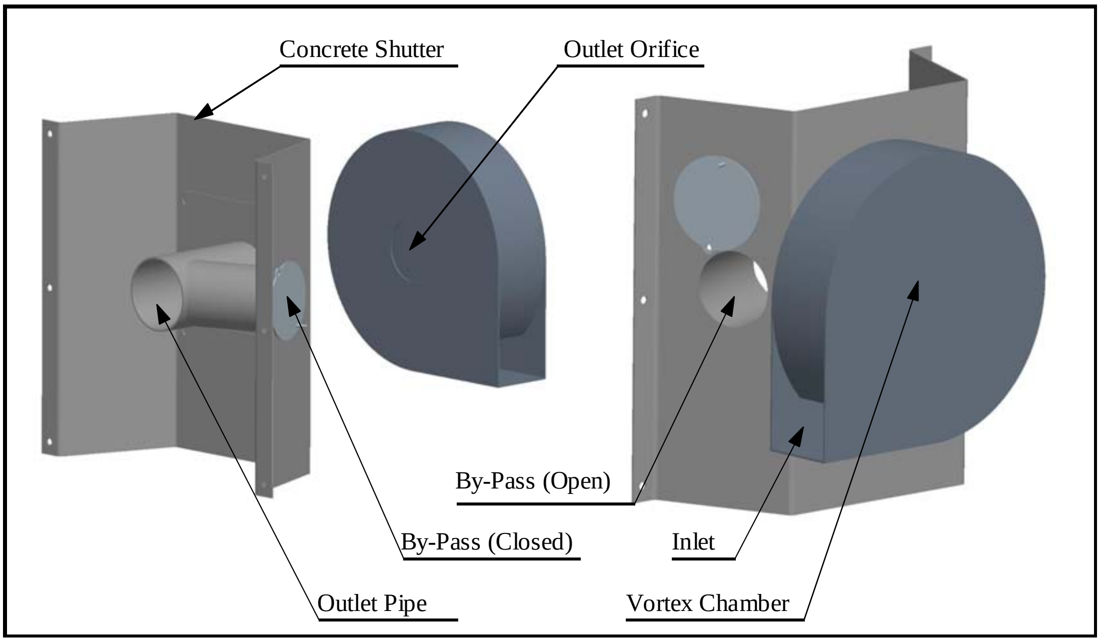

Figure 2.4 – Mounting Concept 2

2.4.1 Installation

Concept 2 may be installed in either a standard Ø1.2m manhole (see figure 2.5) or a rectangular manhole.

- Align the concrete shutter to the outlet pipe on the inside face of the manhole.
- Mark and drill the manhole to take the steel stud anchors.
- Fix the concrete shutter to the manhole with the steel stud anchors.
- Connect the manhole outlet pipe to the vortex chamber outlet.
- Fill the shutter with concrete ensuring no seepage into the outlet pipe.
- Mark and drill the underside of the manhole cover.
- Fix the bypass cord bracket the underside of the manhole ensuring the cord operates freely.

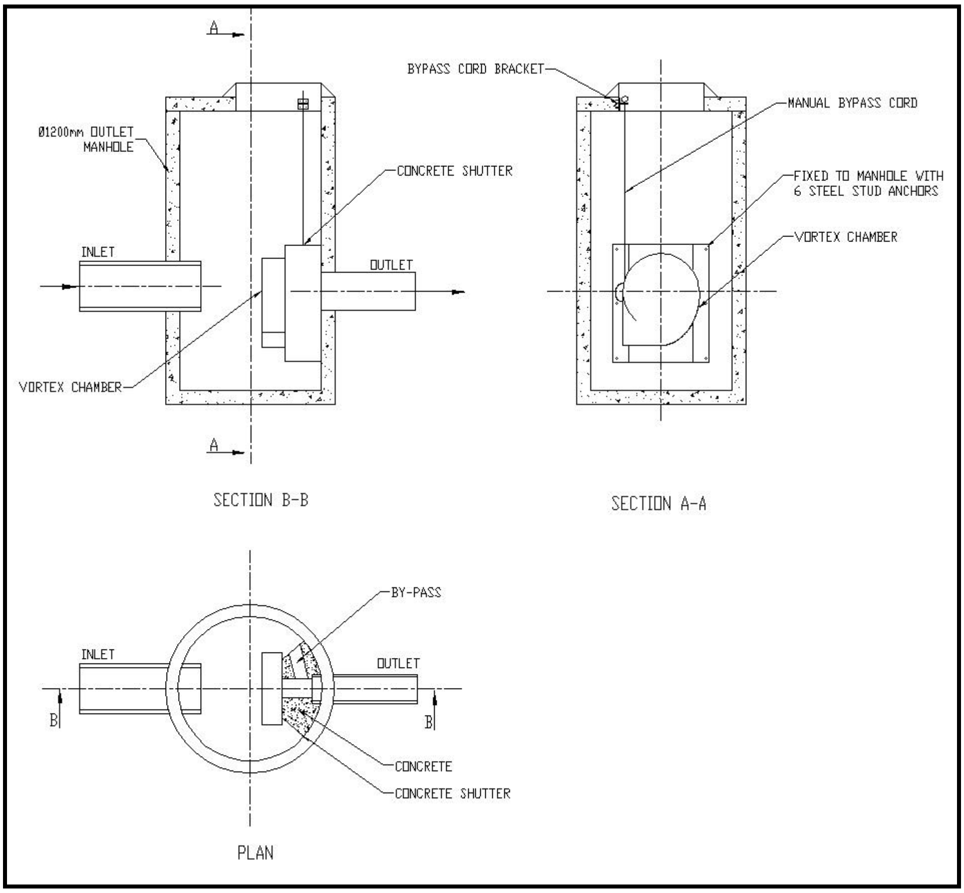

Figure 2.5 – Mounting Concept 2 Installation

The main advantage of the design is the incorporation of a pivoting by-pass door which allows the vortex chamber to be by-passed in the event of a blockage. The main disadvantage is the use of concrete to provide a seal between the outlet pipe and the vortex valve.

2.5 Mounting - Concept 3

Concept 3 was developed to overcome some of the problems associated with the first two concepts. Firstly a specially moulded mounting coupler was developed that easily allowed the vortex chamber seat and seal against the inside of a standard Ø1.2m manhole. This provides a quick and easy method for installing the vortex valve without the need for an in-situ concrete shutter or a pre-cast concrete shutter. The mounting coupler is a specially moulded plastic part that can be manufactured with a curved face (see figure 2.6) to suit the inside of a standard Ø1.2m manhole ring or a flat face for a rectangular manhole.

There is an integrated pivoting by-pass moulded into the side of the mounting coupler which allows manual operation in the event of a blockage. If automatic operation is required a float may be set to open the by-pass door when the water reaches a certain level. If maintenance is required a service plate was incorporated in the back of the vortex chamber which can be removed as required.

A closed cell neoprene gasket was incorporated onto the front face of the mounting coupler. When the unit is installed this gasket provides a watertight seal between the manhole and the mounting coupler.

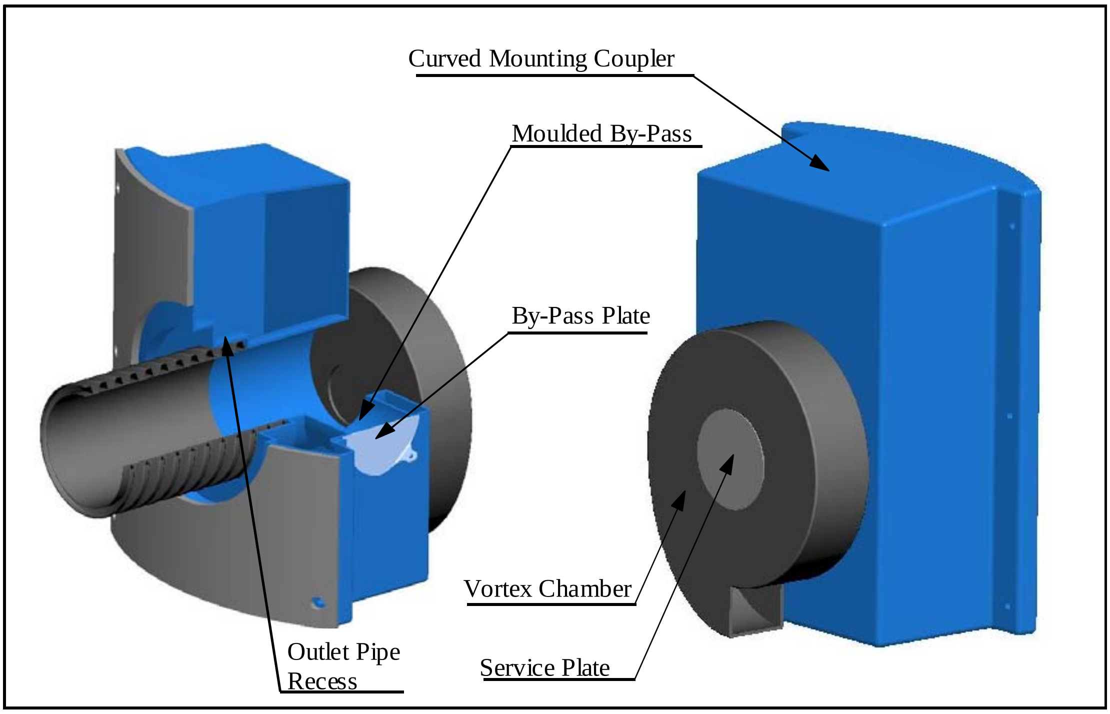

Figure 2.6 – Mounting Concept 3

2.5.1 <u>Installation</u>

Concept 3 can be installed in either a standard Ø1.2m manhole or a rectangular manhole as required once the correct mounting coupler is selected. The unit is installed as follows:

- Align the mounting coupler with the outlet pipe on the inside face of the manhole.
- Mark and drill the manhole to take the steel stud anchors.
- Fix the mounting coupler to the manhole with the steel stud anchors.
- Mark and drill the underside of the manhole cover.
- Fix the bypass cord bracket to the underside of the manhole ensuring the cord operates freely.

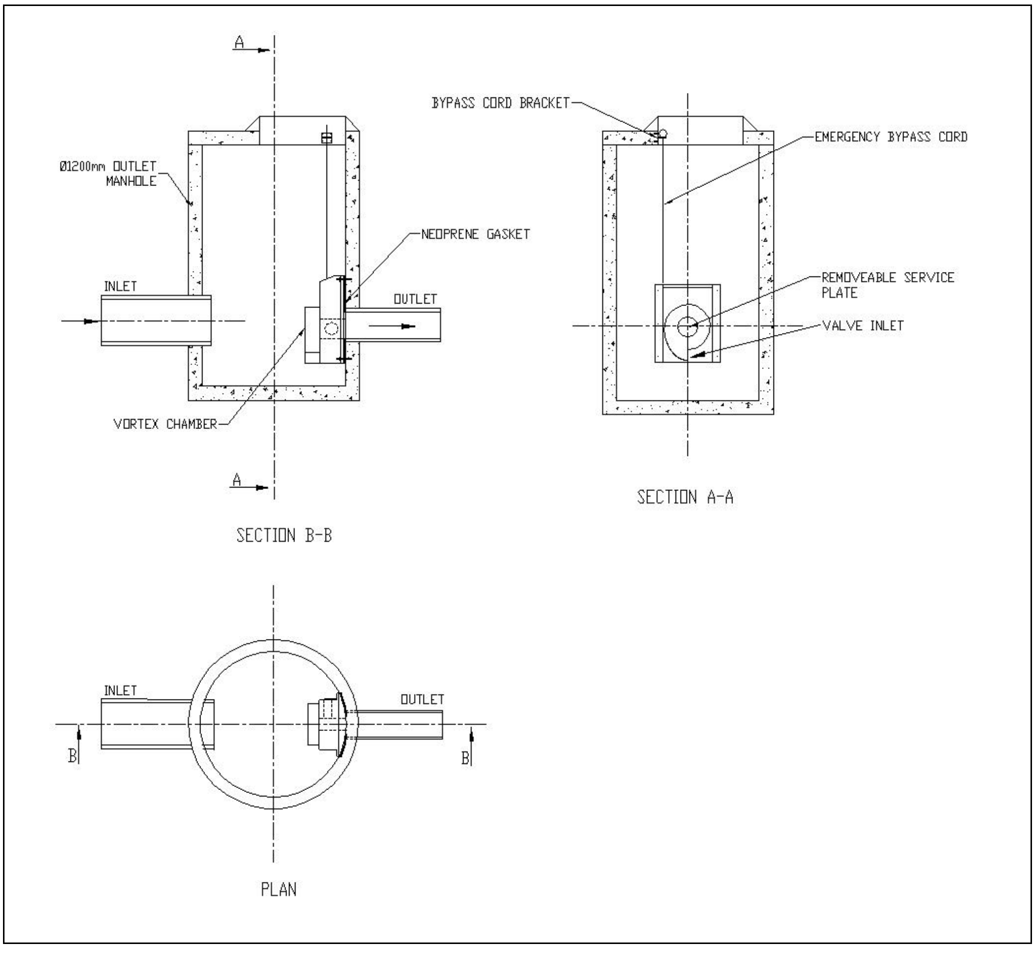

Figure 2.7 – Mounting Concept 3 Installation

The main advantage of this design is the specially moulded mounting coupler which ensures quick and easy installation while providing a sealable receiver for the outlet pipe. It also incorporates a pivoting by-pass door but ensures a watertight connection with the outlet pipe due to its unique geometry.

2.6 Mounting Concept Selection

Concept selection was not a difficult task as the concepts evolved from one to the next, possible problems associated with the design were identified and addressed in successive concepts. Concept three satisfies all the design requirements set out in the product design specification. A weighted matrix table is shown below to outline the evolution of the design from concept one to concept three.

Feature	Weight (1-5)	Concept 1	Concept 2	Concept 3
Installation in a standard Ø1.2m Manhole	5	3 (15)	3 (15)	3 (15)
Installation Option in a Rectangular Manhole	3	3 (9)	3 (9)	3 (9)
Ease of Installation	4	1 (4)	1 (4)	3 (12)
Watertight Seal	2	1 (2)	2 (4)	3 (6)
By-pass Facility	4	1 (4)	3 (12)	3 (12)
Access for Maintanance	4	1 (4)	1 (4)	3 (12)
Service Life & Durability	3	2 (6)	2 (6)	2 (6)
Cost	4	3 (12)	2 (8)	1 (4)
Total		**56**	**62**	**76**

Table 2.1 (Concept Selection)

2.7 Vortex Chamber Design

The design of the vortex chamber is dependent upon the required flow rate specification. The principle geometry is the same in all types of radial vortex flow control devices, this generic shape is a circular chamber with a tangential inlet to initiate a rotational motion inside the chamber, creating a vortex with a horizontal outlet.

Current geometry as seen on all commercial radial vortex flow control devices is shown in figure 2.8 below. When analysed part of the design named area ”A” was identified as having no obvious functional feature. It does not contribute to controlling the flow into the vortex chamber as this is performed by the inlet height “H”.

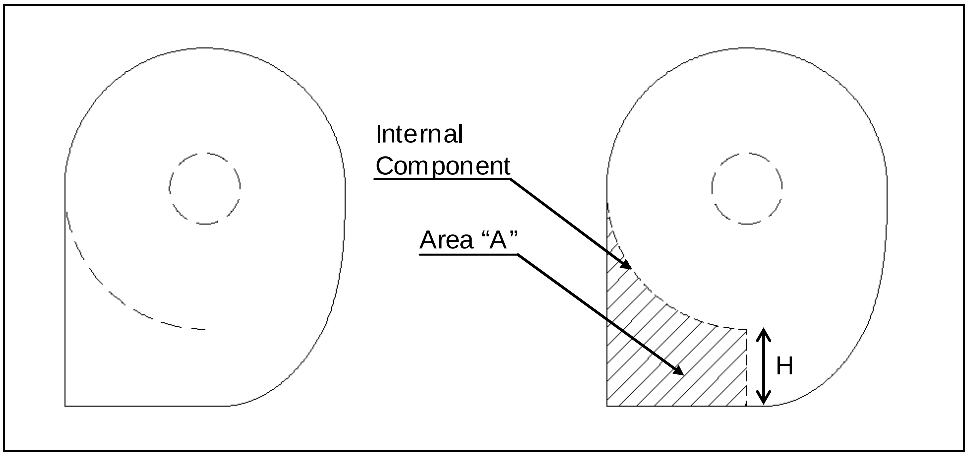

Figure 2.8 – Current Vortex Chamber Geometry

The internal component (see figure 2.8) makes the manufacture of the vortex chamber more complex in plastic whether fabricated or moulded. With no obvious functionality associated with area “A” it was decided to redesign the vortex chamber to simplify the manufacturing process. The new design is shown in figure 2.9 below and has no internal components and still encourages vortex motion with a tangential inlet as seen in the current commercial geometry.

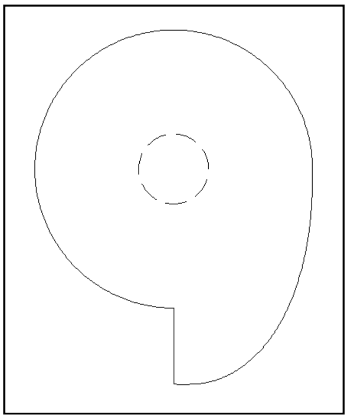

Figure 2.9 – New Vortex Chamber Geometry

2.7.1 Manufacturing Process and Material Selection

The manufacturing process and material selection for the prototype was selected from the following characteristics

1. Raw Material Cost
2. Manufacturing Cost
3. Manufacturability
4. Mechanical Performance

To build cost effective prototypes it was decided to fabricate the initial units from plastic sheets because of the set up costs associated with moulded parts. It can be seen from the graph below in figure 2.10 that moulded parts become cost effective when produced in large amounts but fabricated parts can be made cost effective in very low quantities.

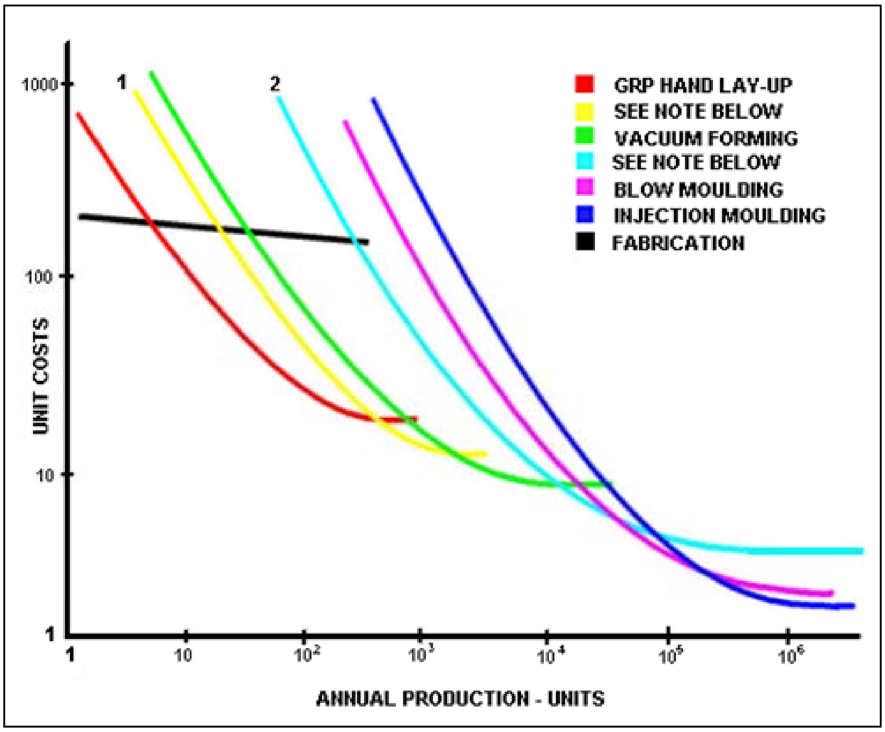

Figure 2.10 – Manufacturing Process Selection Graph (Courtesy of the BPF)

In order to fabricate the units the material needed to be easily cut and welded using standard plastic cutting / welding equipment. The material also required good mechanical properties at a cost effective price. From experience in the industry the author selected polyethylene and polypropylene as the two main plastic materials to choose from. They are two of the most widely used plastic materials with good mechanical properties and fabrication characteristics at a relatively low cost. Polyethylene was selected because the author had it readily available including the fabrication equipment required.

2.7.2 Fabrication of the Vortex Chamber

The required finished product was firstly modelled in a 3D CAD package called Pro Engineer [15], a module within Pro Engineer called sheet-metal was then used to split up the finished part into sections for fabrication. In figure 2.11 and 2.12 below the individual parts of the vortex chamber are shown.

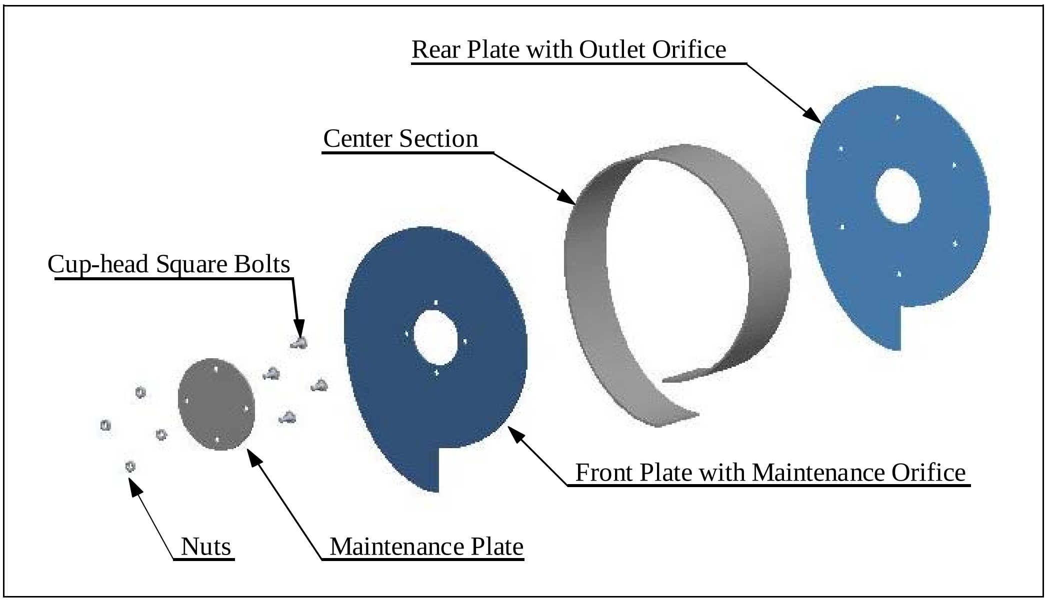

Figure 2.11 – Exploded Vortex Chamber View

The rear plate, front plate and maintenance plate are cut out to size with a CNC controlled water-jet profiling machine. The centre section is cut out as a flat plate and rolled into shape. The rear plate, front plate and centre section are then welded together using a Lister plastic welder. The maintenance plate is fixed to the front of the unit with four stainless steel cup-head square bolts, hex head nuts and spring washers.

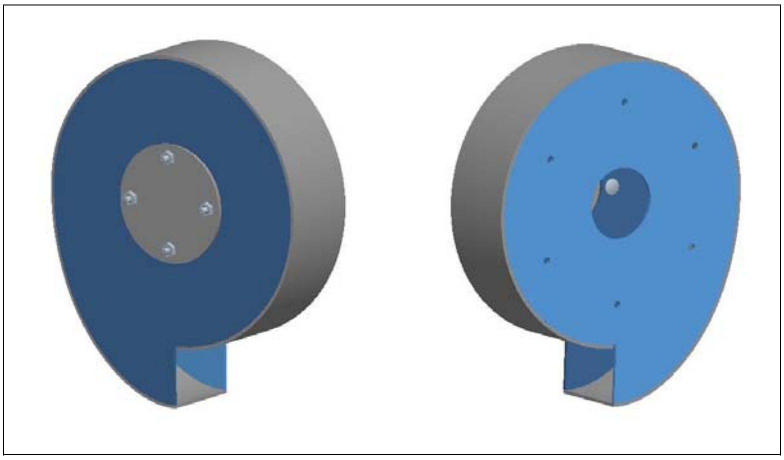

Figure 2.12 - Assembled Vortex Chamber

2.8 Mounting Coupler Detailed Design

The mounting coupler was specially designed for easy installation in a standard Ø1.2 m storm water manhole with a modified version designed for a rectangular manhole. It's primary function is to couple a vortex flow control device to a storm water manhole while allowing easy installation and accommodating a manual by-pass in the event of a blockage.

It was decided to rotationally mould the unit rather than fabrication due the complex nature of the design. Rotational moulding of the unit offered great flexibility in the design with the ability to use unique features such as the moulded in by pass and outlet pipe couplers while ensuring precise repeatability during production.

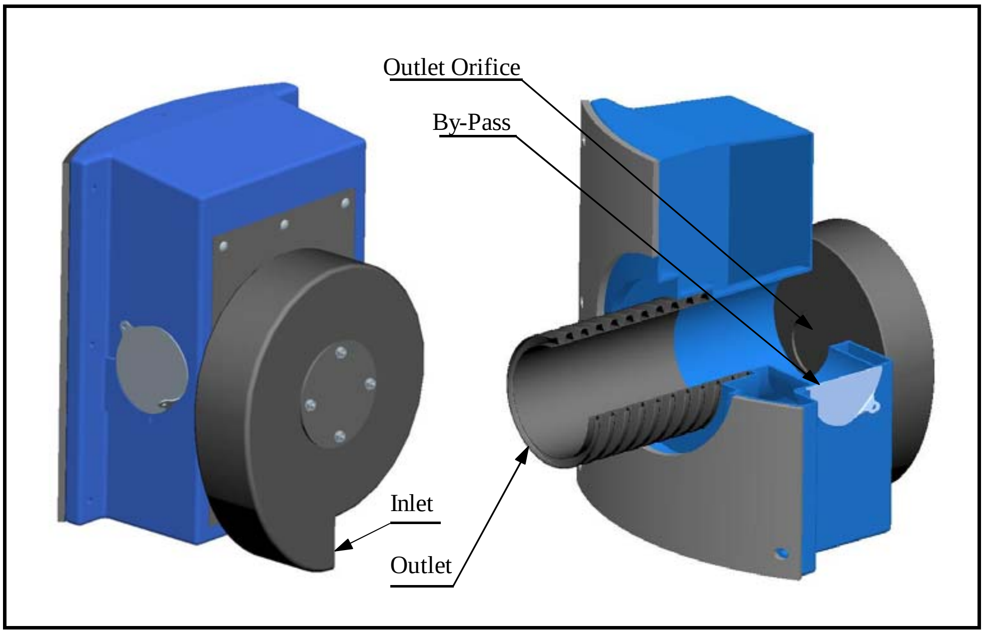

Figure 2.13 – Vortex Valve

2.8.1 Features

- Curved front to sit against the inside of a Ø1.2m storm water manhole.
- Simple mould modification to give a flat front for rectangular manholes.
- Integrated by-pass operated manually or automatically.
- Quick and easy installation.
- Outlet pipe couplers built into unit for 225mm and 300mm pipe sizes.
- Neoprene Gasket to seal against the inside face of the manhole.
- Easy assembly of the vortex chamber with the use of an adaptor plate.
- Lightweight and easy to handle.

2.9 Vortex Valve Assembly

The vortex valve is completed with the assembly of the mounting coupler and vortex chamber as shown in figure 2.14. The vortex chamber sub-assembly is bolted to the mounting coupler with stainless steel cup-head square bolts, hex head nuts and spring washers. A silicone gasket is used between the vortex chamber and the mounting coupler to ensure all water that flows to the outlet pipe passes through the vortex chamber with no water leaking between the two sub-assemblies.

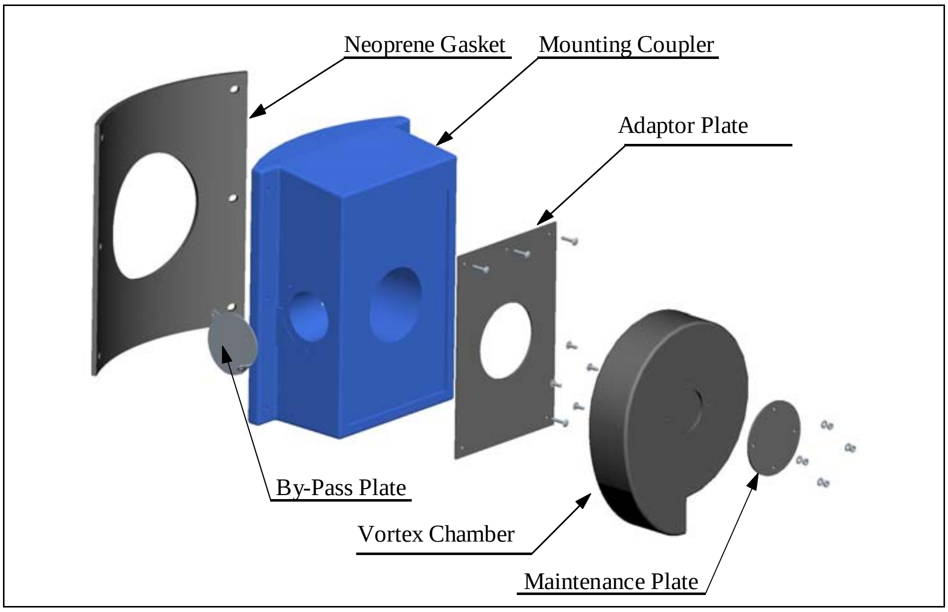

Figure 2.14 - Vortex Valve Exploded

Figure 2.15 - Photo of Actual Vortex Valve

2.10 Vortex Valve Installation

The vortex valve is installed as follows: (see figure 2.16 for illustration).

- Cut a slightly oversized hole in the manhole for the outlet pipe.
- Align the vortex valve with the hole ensuring correct invert levels.
- Drill through the vortex valve into the manhole and fix with six steel stud anchors.
- Insert the outlet pipe into the vortex valve**.**
- Fix the by-pass cord to the underside of the manhole biscuit allowing remote operation of the by-pass cord from ground level when the manhole cover is open.

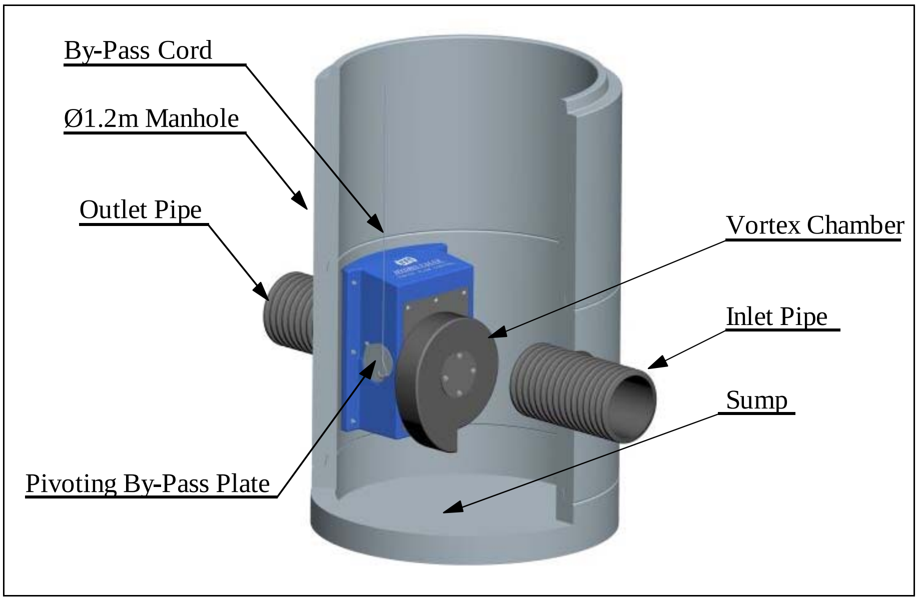

Figure 2.16 – Vortex Valve Installed in Ø1.2m manhole

3.0 Introduction

The design approach taken, was to design and develop a test rig for generating a head / discharge curve from a standard size flow control device. In order to be able to test an actual unit a full scale test rig would have to be developed, a full scale model was used because of the inaccurate assumptions that are associated with scaled models.

A standard size manhole of 1.2 meters in diameter was selected because of it widespread use in storm water drainage systems along with the fact that up to 90% of all current vortex flow control devices on the market fit into this size of manhole [16,17].

3.1 Objectives

- Create a water source in the manhole which can be controlled to (a) keep the head constant and (b) increase the head as desired.
- Incorporate an incremented sight glass in the manhole to give the operator a visual indication of the water level in the manhole.
- The ability to measure the flow rate out of the vortex valve at various head heights.

3.2 Test Rig Manhole

All storm water manholes are installed below ground because they operate a gravity flow system but for this test rig an over ground manhole was selected for the following reasons:

- The ability to visually see the level in the manhole through a sight glass.
- Easy access
- The ability to visually inspect for leaks
- The cost benefit
- The advantage of not needing an underground storage tank

A supplier was identified that could custom fabricate a high density polyethylene manhole to the required design. The design objectives of the manhole were as follows:

- Internal diameter to suit mounting coupler design
- Overall height capable of testing to a head height of 2 meters
- Watertight at base
- Outlet Hole
- Outlet pipe is sufficient height to empty into a holding / measuring tank
- Internal Ladder for access
- Integrated incremented sight glass

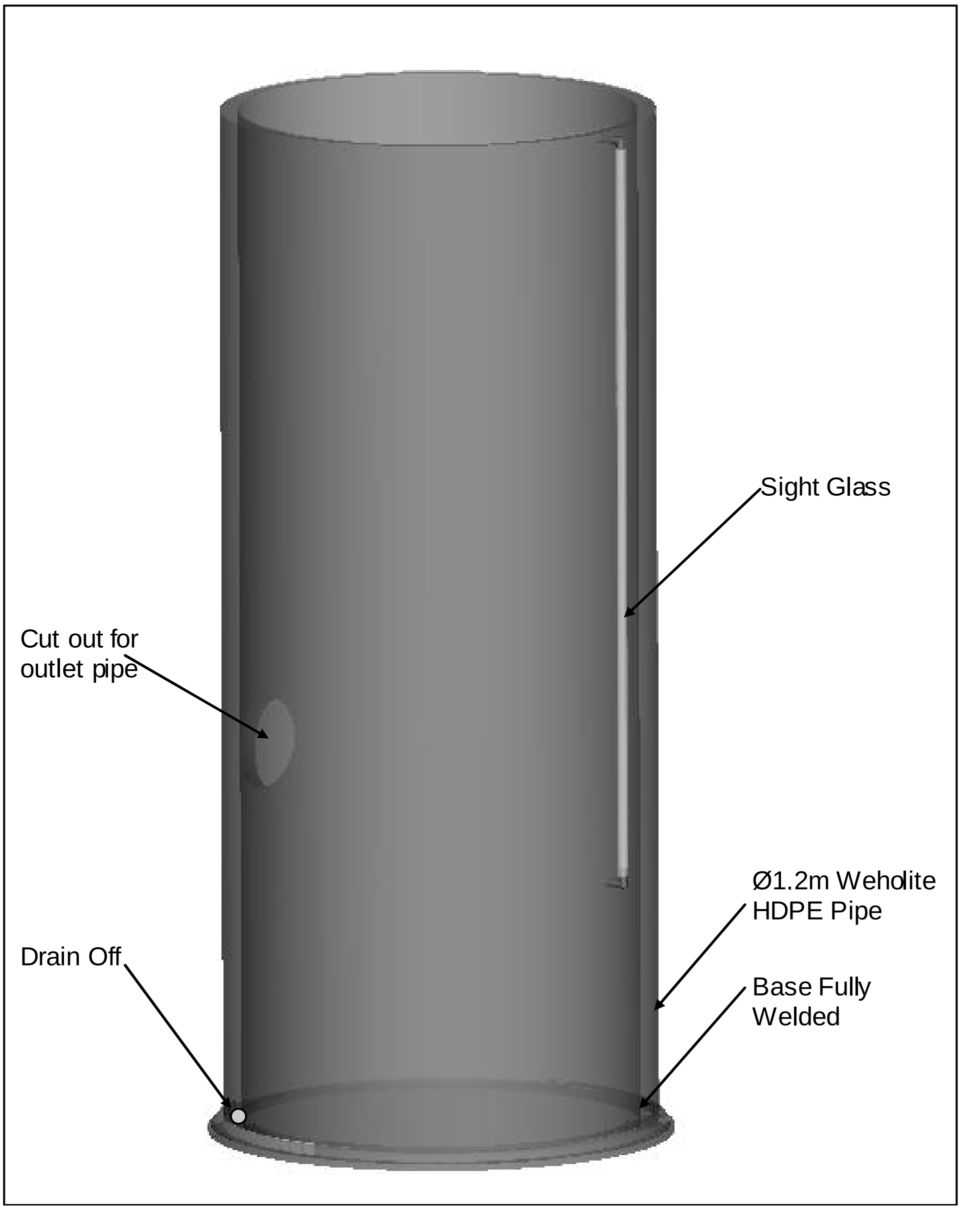

Figure 3.1 – Test Rig Manhole

3.2.1 Manhole Specification

Size:	Ø1.2m (Internal) X 3.2m High
Capacity:	3600 Litres
Material:	High density polyethylene
Outlet Diameter:	300mm – suitable for a 225mm twin wall drainage pipe
Ladder:	Standard Aluminium ladder securely bolted to inside of manhole
Base:	20mm HDPE sheet welded all round internally and externally
Sight Glass:	Ø25mm transparent semi rigid tube
Drain off Valve:	25mm level operated aluminium ball valve

3.3 Flow Measurement Device and Water Holding Tank

There were three main options available when choosing a method of measuring the flow exiting the manhole through the vortex flow control device.

- An open channel flow meter
- An ultrasonic flow meter
- Weighing the volume of water exiting the system over a known period of time.

After an initial investigation it was discovered that both the open channel flow meter and the ultrasonic flow meter were very expensive and have a budget cost of between €2,000 and €4,500. The author had access to a suitable weighing scales and holding tank so the option of weighing the volume of water exiting the system over a known period of time was chosen.

Data logging software was purchased and connected to the control panel of the weighing scales via a laptop computer, this allowed live readings of the weight of water (and therefore capacity of water) to be taken. The flow rate is determined by weighing the water that flows through the vortex valve over a set period of time. The weight in kg's is the capacity in litres (assuming a density of water of 1000kg/m³), this is then divided by the number of seconds the test was run at a constant head height to give the flow rate in litres per second.

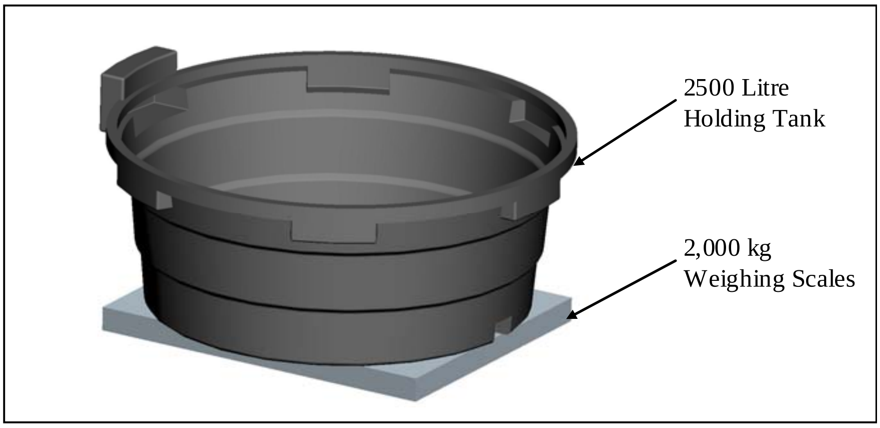

Figure 3.2 – Test Rig Holding Tank and Weighing Scales

3.3.1 Weighing Scales and Holding Tank Specification

Holding Tank Size:	Ø2.0m X 0.8m
Capacity:	2500 Litres
Material:	High density polyethylene
Weighing Scale Size:	1.5m X 1.5m X 0.15m
Weighing Scale Max Reading:	2,000kgs
Weighing Scale Increments:	0.01kgs

3.4 Water Supply to Manhole

There were two main options available to get a water supply into the manhole:

a) To pump water in from a reservoir tank.
b) To gravity feed water into the manhole from a header tank

The main constraint was the maximum flow rate at which the water would enter the manhole and for what duration. The maximum flow rate into the manhole would have to be greater than the maximum flow exiting the manhole from the vortex valve on test. The maximum flow capability of the test rig would be limited by the physical size of the pipe work entering the tank and the pressure from the water source.

Both options available were capable of delivering large flow rates with the pumped options the most suitable because of the consistent flow rate. The main decision in choosing either the pumped or gravity fed options was based on cost. A cost comparison was carried out on each option as seen in table 3.1 below.

Components	Pumped Option Cost	Header Tank Option Cost
Pump with 15l/s outlet and head of 3.5m	€1,650	
100mm Pipe work for Pump	€125	
Header Tank And Frame		€300
Standard Support Frame		€150
Custom Support Frame		€100
Pipes & Fittings		€150
Pump to fill header tank		€650
Total Cost	€1,775	€1,350

Table 3.1 – Cost Comparison on Water Supply

It can be seen that the pumped option is more expensive than the header tank by €425, the pumped option is the preferred option but due to cost constraints the header tank option was selected. The header tank is a 2,000 litre plastic tank with a steel support frame, this was installed on top of another standard support frame and a custom support frame to lift the exit of the header tank to a point above the top of the manhole. A 100mm PVC pipe was used to connect the exit of the header tank to the manhole. See assembly section for more details.

The maximum flow rate from the header tank was expected to be between 10-20 l/s depending on the head of water in the tank and efficiency losses through the pipe work.

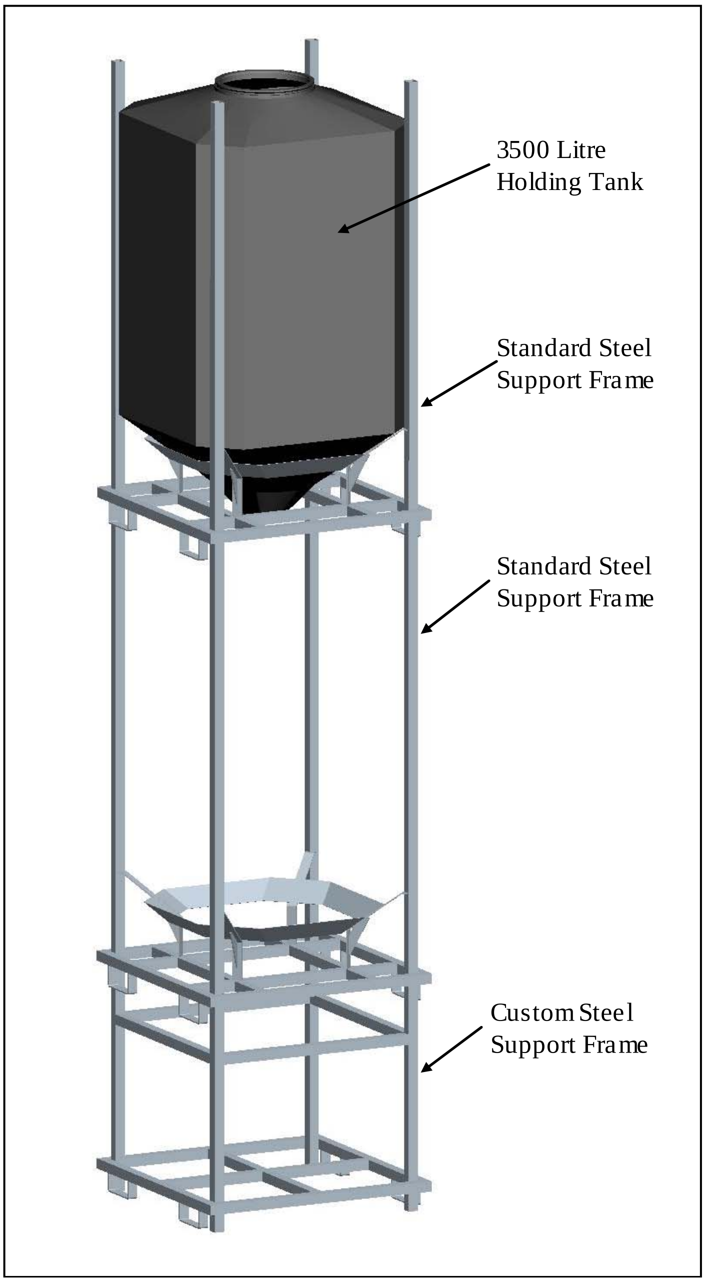

Figure 3.3 – Raised Header Tank

3.4.1 <u>Header Tank Specification</u>

Holding Tank Size:	Approximately 1.5m X 1.5m X 2m
Capacity:	2500 Litres
Material:	High density polyethylene
Support Frame Material:	Steel (Galvanised)
Outlet Pipe Size:	100mm
Outlet Seal:	100mm In situ Rubber Seal
Pump to fill header tank	ABS Submersible pump (model 445)

3.5 Test Rig Assembly

All components of the test rig were assembled as shown below in figure 3.4. The flow through the test rig is as follows.

- The header tank is initially filled with the 100mm ball valve in the off position.
- The ball valve is then opened which allows the manhole to fill to the invert of the vortex valve outlet pipe through the 100mm header tank outlet.
- Once the water starts to flow out of the vortex valve outlet pipe and into the holding tank the ball valve is turned to the off position.
- The header tank is topped up and the rig is ready for initial testing.

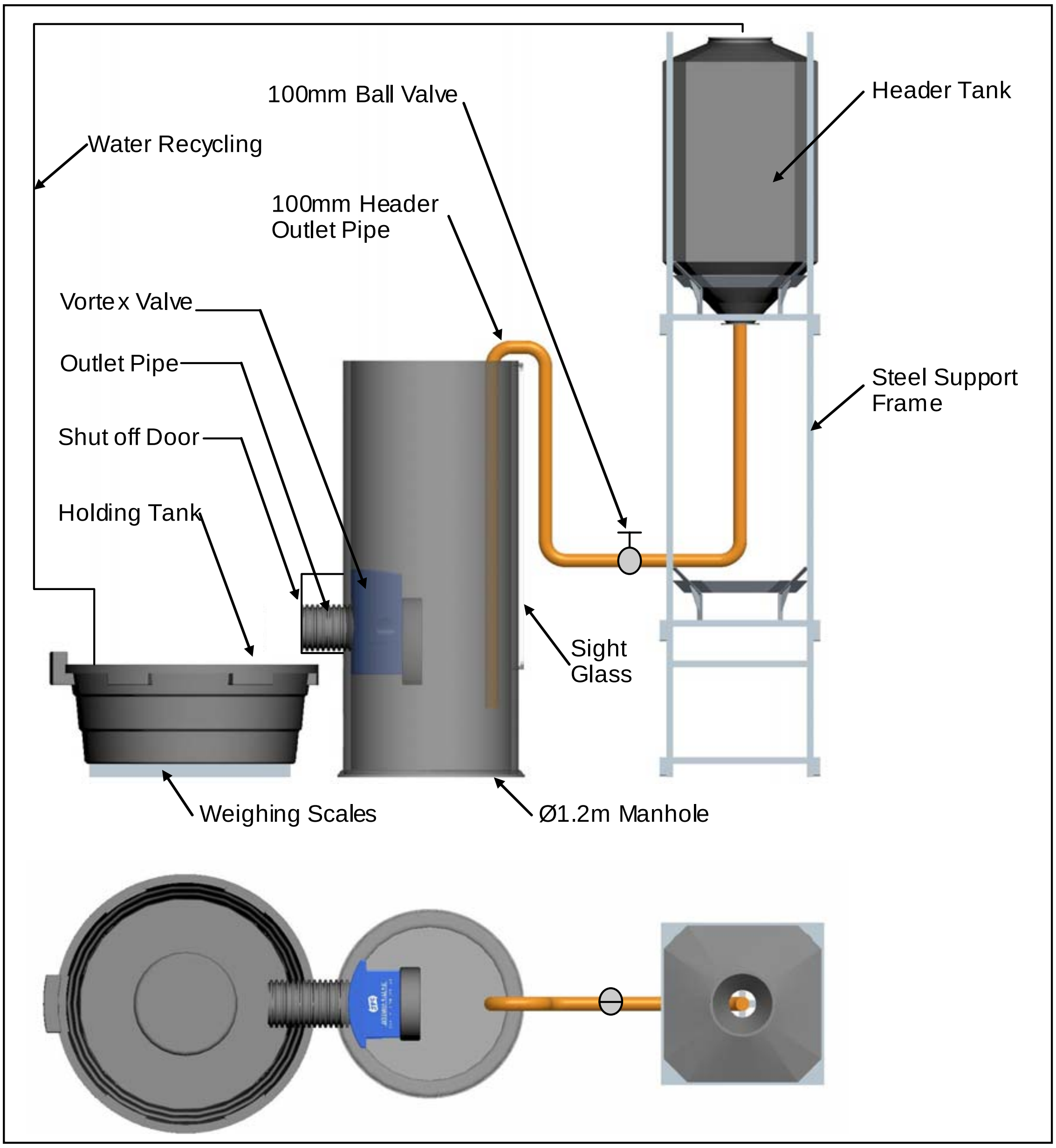

Figure 3.4 - Test Rig Assembly

Figure 3.5 – Photographs of Test Rig

3.6 Test Procedure

The test procedure was designed to calculate the flow rate from the vortex valve at head heights incrementing from 0 to 2000mm in steps of 100mm. By combining and graphing all these flow rates and head heights the performance characteristic of the vortex valve can be generated.

The following steps were carried out in sequence to test the performance curve of a vortex valve:

- Fill the header tank fully and fill the manhole to the point where water starts to exit the outlet pipe i.e. zero head.
- Fill the holding tank with 100mm of water. This removes any fluctuations in the weighing scale readings associated with the water falling from the outlet pipe into the holding tank.
- Open the ball valve allowing water flow into the manhole through the vortex valve and into the holding tank.
- Once the water reaches a head height of 100mm adjust the ball valve and keep the head height constant.
- The recording equipment connected to the weighing scales was activated to record the weight every 2 seconds over a period of 30 seconds. This gave an accurate account of the volume of water that passed through the valve over that time period at a constant head height.
- The flow rate at that particular head height was calculated by dividing the change in mass of the tank in kg's by the duration of the test in seconds. This gave mass flow rate in kg/s and therefore l/s assuming a density of 1000 kg/m^3 for water.
- The holding tank was pumped into the header tank and topped up as required from a water hose until the tank was full again.
- The head height was increased to 200mm and the procedure repeated until the mass flow rate was obtained.
- This test was carried out at increments of 100mm between 0 and 2000mm.
- All the test results were plotted in a graph of head height vs. flow rate to give the performance characteristic of the valve.

3.7 Test Rig Performance Test

It was necessary to establish the maximum flow rate that could be passed through the test rig before initial prototype geometry was selected. A simple test was carried out as follows:

- A vortex valve mounting adaptor was attached to the inside of the manhole with no vortex chamber assembly. (This allowed unrestricted flow through to the holding tank)
- The header tank was filled and the manhole sump primed (therefore when the ball valve is opened water will flow into the holding tank)
- The 100mm ball valve is opened until there is approximately 200mm of water in the holding tank.
- The header tank is refilled from an external water source.
- The weighing scales is set to zero.
- The 100mm ball valve is fully opened for 30 seconds and shut off.
- A reading is taken from the weighing scales of 377.25kgs.
- 377.25kg / 30 sec = 12.575 kg/s = 12.575 l/s.
- An approximate maximum flow rate of 12.5l/s was obtained for the test rig.

3.8 Initial Vortex Valve Prototype Geometry

An initial prototype geometry was developed to require a maximum flow rate of less than 12l/s. An overall swirl diameter of 350mm was arbitrarily selected, an outlet diameter of 100mm was again arbitrarily selected as a starting outlet diameter. The inlet height and width of the unit of 88mm was selected as this provided approximately the same inlet and outlet cross sectional area.

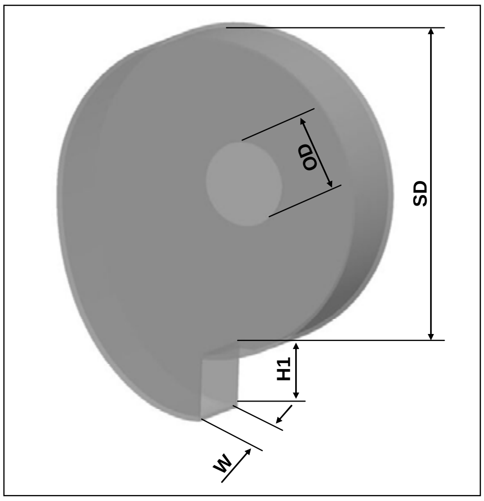

Figure 3.6 - Initial Prototype

SD =	Swirl Diameter (Internal)	(350mm)
OD =	Orifice diameter (Outlet)	(100mm)
W =	Width (Internal)	(88mm)
H1 =	Height (Internal)	(88mm)

3.9 Initial Vortex Valve Prototype Performance

The unit was manufactured and tested as outlined in section 3.6 to obtain its performance characteristics. Figure 3.7 shows the prototype performance curve plotted with performance curve of a Ø45.5mm orifice plate as it approximately matches the vortex valve curve after the kickback point.

At the start of the performance curve (red) water is freely flowing through the vortex valve unrestricted. Once a head height of approximately 350mm is obtained, the flush flow part of the curve is reached at approximately 4.6l/s. The flow rate then begins to slow down as the head height increases, at a head height of approximately 600mm the kickback point is reached at approximately 3.8l/s. The vortex valve performance curve now begins to approximately match that of a Ø45.5mm orifice plate to a maximum tested height of 2m.

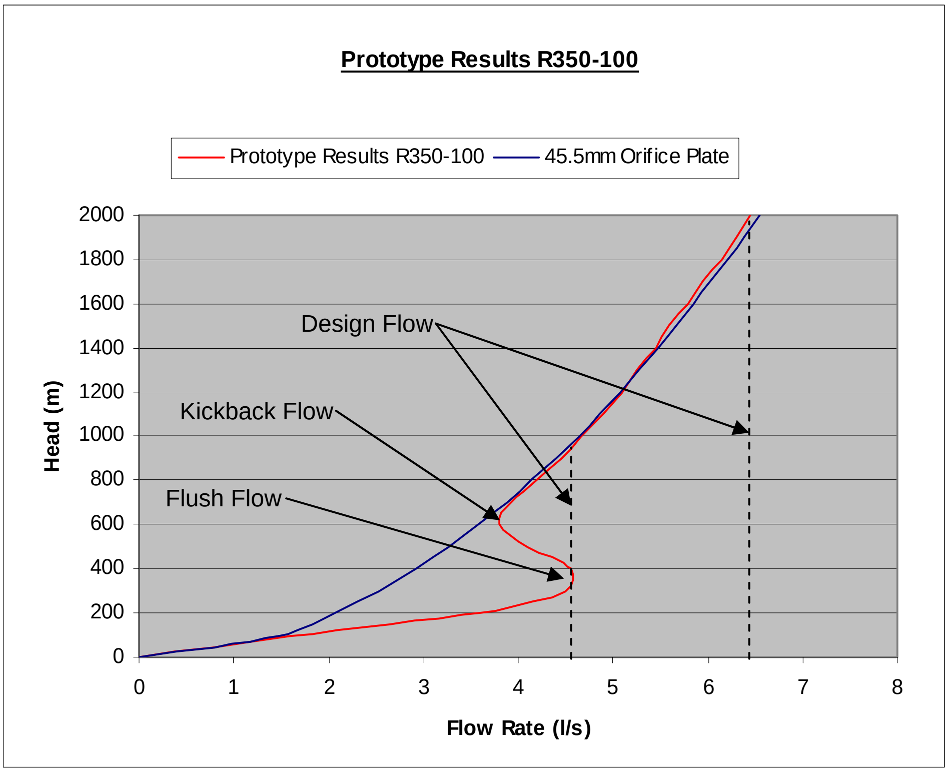

Figure 3.7 - Initial Prototype Performance Curve

The interesting part of the curve is the “s” shape due to the flush flow and kickback flow. The reason for this is due to an air pocket that is created in the vortex chamber as the head height increases (see figure 3.8). Once the head height reaches the top of the outlet pipe an air pocket is created in the top of the vortex chamber which causes a pressure deferential. This can be seen on the performance curve where the flow rate starts to decrease with increased head height between the flush flow and kickback flow points. As the head height increases, enough hydrostatic pressure is generated to move the air pocket and initiate vortex motion.

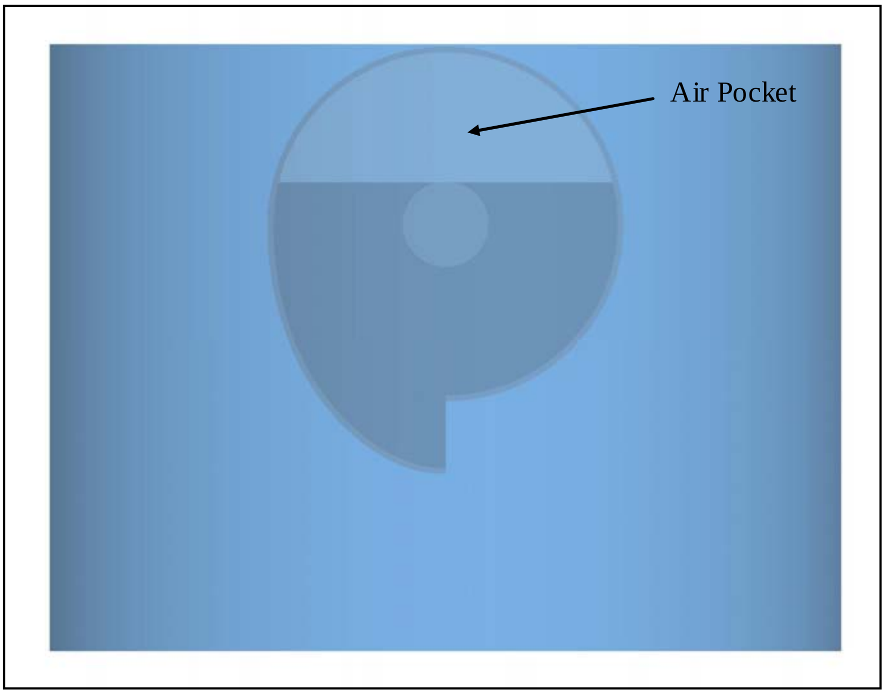

Figure 3.8 – Air Pocket on Vortex Chamber

The characteristics of the unit were found to be the following:

Swirl Diameter (Internal)	(350mm)
Orifice diameter (Outlet)	(100mm)
Width (Internal)	(88mm)
Height (Internal)	(88mm)

Design Flow:	4.6 – 6.41 l/s depending on head height
Flush Flow:	4.6 l/s
Kickback flow:	3.8 l/s

Corresponding Orifice Plate Diameter after Kickback Point: Ø45.5mm

CSA or Vortex Valve Outlet vs. CSA or Orifice Plate Outlet: Vortex Valve 4.8 times larger

4.0 Introduction

Following on from the initial prototype testing in the last chapter, a series of tests were carried out to determine the influence of each of the main geometric variables on the performance of the vortex valve. The following geometric variables were varied individually:

a) Outlet opening diameter
b) Width of the vortex valve
c) Inlet height of the vortex valve
d) Overall Swirl Diameter

From the results of the testing a relationship was chosen between each of the geometric variables based on the following objectives:

1. Outlet opening diameter to have a cross sectional area 3 – 6 times that of the opening on an orifice plate of the same specification.
2. Inlet and outlet opening to be of similar size to minimise the possibility of a blockage when in service.
3. The distance between the kickback point and the flush flow point along the X axis is to be minimised to allow the design flow to be reached at lower head heights.
4. “Area A” is to be maximised while keeping the kickback line as close to vertical as possible (see figure 4.1 below). This will maximise the flow through the vortex valve as the head height increases.

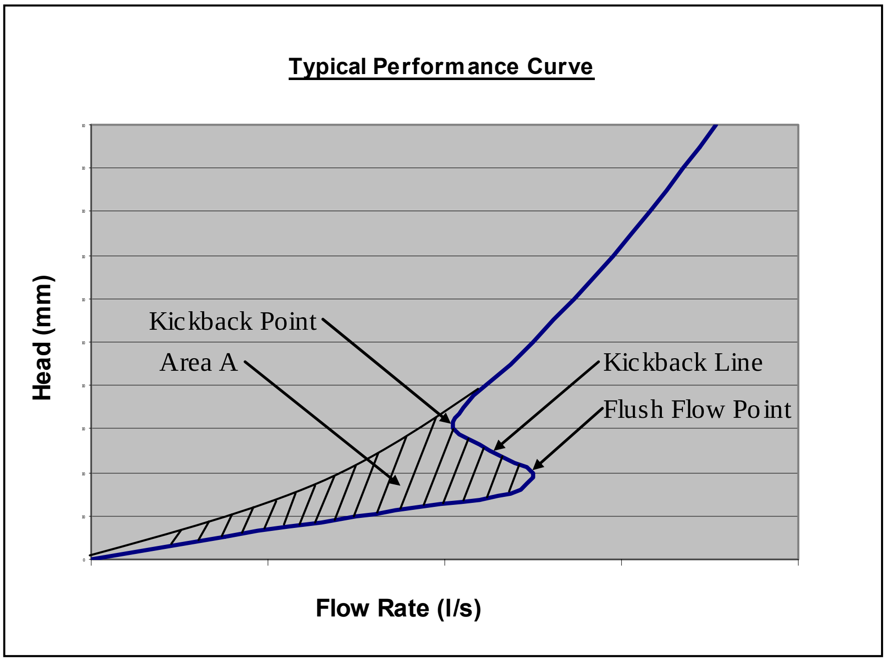

Figure 4.1 – Area A on Typical Performance Curve

4.1 Varying the Vortex Valve Outlet Diameter

Following the initial prototype testing, four more units were manufactured with the same geometry as the initial prototype except for the outlet orifice diameter. Two units were manufactured with larger openings and two with smaller openings as outlined below. Each unit was individually tested to establish the relationship between the diameter of the outlet orifice and the flow curve of the unit. The following orifice diameters were tested:

Unit 1 – Outlet Orifice Ø50mm

Unit 2 – Outlet Orifice Ø75mm

Unit 3 – Outlet Orifice Ø100mm (initial prototype)

Unit 4 – Outlet Orifice Ø125mm

Unit 5 – Outlet Orifice Ø150mm

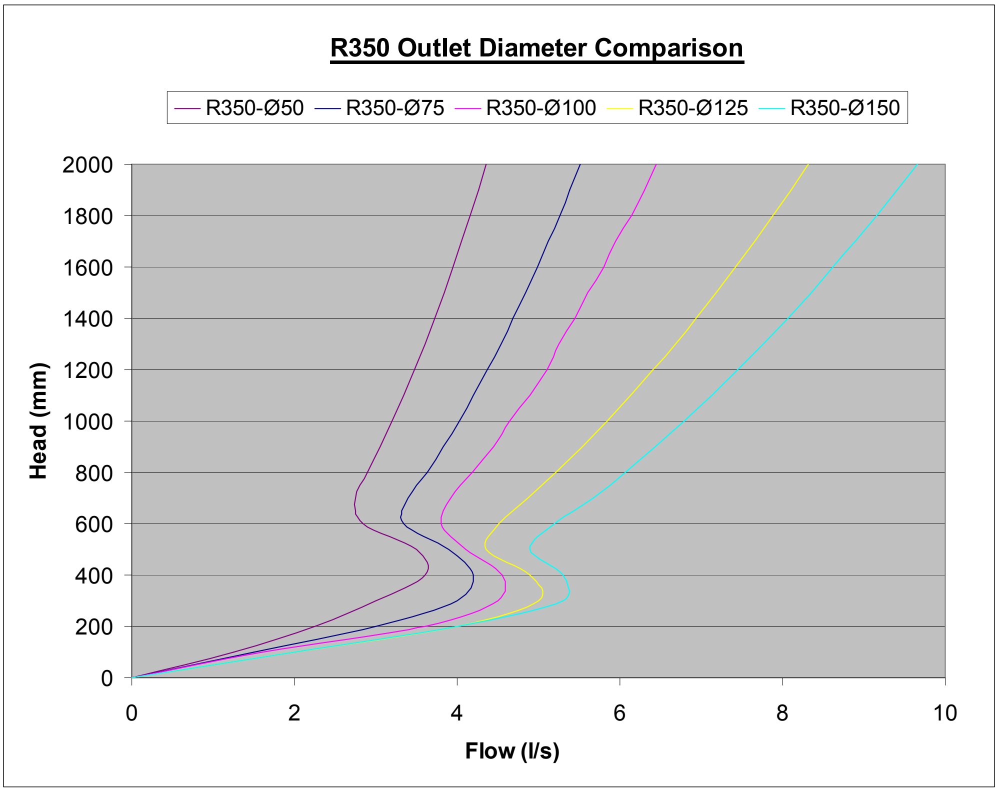

Figure 4.2 – Varying the Outlet Diameter

The performance curve of each of the five units tested are plotted in figure 4.2 above, the flow capacity of each unit increases as the outlet opening diameter is increased. It can be seen that as the outlet opening diameter increases the kickback and flush flow point of the curve decreases. The distance between the flush flow and kickback flow points also decreases as the outlet opening diameter is increased. The design flow region of the curve shows a large increase as the outlet opening diameter is increased.

4.1.1 Satisfying Design Objectives

The first objective was for the vortex valve outlet cross sectional area to be 3 – 6 times larger than a corresponding orifice plate to minimise blockages. It can be seen from table 4.1 that it needs to be a minimum of 75mm in diameter to satisfy this constraint (Curve 2).

Vortex Valve Outlet Diameter (mm)	Vortex Valve CSA (mm²)	Corresponding Orifice Plate Diameter (mm)	Corresponding Orifice Plate CSA (mm²)	CSA Difference (times)
50	1,963	38	1,134	1.73
75	4,416	42.5	1,418	3.11
100	7,850	45.5	1,625	4.83
125	12,266	50.5	2,002	6.13
150	17,663	54.5	2,332	7.58

Table 4.1 – Cross Sectional Area Analysis

The data above in table 4.1 was plotted below in figure 4.3. It can be seen that as the vortex valve outlet opening diameter increases, the corresponding orifice plate diameter to achieve the same specification above the kickback point increases in an approximately linear fashion.

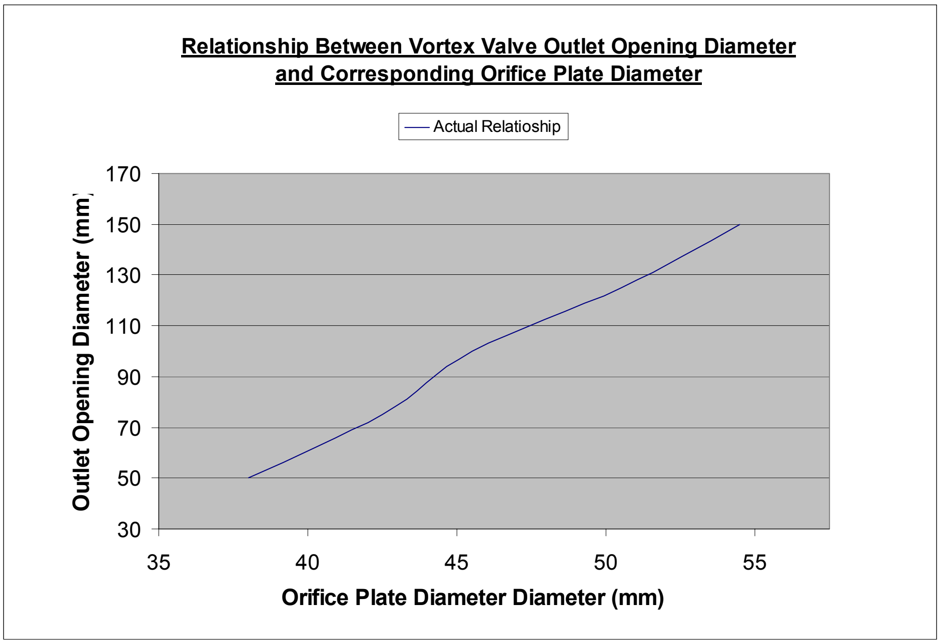

Figure 4.3 – Outlet Diameter and Orifice Plate Relationship

The third objective is best satisfied by the largest vortex valve outlet opening diameter (Ø150mm – Curve 5) in that its design flow range starts at the lowest head height. The fourth objective is best satisfied by curve 3 with the Ø100mm outlet as after this point "area A" begins to decrease. The best curve that satisfies all constraints is curve 3 with the Ø100mm outlet opening diameter.

4.1.2 Relationship Analysis

A relationship analysis was carried out to determine if the kickback part of the performance curve could be linearly modelled as the outlet opening diameter is increased. This information will be then used in deciding the best way to build a model to predict the performance curve under a given specification.

The effect of the increased outlet opening diameter on the flush flow point and the kickback flow point is shown in figure 4.4 below. As the outlet opening diameter increases so does the flush flow point and kickback flow point, both increase the flow rate at different rates but they both can be linearly approximated.

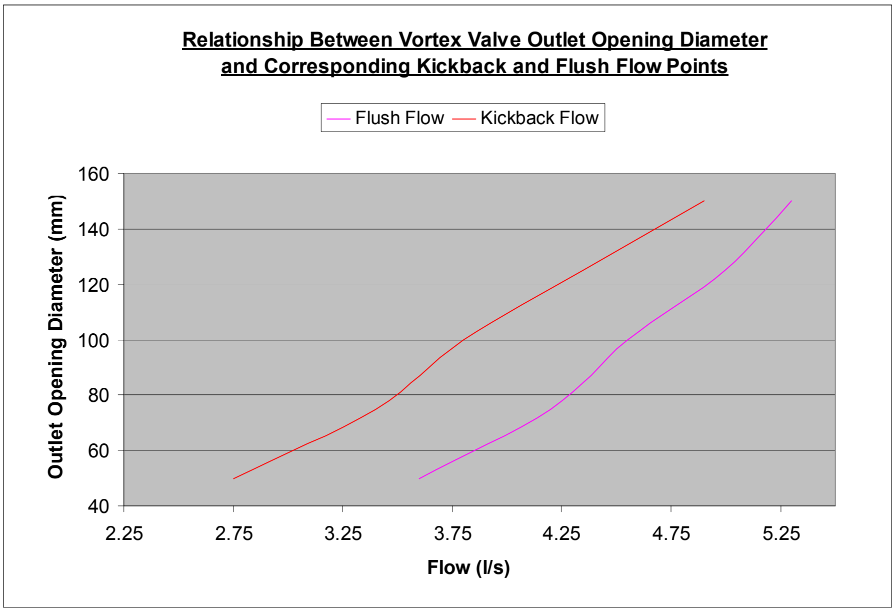

Figure 4.4 – Outlet Diameter and Flow Relationship

It can be seen below in figure 4.5 that as the outlet opening diameter increases the head height required to reach the kickback flow point decreases. This is because with the larger orifice opening there is less of an air pocket trapped in the top of the vortex valve thus requiring less hydrostatic pressure to initiate the vortex (see figure 3.8). The kickback flow is approximately linear between outlet opening diameters of Ø70mm and Ø120mm with the flush flow approximately linear between Ø50mm and Ø120mm.

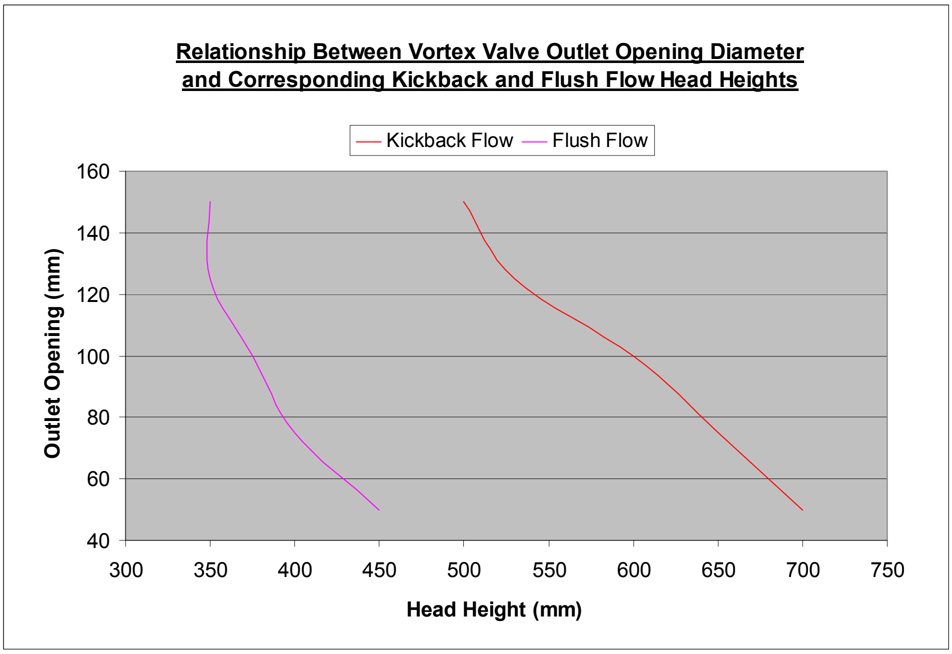

Figure 4.5 – Outlet Opening Diameter and Head Relationship

4.1.3 Summary of Increasing Vortex Valve Outlet Opening Diameter

The outlet opening diameter was increased from 50mm to 150mm in increments of 25mm. The following conclusions were made on the effect of the increase on the performance curve of the unit.

- Linearly increases the flow allowed to pass through the unit
- Linearly increases the kickback and flush flow point in flow axis
- Linearly decreases the kickback and flush flow point in head height axis
- Curve 3 with an outlet opening diameter of Ø100mm best satisfies all design objectives as set out in section 4.0.

4.2 Varying Vortex Valve Width

The initial prototype was again used as the base geometry, all variables were kept constant apart from the internal width of the unit as outlined below.

OD = Orifice diameter (Outlet) (100mm)

SD = Swirl Diameter (Internal) (350mm)

W = Width (Internal) (75,100,125,150,175mm)

H = Inlet Height (Internal) (88mm)

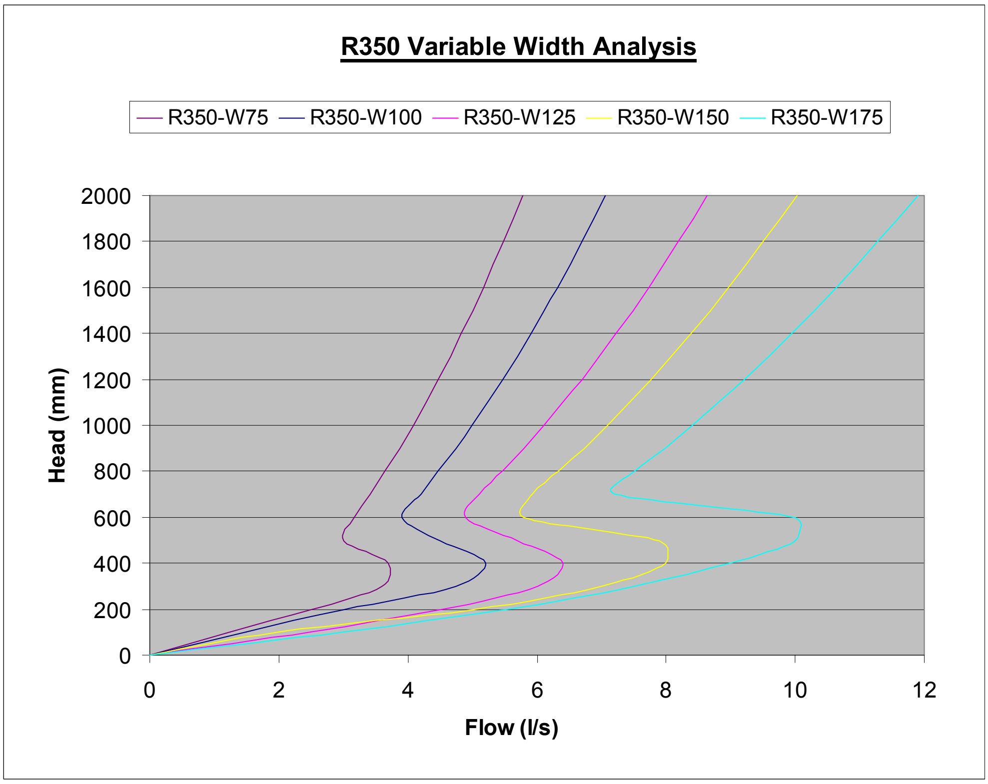

Figure 4.6 – Varying the Width of the Vortex Valve

The performance curve of each of the five units tested are plotted in figure 4.6 above, the flow capacity of each unit increases as the width of the vortex valve is increased. It can be seen that increasing the width of the vortex valve from 75mm to 175mm increases the flow by 4-7l/s. Increasing the width also increases the kickback point of the curve and moves the kickback line of the curve to a more horizontal position. As the width is increased it also increases the head height required to reach the kickback and flush flow points.

4.2.1 Satisfying Design Objectives

The first objective was for the vortex valve outlet cross sectional area to be 3 -6 times larger than a corresponding orifice plate to minimise blockages. It can be seen from table 4.2 that it can be up to a maximum of 150mm in width to satisfy this constraint.

Vortex Valve Width (mm)	Vortex Valve Outlet CSA (mm²)	Corresponding Orifice Plate Diameter (mm)	Corresponding Orifice Plate CSA (mm²)	CSA Difference (times)
75	7,850	42.5	1,418	5.54
100	7,850	47.75	1,790	4.39
125	7,850	52	2,123	3.70
150	7,850	56	2,462	3.19
175	7,850	61.5	2,969	2.64

Table 4.2 – Width Analysis

The data above in table 4.2 was plotted below in figure 4.7. It can be seen that as the vortex valve width is increased the corresponding orifice plate diameter to achieve the same specification above the kickback point increases in an approximately linear fashion.

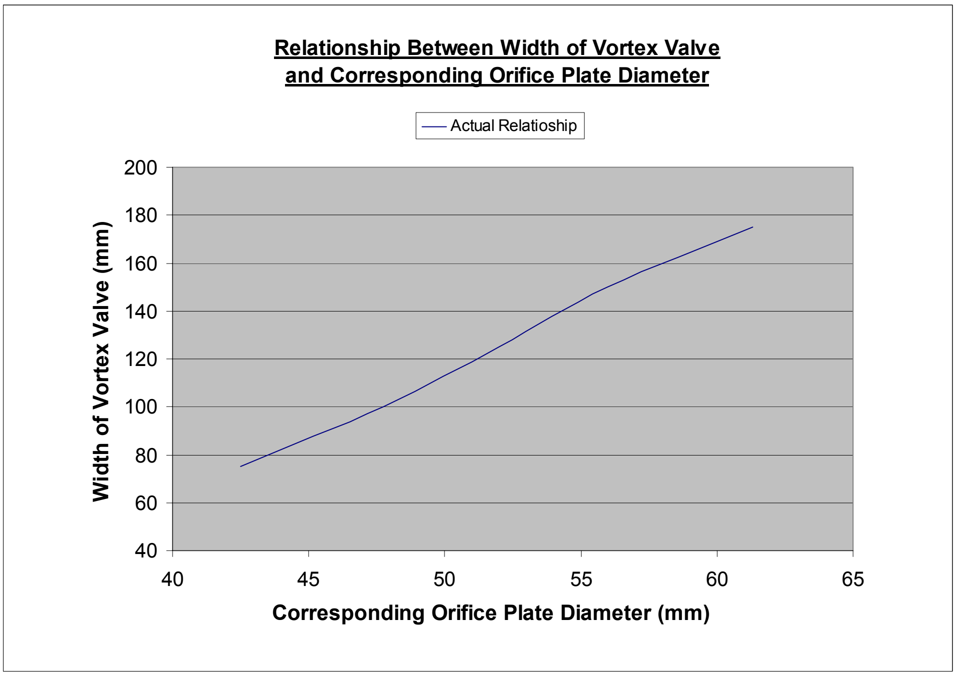

Figure 4.7 – Vortex Valve Width and Orifice Plate Relationship

The second objective is best satisfied by curve 2 at a width of 100mm.The third objective is best satisfied by the smallest width vortex chamber at 75mm because its design flow range starts at the lowest head height. The fourth objective is best satisfied by the largest width vortex valve at 175mm but it has a big disadvantage due to the high head height required to reach the design flow range. The curve that best satisfies all objectives is curve 2 with a width of 100mm.

4.2.2 Relationship Analysis

A relationship analysis was carried out to determine if the kickback part of the performance curve could be linearly modelled as the width of the vortex chamber is increased. This information will be then used in deciding the best way to build a model to predict the performance curve under a given specification.

The effect of the increased width on the flush flow point and the kickback flow point is shown in figure 4.8 below. As the width increases so does the flush flow at an approximately linear rate after 4.5l l/s. The kickback flow increases at a different rate but can be seen to be approximately linear throughout.

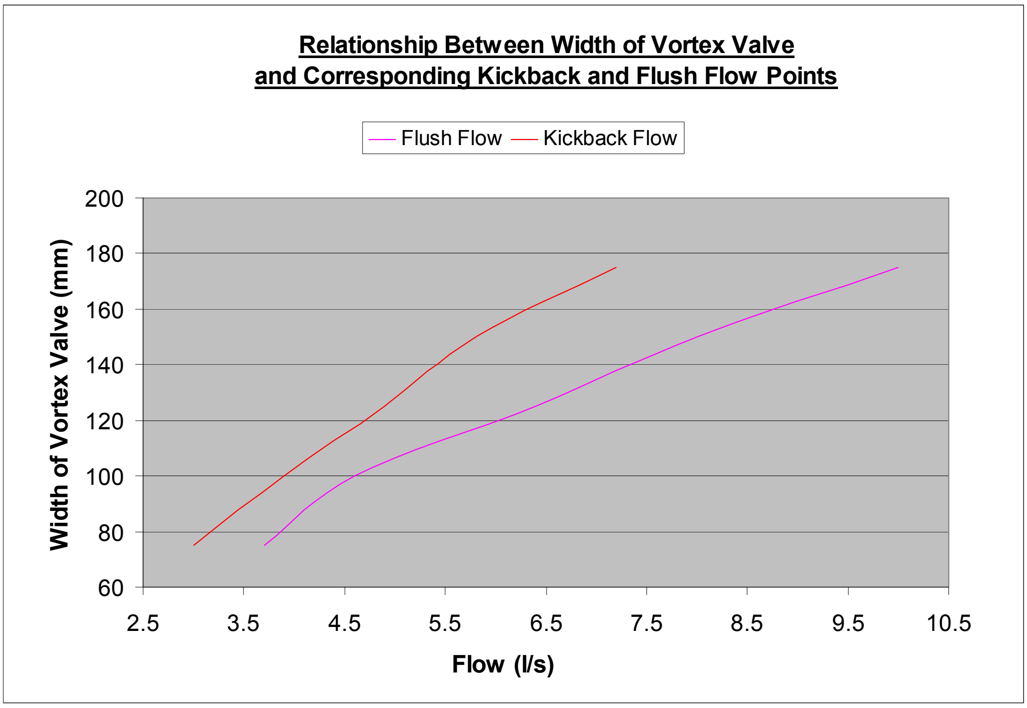

Figure 4.8 – Outlet Diameter and Flow Relationship

As the outlet opening diameter increases the head height required to reach the kickback flow and flush flow points increases. This is because with the larger width vortex valve there is more of an air pocket trapped in the top of the vortex valve thus requiring more hydrostatic pressure to initiate the vortex (see figure 3.8). It can be seen from figure 4.9 they increase in a non linear fashion.

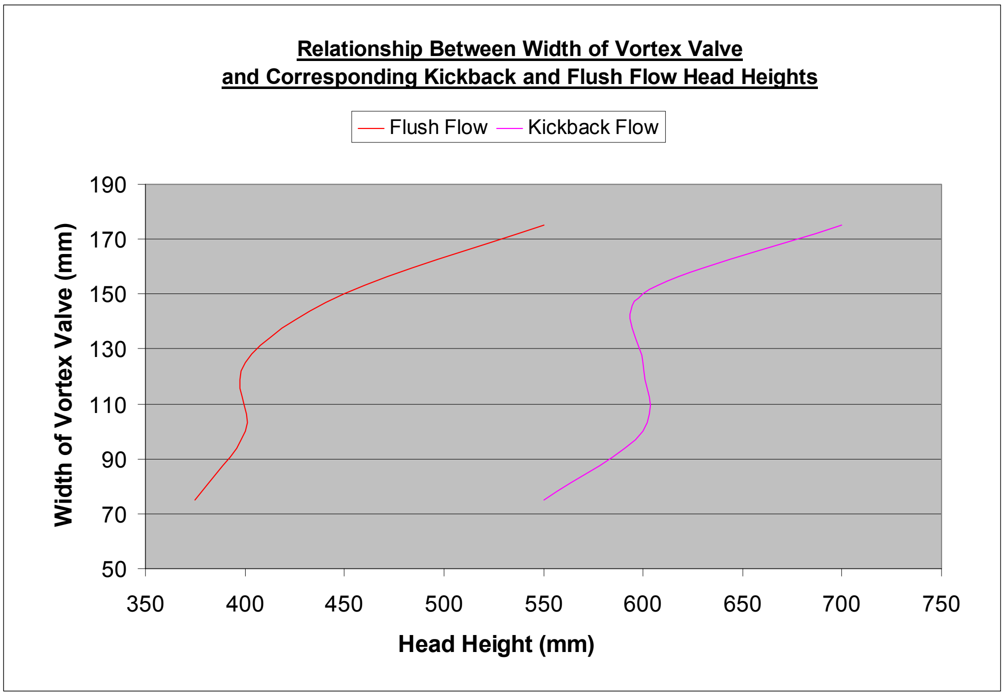

Figure 4.9 – Width and Orifice Plate Relationship

4.2.3 Summary of Increasing Width of Vortex Valve

The width of the vortex valve was increased from 75mm to 175mm in increments of 25mm. The following conclusions were made on the effect of the increase in the width of the vortex valve.

- Linearly increases the flow allowed to pass through the unit after the kickback point
- Linearly increases the kickback and flush flow point in the flow axis
- Non-linearly increases the kickback and flush flow point in head height axis
- Curve 2 with a width of Ø100mm best satisfies all design objectives as set out in section 4.0.

4.3 Varying Vortex Valve Inlet Height

The initial prototype was again used as the base geometry, all variables were kept constant apart from the inlet height as outlined below.

OD = Orifice diameter (Outlet) (100mm)
SD = Swirl Diameter (Internal) (350mm)
W = Width (Internal) (88mm)
H = Inlet Height (Internal) (48,68,88,108 and128mm)

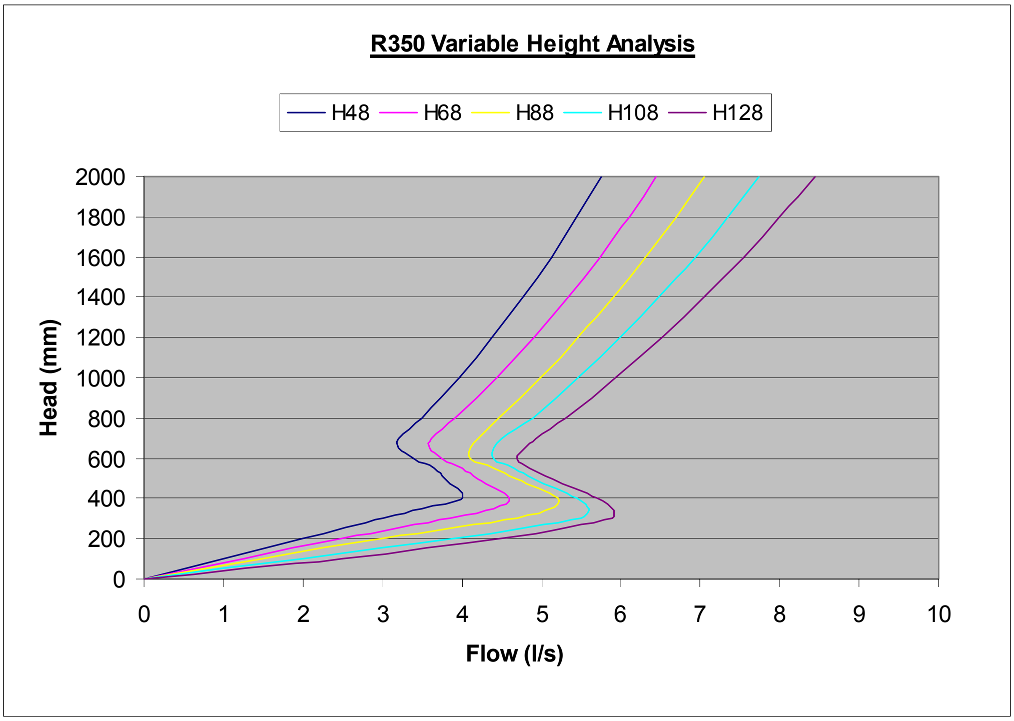

Figure 4.10 – Variable Inlet Height Analysis

The performance curves of each of the five units tested are plotted in figure 4.10 above. The flow capacity of each unit increases by approximately 2-3l/s as the inlet height of the unit is increased from 48mm to 128mm in increments of 20mm. As the inlet height is increased it decreases the head heights required to reach both the flush flow and kickback flow points. This is because as a larger volume of water is allowed to enter the vortex chamber less hydrostatic pressure is required to initiate the vortex motion. The slope of the kickback line is quite similar at each inlet height.

4.3.1 Satisfying Design Objectives

The first objective was for the vortex valve outlet cross sectional area to be 3 -6 times larger than a corresponding orifice plate to minimise blockages. It can be seen from table 4.3 that it needs to be a minimum of 75mm in diameter to satisfy this constraint (Curve 2).

Inlet Height (mm)	Vortex Valve Outlet CSA (mm^2)	Corresponding Orifice Plate Diameter (mm)	Corresponding Orifice Plate CSA (mm^2)	CSA Difference (times)
48	7,850	43	1,451	5.41
68	7,850	45.5	1,625	4.83
88	7,850	47.5	1,771	4.43
108	7,850	50	1,963	4.00
128	7,850	52	2,123	3.70

Table 4.3 – Inlet Height Analysis

The data above in table 4.3 was plotted below in figure 4.11. It can be seen that as the vortex valve inlet height is increased the corresponding orifice plate diameter to achieve the same specification above the kickback point increases in an approximately linearly fashion.

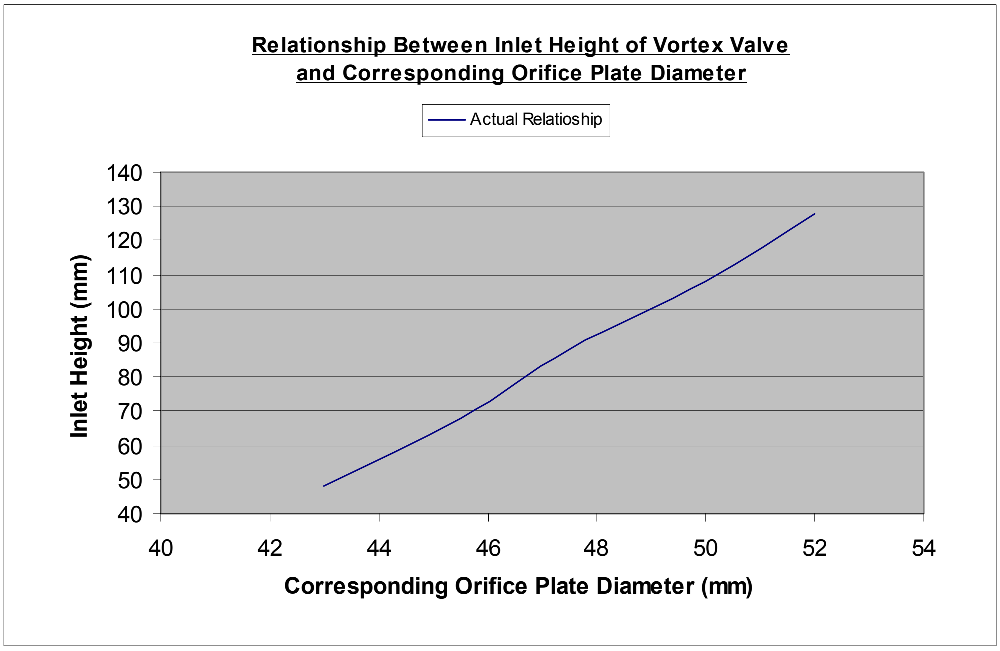

Figure 4.11 – Vortex Valve Inlet Height and Orifice Plate Relationship

The second objective is best satisfied by the inlet height of 108mm. The third objective is best satisfied by the inlet height at 48mm but it can be seen that increasing the inlet height has little effect on the design flow range when compared with the two previous variables. The fourth objective is best satisfied by the largest inlet height at 128mm. The inlet height that best satisfies all constraints is 88mm.

4.3.2 Relationship Analysis

A relationship analysis was carried out to determine if the kickback part of the performance curve could be linearly modelled as the inlet height of the vortex chamber is increased. This information will be then used in deciding the best way to build a model to predict the performance curve under a given specification.

The effect of the increased inlet height on the flush flow point and the kickback flow point is shown in figure 4.12 below. As the inlet height increases so does the flush flow at an approximately linear rate. The kickback flow increases at a similar rate and can also be seen to be approximately linear throughout.

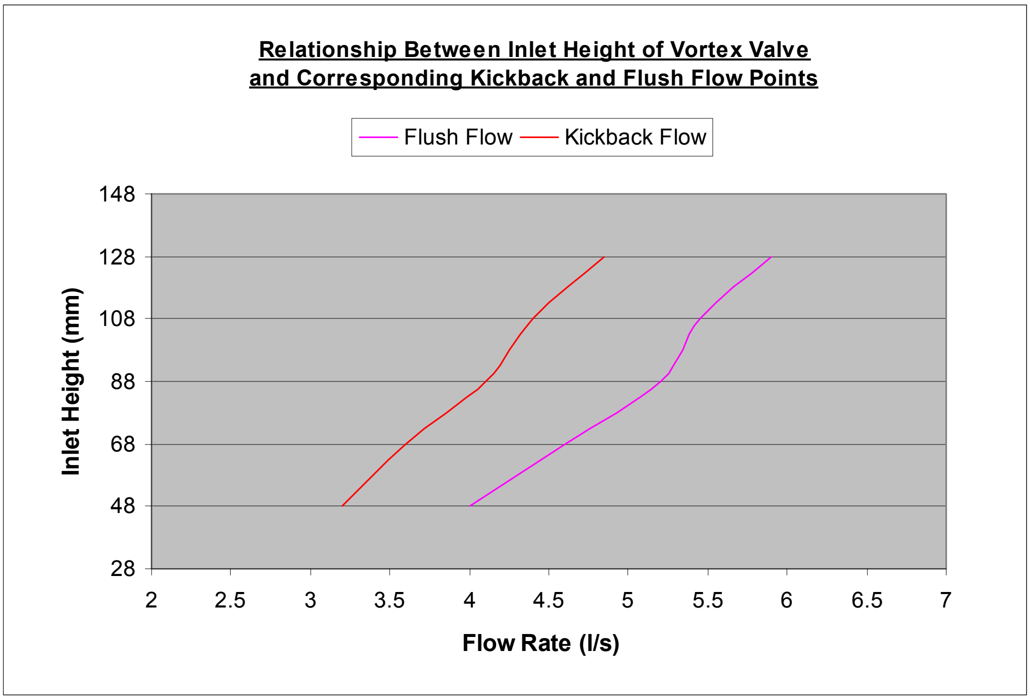

Figure 4.12 – Inlet Height and Flow Relationship

As the inlet height increases the head height required to reach the kickback flow and flush flow points decreases. This is because with the larger inlet height there is more water allowed into the vortex chamber to displace the air pocket trapped in the top of the vortex valve thus requiring less hydrostatic pressure to initiate the vortex (see figure 3.8). It can be seen from figure 4.13 that the flush flow has a linear range between 68mm and 108mm and the kickback flow has a linear range between 68mm and 128mm.

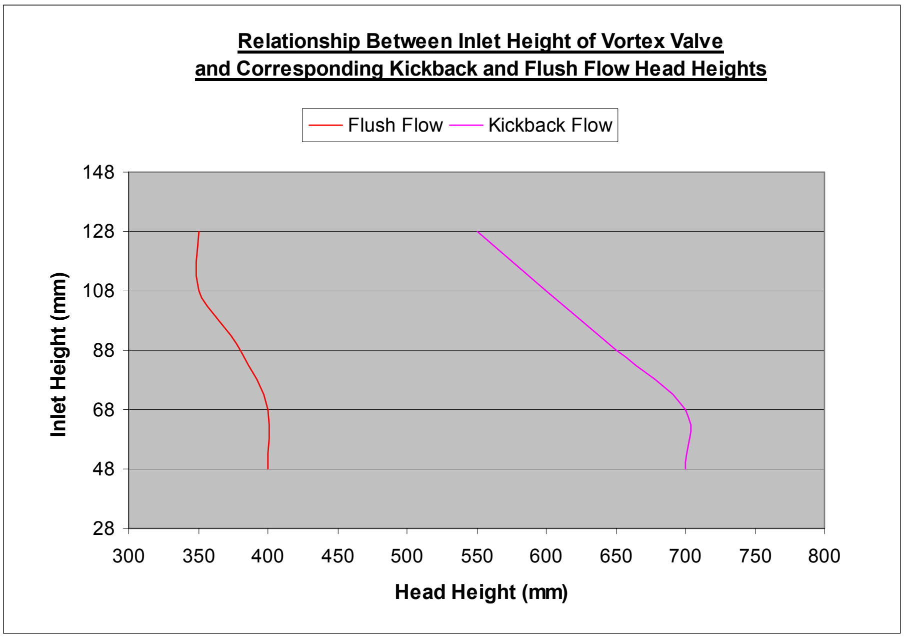

Figure 4.13 – Inlet Height and Head Height Relationship

4.3.3 Summary of Increasing Inlet Height of Vortex Valve

The inlet height of the vortex valve was increased from 48mm to 128mm in increments of 20mm. The following conclusions were made on the effect of the increase in the inlet height of the vortex valve.

- Linearly increases the flow allowed to pass through the unit after the kickback point
- Linearly increases the kickback and flush flow points in the flow axis
- Non-linearly decreases the kickback and flush flow point in head height axis
- Curve 2 with an inlet height of 88mm best satisfies all design objectives as set out in section 4.0.

4.4 Establishing the Relationship between Geometric Variables

Varying the swirl diameter of the vortex valve was not carried out independently of the other variables as with the previous comparisons. The swirl diameter is the largest geometric variable and will therefore have the largest effect on flow rate. It is the main variable that changes in commercial vortex valves and it was decided to select a relationship between each of the other variables and scale the overall geometry as the swirl diameter was increased / decreased.

4.4.1 Outlet Opening Diameter

The outlet opening diameter was constrained by the fact that its CSA was required to be 3-6 times that or a corresponding orifice. Therefore an outlet opening diameter between 75mm and 125mm will satisfy that objective. All objectives are best satisfied using an outlet opening diameter of approximately 100mm as can be seen in section 4.1. The exact size is determined in conjunction with the width of the vortex valve as outlined below in section 4.4.2.

4.4.2 Width of the Vortex Valve

The width of the vortex valve was constrained by the outlet opening diameter as the inlet and outlet openings were required to be of similar size to minimise blockage during service. Therefore it was decided to make the width of the vortex valve and the outlet opening diameter the same size. A ratio of 4:1 between the swirl diameter, and both the outlet opening diameter and the width of the vortex valve will give a size of 88mm. This in turn provides an outlet opening diameter with a CSA 4 times greater than the corresponding orifice plate satisfying the first objective.

4.4.3 Inlet Height of the Vortex Valve

The inlet height of the vortex valve was constrained by both the outlet opening diameter and the width of the vortex valve. To minimise blockages in service the inlet height was set equal to both the width and outlet opening diameter at a ratio of 4:1 with the swirl diameter.

4.5 Varying the Swirl Diameter

The effect of increasing / decreasing the swirl diameter was investigated by testing six units with swirl diameters between 200mm and 450mm in increments of 50mm. The relationship between the swirl diameter and the other geometric variables established in the previous section was used on all units.

SD =	Swirl Diameter (Internal)	(200, 250, 300, 350, 400, 450mm)
OD =	Orifice diameter (Outlet)	(swirl diameter / 4)
W =	Width (Internal)	(swirl diameter / 4)
H1 =	Height (Internal)	(swirl diameter / 4)

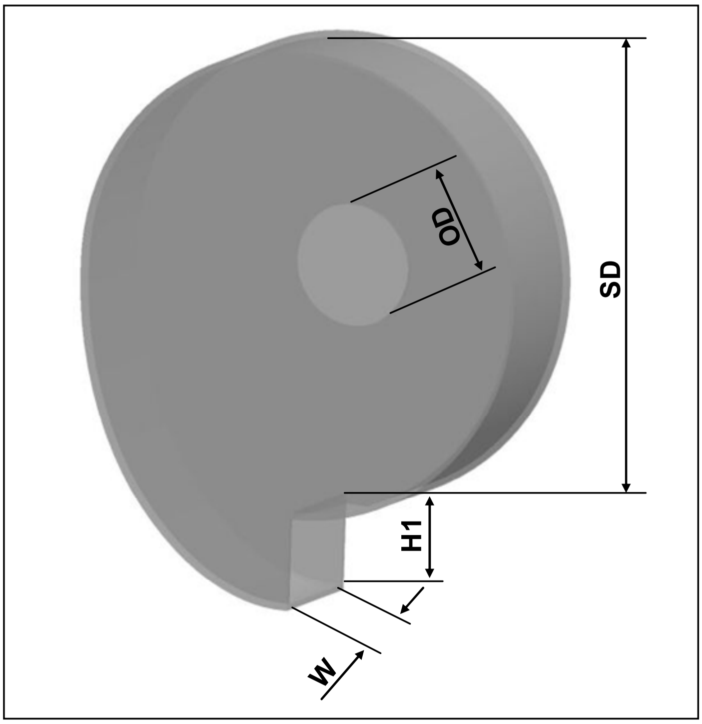

Figure 4.14 – Prototype Geometry

The performance curve of each of the six units tested are plotted in figure 4.15 below, the flow capacity of each unit increases by approximately 7 l/s as the swirl diameter is increased between 200m and 450mm. Figure 4.15 also shows that as the swirl diameter is increased it increases both the flush flow and kickback flow points. It also increases the head height required to reach the flush flow and kickback flow points because of the extra hydrostatic pressure required to move the air pocket and initiate the vortex.

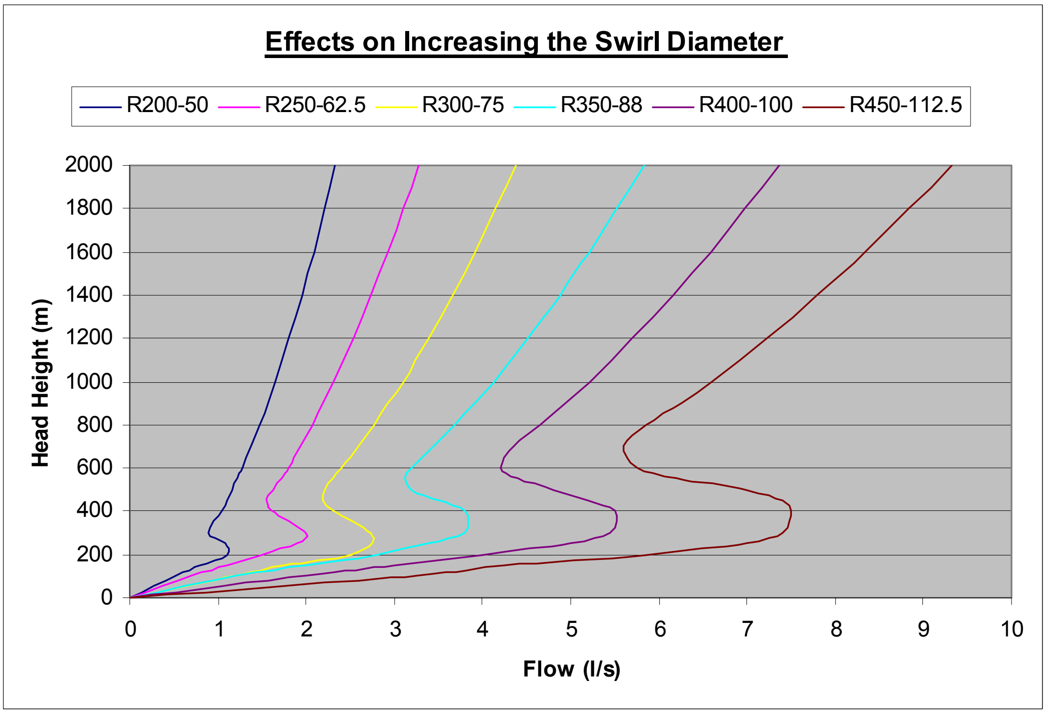

Figure 4.15 – Varying the Swirl Diameter

4.5.1 Relationship Analysis

A relationship analysis was carried out to determine if the performance of the units increased at a linear rate as the swirl diameter is increased. This information will be then used in deciding the best way to build a model to predict the performance curve under a given specification.

The relationship between the swirl diameter of the vortex valve and the corresponding orifice plate diameter of the same specification can be seen below in figure 4.16. It shows a linear relationship between the two in the region of the performance curve above the kickback flow point. Therefore if the orifice plate diameter is known for a specific flow specification, the corresponding vortex valve swirl diameter and therefore the complete vortex valve geometry can be determined.

The effect of the increased swirl diameter on the flush flow point and the kickback flow point is shown in figure 4.17 below. As the swirl diameter increases so does the flush flow and kickback flow at a non linear rate.

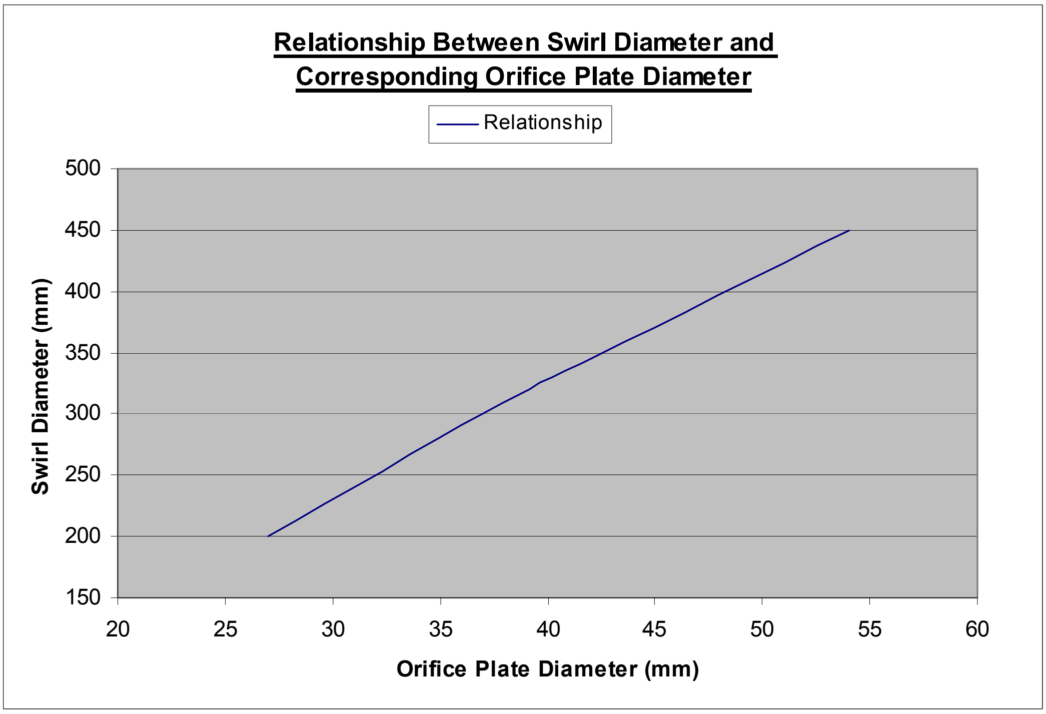

Figure 4.16 – Swirl Diameter and Orifice Plate Relationship

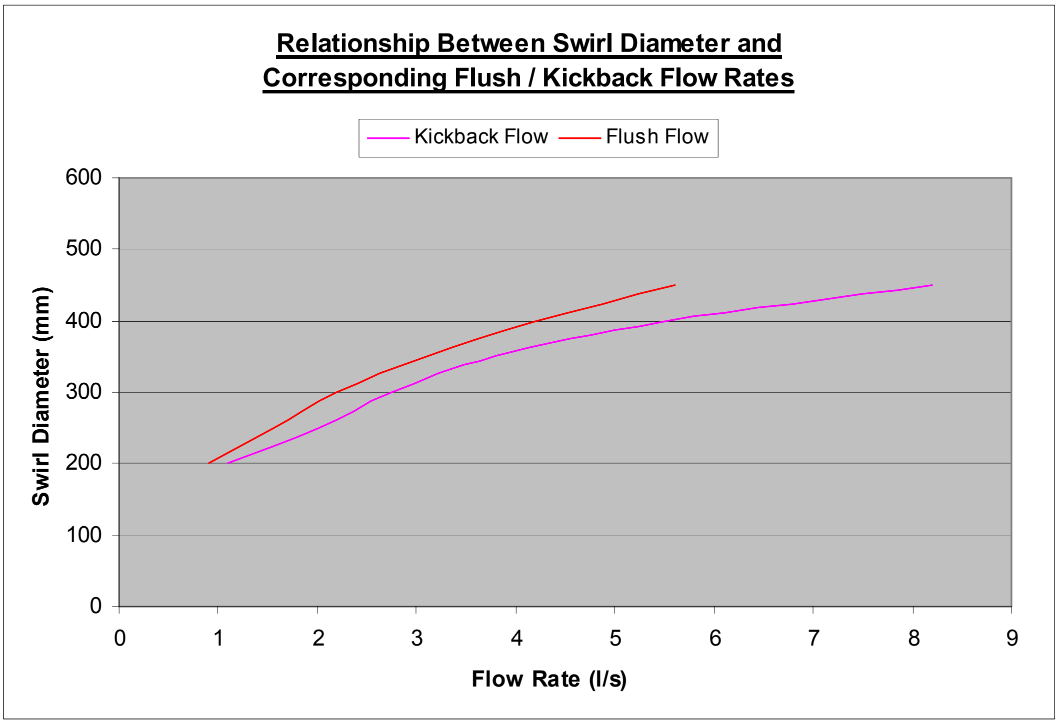

Figure 4.17 – Swirl Diameter and Flush Flow / Kickback Flow Relationship

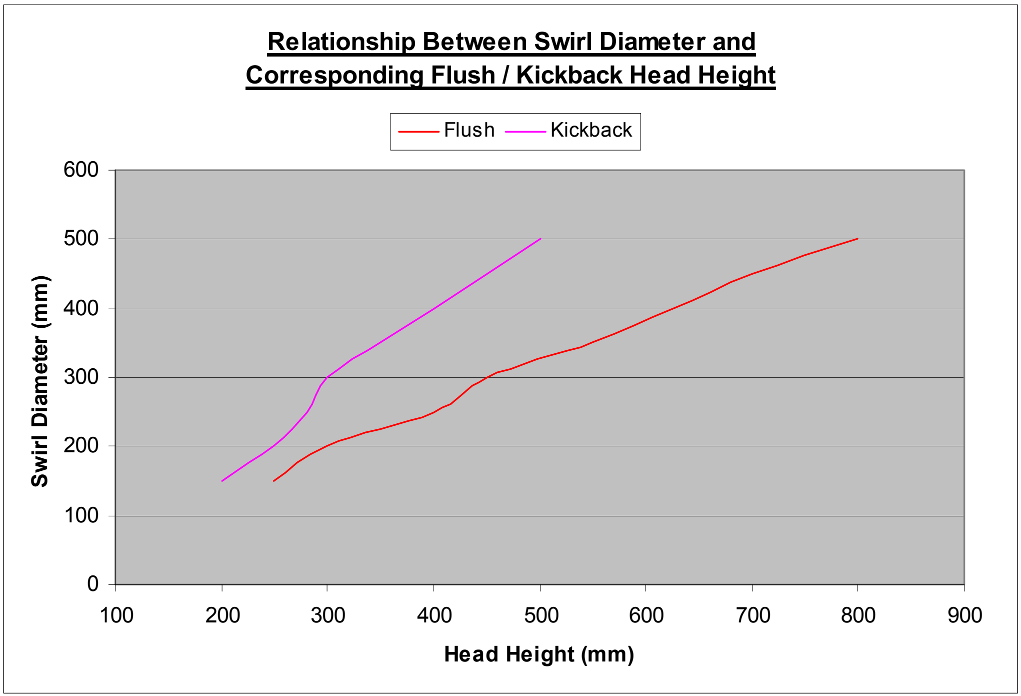

Figure 4.18 – Swirl Diameter and Flush Flow / Kickback Flow Head

The effect of the increased swirl diameter on the head height required to reach the flush flow point and the kickback flow point is shown in figure 4.18 above. As the swirl diameter increases so does the flush flow and kickback flow at an approximately linear rate.

4.5.2 Summary of Increasing Swirl Diameter of Vortex Valve

The swirl diameter was increased from 200mm to 450mm in increments of 50mm. Each of the other variables were scaled up as appropriate to give the same geometric relationship. The following conclusions were made on the effect of the increase in the swirl diameter of the vortex valve.

- Linearly increases the flow allowed to pass through the unit after the kickback point
- Non-linearly increases the kickback and flush flow points in the flow axis
- Approximately linearly increases the head height required to reach the kickback and flush flow points.

4.6 Vortex Valve Geometry Modelling

An important feature of any vortex valve design is the ability to accurately predict it's geometric dimensions for any given specification without the need for testing individual units. For example, if a specific design required a flow rate of 6l/s at a head height of 1000mm what is the geometry of the unit required? A model was built from the results obtained during the full scale testing as follows.

- A linear relationship was established between the performance of the vortex valve at a given swirl diameter and a corresponding orifice plate at the same flow specification as detailed in section 4.5.1.
- Using the formula for discharge through a small orifice [18], the orifice plate diameter can be determined from a specific flow rate and head height i.e. specification of the vortex valve.
- Insert this orifice plate diameter into the linear equation obtained from figure 4.19 below (y=9.2389x – 45.709) to provide an equivalent vortex valve swirl diameter.
- The swirl diameter is then divided by four to find the width, inlet height and outlet opening diameter as outlined in section 4.4

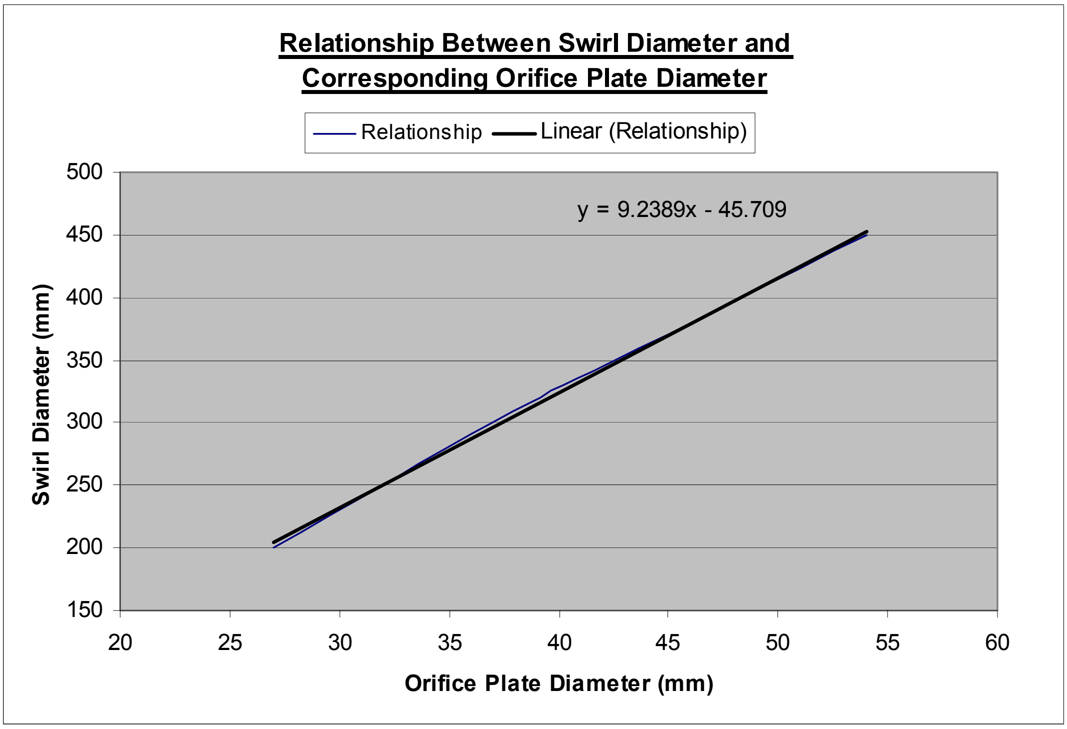

Figure 4.19 – Linear Equation Swirl Diameter and Orifice Plate Relationship

4.6.1 Example:

Required Design Flow = 6l/s

Required Design Head = 1000mm

Formula for Flow through a small Orifice:

Q = CD x A x √2gh [18]

Q = Flow in cubic meters per second (m^3/s)

A = CSA of the orifice diameter in meters (m)

G = Acceleration due to gravity (m^2/s)

H = Head Height in meters (m)

CD = Coefficient of Discharge (0.65)

0.006 = .65 X A X √(2 X 9.81 X 1)

0.006 = A X 2.879

A = 0.00208406 m^2

r^2 = 0.000663m

r = 0.02576m

Orifice Plate Diameter = 0.0515m = 51.5mm

Substituting this value for “x” in the formula given in figure 4.26 = 430.1mm

Swirl diameter = **430.1mm**

Outlet Opening Diameter = 430 / 4 = 107.5mm

Width = 430 / 4 = 107.5mm

Inlet Height = 430 / 4 = 107.5mm

4.7 Vortex Valve Performance Curve Modelling

There are two ways in which the performance curve of a specific geometry can be modelled, both methods offer individual advantages and disadvantages.

4.7.1 Unique Swirl Diameter Vortex Valves

Using a unique swirl diameter for each individual specification enables the relationship between all geometric variables to be kept constant. Therefore increasing / decreasing the overall size of the unit to the required dimensions as outlined in section 4.6 can be used to give a specific performance. The model used to predict the vortex valve performance curve using a unique swirl diameter was built as follows:

- A Microsoft excel calculator (see figure 4.20) was built from the data in section 4.6 to predict the geometry of the vortex valve with a known specification. (e.g. flow rate and head height)

Vortex Valve Calculator	
Gravity (m/s)	9.810
Head (mm)	1200.000
Head Height (m)	1.200
Coefficient of Discharge	0.650
Outlet Flow Rate (l/s)	4.500
	6.923
CSA of Orifice	5996.071
Inlet Height	68.624
sqrt 2 gh	4.852
Q/sqrt 2 gh = (A)	0.001
r sqrd	0.000
r	0.021
Orifice Diameter (mm)	42.62
Vortex Outlet Diameter (mm)	87.4
Vortex Swirl Diameter (mm)	350
Vortex Width (mm)	87.4
Head (mm)	**1200**
Desired Flow Rate (l/s)	**4.5**

Figure 4.20 – Vortex Valve Calculator

- Using the data generated in section 4.5 a linear model was built in Microsoft Excel to predict the flow rate for a specific swirl diameter at each head height. The data was taken from table 4.4 below and used to create a linear equation as shown in figure 4.21 below.

	200	250	300	350	400	450
0	0.00	0.00	0.00	0.00	0.00	0.00
100	0.52	0.70	1.20	1.20	2.00	3.25
200	1.10	1.50	2.50	2.80	4.00	5.86
300	0.90	2.00	2.74	3.80	5.45	8.00
400	1.04	1.60	2.30	3.80	5.50	8.20
500	1.17	1.64	2.20	3.20	4.80	7.70
600	1.28	1.79	2.40	3.19	4.20	5.75
700	1.38	1.94	2.59	3.45	4.36	5.60
800	1.47	2.07	2.77	3.69	4.66	5.85
900	1.56	2.20	2.94	3.91	4.94	6.25
1000	1.65	2.31	3.09	4.12	5.21	6.59
1100	1.73	2.43	3.25	4.32	5.46	6.91
1200	1.80	2.54	3.39	4.51	5.70	7.22
1300	1.88	2.64	3.53	4.70	5.94	7.51
1400	1.95	2.74	3.66	4.88	6.16	7.80
1500	2.02	2.83	3.79	5.05	6.38	8.07
1600	2.08	2.93	3.91	5.21	6.59	8.34
1700	2.15	3.02	4.03	5.37	6.79	8.59
1800	2.21	3.11	4.15	5.53	6.99	8.84
1900	2.27	3.19	4.26	5.68	7.18	9.08
2000	2.33	3.27	4.38	5.83	7.36	9.32

Table 4.4 – Results from section 4.5

- The required swirl diameter as determined from the vortex valve calculator is substituted for x in the example shown at a head height of 1000mm in figure 4.21.

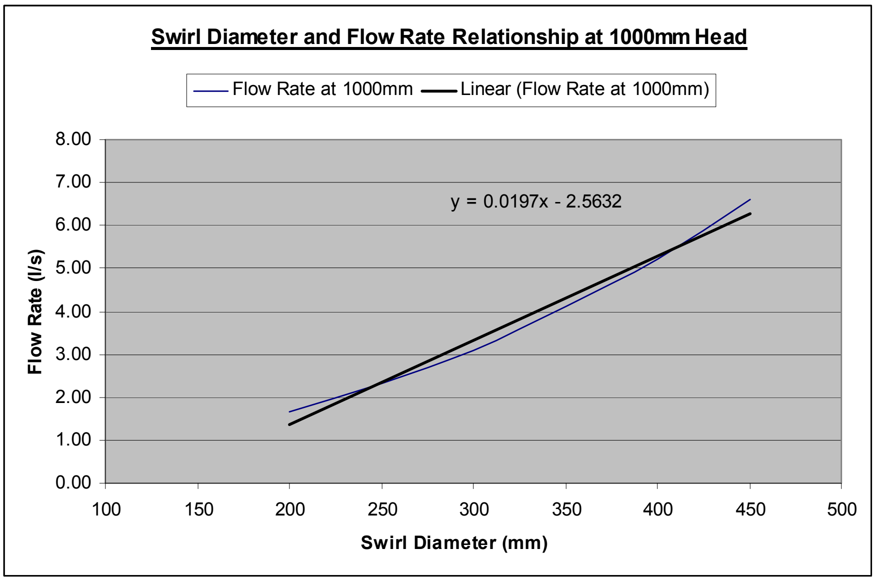

Figure 4.21 – Linear relationship example at 1000mm

- This provides the flow rate at a given swirl diameter for that head height. By creating a model for each head height, the vortex valve calculator can automatically generate a performance curve as shown in figure 4.22 below.

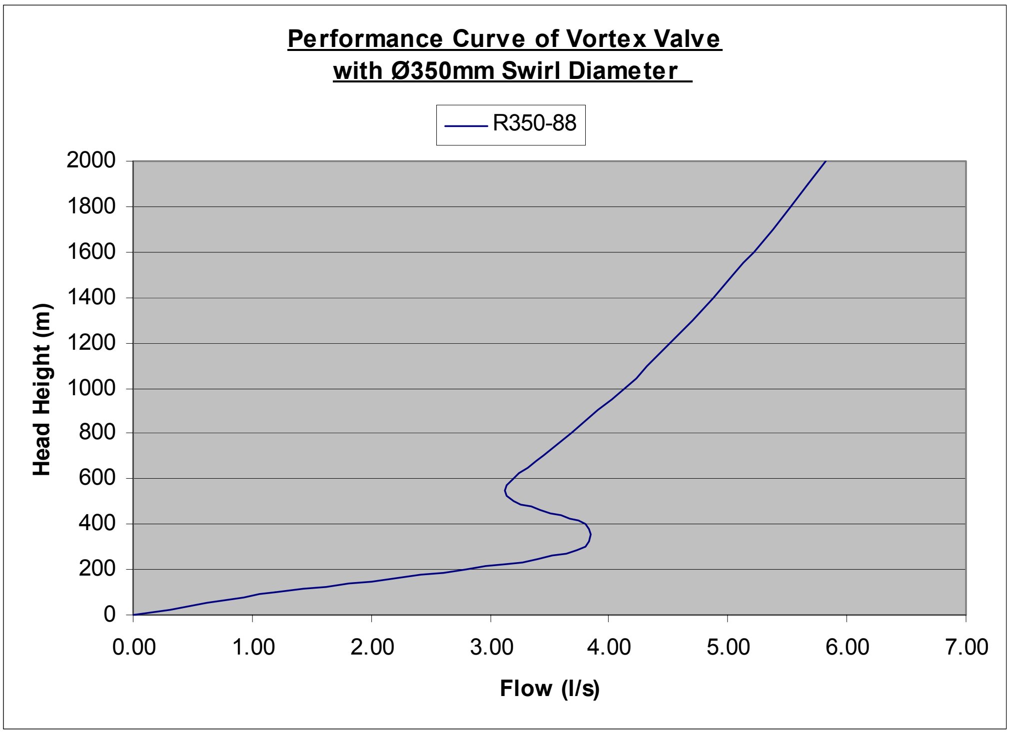

Figure 4.22 – Vortex Valve Calculator Generated Performance Curve

Advantages to the Unique Swirl Diameter model

- Accurate performance of a given specification can be determined above the flush flow point.
- CSA of the vortex valve is always 4 times that of the corresponding orifice plate.
- Useful model if only interested in the design flow value.

Disadvantages to the Unique Swirl Diameter model

- Performance of the vortex valve before the kickback flow point cannot be accurately predicted because of the non linear relationships. (see figure 4.17 and 4.18)
- The non linear relationships associated with the model around the flush flow and kickback flow points means there will be inaccuracies with storage volume calculations using the data from the model.

4.7.2 Standard Swirl Diameters Vortex Valves

All the testing for this model was not carried out as part of the research due to time and cost constraints but the results of section 4.1 and 4.5 show that it will accurately model the performance curve within a specific range.

Using a standard range of vortex valve with set swirl diameters the units can be customised to suit a specific performance requirement i.e. flow rate. Using the results from section 4.1 it can be said there is a linear relationship between the performance curves of the vortex valve as the outlet opening diameter is increased / decreased within a certain range.

The range is determined as follows:
Minimum Orifice Diameter = Swirl Diameter / 5
Maximum Orifice Diameter = Swirl Diameter / 3

Therefore if a number of standard vortex valves sizes were built with the same geometric relationship as outlined in section 4.6, it is possible to pick the nearest standard size swirl diameter for a given specification and modify the outlet opening diameter to give the specific performance required and accurately predict its performance curve.

As an example the following range may be selected.

Unit 1 – Swirl Diameter 200mm
Unit 2 – Swirl Diameter 250mm
Unit 3 – Swirl Diameter 300mm
Unit 4 – Swirl Diameter 350mm
Unit 5 – Swirl Diameter 400mm
Unit 6 – Swirl Diameter 450mm

In order for the linear relationship of the standard size vortex valves to be used each vortex valve needs to be tested as follows:

- At normal outlet opening diameter (4:1 relationship)
- At maximum outlet diameter (swirl diameter / 3)
- At minimum outlet diameter (swirl diameter / 5)

Using the results of these tests a linear model can be built for the performance of that specific vortex valve with varying outlet opening diameters.

An example of the steps carried out to accurately model the performance curve using this method is outlined below:

1. Using the method outlined in section 4.6 the required ideal geometric size of the vortex valve can be determined.
2. The available range of vortex valves are analysed to match the desired swirl diameter to the nearest standard size.
3. Using the Microsoft Excel model of that standard size vortex valve the design flow rate was used as an input at the required head height. This then outputs a corresponding outlet opening diameter and performance curve for that specific standard size unit.

Advantages to using a Range of Set Swirl Diameters

- An accurate performance curve can be determined at all head heights.
- It optimises the manufacturing process of the vortex valves in a production environment.
- The performance curve can be used to accurately calculate the required storage volume of an attenuation system.

Disadvantages to using a Range of Standard Swirl Diameters

- The CSA of the outlet opening diameter changes depending on the required specification.

4.8 Limitations Experienced During Testing

Two problems were identified during all the full scale testing:

1. The full scale test rig could not handle flow rates above 12l/s which was a disadvantage in not being able to test larger size vortex valves with larger flow rates.
2. The optimal relationship between the geometric variables as set out in section 4.4 requires very large vortex valves for flow above approximately 15-20l/s. Above this rate the physical size of the vortex valve would make it difficult to install in a standard Ø1.2m storm water manhole.

To identify a possible solution for these two problems it was decided to investigate if computational fluid dynamics (CFD) could be used to simulate flow through the vortex valve and evaluate its correlation with physical test results.

4.9 Computational Fluid Dynamics

CFD was used to simulate fluid flow through the vortex valve, there are three main steps in a CFD simulation using Ansys CFX software – 1) Pre-processing which includes geometry creation, meshing, physics and numerics. 2) Solving and 3) Post-processing [13]. Each stage is critical as incorrect assumptions or decisions made in developing the model will lead to inaccuracies in the results. For this reason the model was developed using experimental data for validation purposes.

4.9.1 Model Setup

Pre Processing - Geometry

A 3D modelling package called Pro Engineer was used to generate the geometry for the analysis. A simplified representation of a vortex valve in a rectangular manhole was used as can be seen in figure 4.23. The volume occupied by air / water in the manhole was modelled for the simulation.

Pre-Processing – Meshing

The geometry created in Pro Engineer was transferred to Ansys CFX-Mesh, here the geometry was broken down into regions. Similar surfaces were assembled together to form regions. Specific meshing constraints were then applied to each region to give a high quality mesh.

	Vortex Chamber	Manhole Walls	Outlet Pipe	Manhole Opening (Top)	Outlet Pipe Opening
Angular Resolution (°)	15	30	15	30	15
Max. Edge Length (mm)	24	50	24	50	24
Min. Edge Length (mm)	8	10	8	10	8

Table 4.5 – Mesh Settings

Advanced mesh inflation was used on boundary layers to give a more concentrated mesh at surface / fluid interfaces. The following inflation and mesh settings were used on the regions.

	Vortex Chamber	Manhole Walls	Outlet Pipe
No. of Inflated Layers	5	5	5
Expansion Factor	1.2	1.2	1.2
Min. internal angle (°)	2.5	2.5	2.5
Max. external angle (°)	10	10	10

Table 4.6 – Advanced Mesh Settings

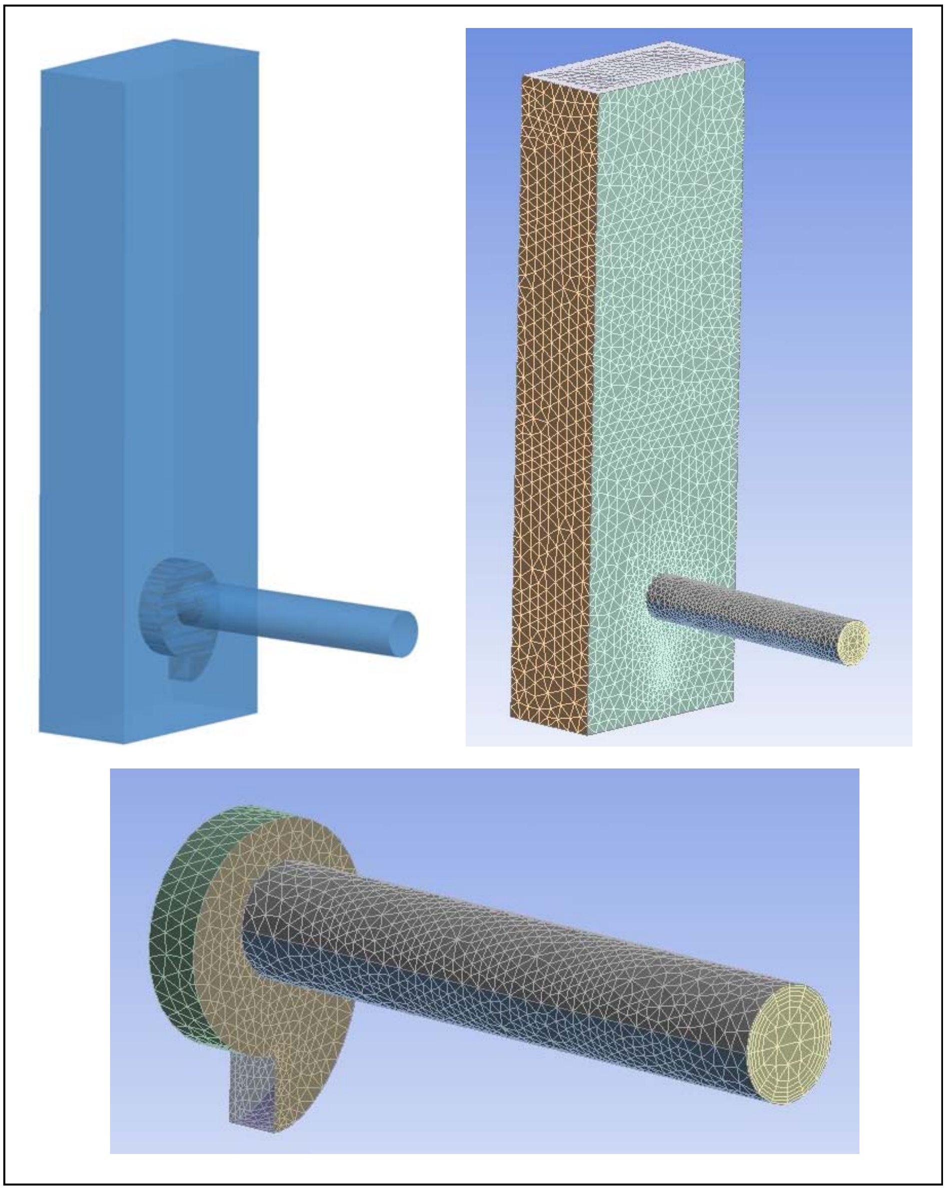

Figure 4.23 – CFD Mesh

Mesh settings are a compromise of accuracy and computation time, these settings were optimized in the validation section to give an acceptable quality of result data and computation time. Surface meshes as shown in figure 4.23 were computed to volume meshed for use with the pre-processor in the setup of the physics model [20].

<u>Pre-Processing – Physics and Numerics</u>

Once the geometry and meshing was complete the mesh was imported into CFX-Pre for further post processing relating to simulation type material properties, boundary conditions, operating conditions, Initial conditions as well as solution parameters.

Firstly the type of simulation to be carried out was defined, either a steady state or transient analysis. Using a steady state simulation, an individual model would need to be run for each position of hydrostatic head. Therefore twenty models would need to be built to simulate the performance of a vortex valve in a two meter manhole. Because of the work and time involved in setting up and running a model for each hydrostatic head position it was decided to perform one transient analysis as the manhole fills from the outlet of the vortex valve to the top of the manhole. The following simulation type settings were used:

- Transient Analysis
- Duration of 2.5 minutes
- Time steps of 0.5 seconds

The imported mesh was defined as a domain that contained two fluids, both water and air. The reference pressure was set as atmospheric at 1atm, buoyancy was selected with gravity specified in the correct orientation.

A multiphase homogenous model was used with free surface flow because of the interface between water and air in the manhole. A shear stress Transport turbulence model was chosen to simulate the flow inside the manhole and vortex valve. Buoyancy turbulence was set to production and the turbulent wall function was given a kappa coefficient of 0.3. Material models for water and air at 25°C were used from the library in the software and specified as continuous fluids. A free surface interface transfer model was used with maximum length scale of area density set to 0.01m. Boundary conditions were applied to the regions specified in the meshing software as outlined below in table 4.7 and 4.8 [20-21].

	Vortex Chamber	Manhole Walls	Outlet Pipe
Boundary Type	Wall	Wall	Wall
Wall Influence on Flow	No slip	No slip	No slip

Table 4.7 – Boundary Conditions on Walls

	Manhole Opening (Top)	Outlet Pipe Opening
Boundary Type	Opening	Outlet
Flow Regime	Subsonic	Subsonic
Mass and Momentum	Static Pressure	Avg. Static Pressure
Turbulence	Medium (5%)	n/a
Volume Fraction (air)	1	n/a
Volume Fraction (water)	0	n/a

Table 4.8 – Boundary Conditions on Openings

A number of expressions were defined as outlined below, these expressions were then used in defining the initial conditions.

Hydrostatic Pressure - hypres = 1000[kgm^-3] X 9.81[ms^2] X [inih-y] X watvf
Initial Height (zero) – inih = 0.4[m]
Water volume fraction – step((inih-y)/1.[m])

The following initial conditions were set:
Cartesian Velocity Components – u,v and w = 0
Relative Pressure = Hydrostatic Pressure expression hypres
Turbulent kinetic energy activated with a fractional intensity of 0.05
Turbulent eddy dissipation activated
Eddy viscosity ratio set to 10
Volume Fraction of Air at 25²C set to 1-watvf (expression)
Volume Fraction of water set at watvf (expression)

A water source was generated at the coordinates 0.1,0,0 in the sump of the manhole, this water source is what fills the manhole and the rate of fill was specified at 12 kg/s = 12l/s.

Within the solver control settings the advection scheme is set to high resolution with a second order backward euler transient scheme selected. Convergence control was set at a maximum number of coefficient loops of 5. The convergence criteria was set as residual type RMS with a residual target of 1e-4. Equation class was set as continuity.

Solver

The Ansys CFX Solver uses a unique hybrid finite-element/finite-volume approach to discretizing the Navier-Stokes equations. As a finite volume method, it satisfies strict global conservation by enforcing local conservation over control volumes that are constructed around each mesh vertex or node. The finite element methodology is used to describe the solution variation (needed for various surface fluxes and source terms) within each element. Advection fluxes are evaluated using a high-resolution scheme that essentially is second-order accurate and bounded. For transient flows, as with the vortex valve analysis an implicit second order accurate time differencing scheme is used [13-14].

The solver window was set to display mass flow rate in kg/s, with water having a density of 1000kg/m³ this display was the same as litres / second. An example is shown below in figure 4.24 of the performance curve generated by the solver, the data can be directly exported to Microsoft Excel for manipulation.

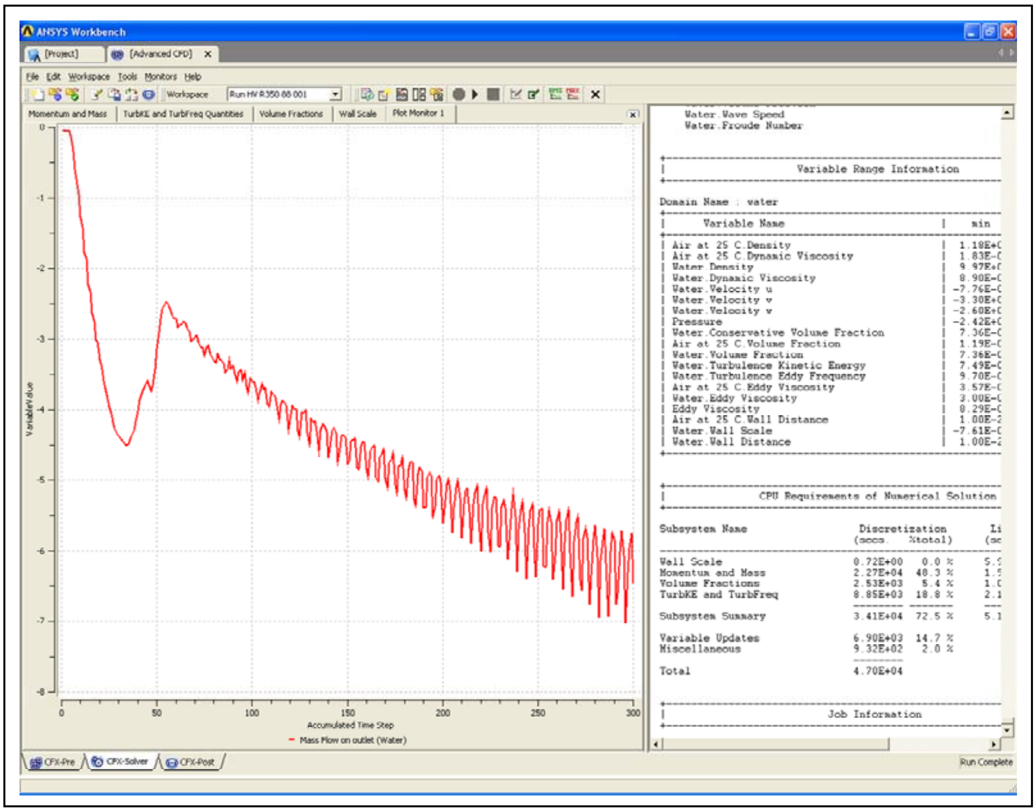

Figure 4.24 – Solver Output Window

Post Processing

Post processing is the final step in a CFD analysis, it translates the large quantities of data generated by the solver into graphical representations of the fluid flow. This can be in the form of streamlines, isosurfaces, planes, vectors etc. and can be based on any or the problem variables e.g. pressure, water volume fraction, etc. etc. [13-14]

Post processing was used in this project to shows flow paths through the vortex valve and gain a better understanding of pressure's inside the valve. The main information regarding the performance curve of the specific geometry being tested is taken directly from the solver in numerical form after a solution is complete.

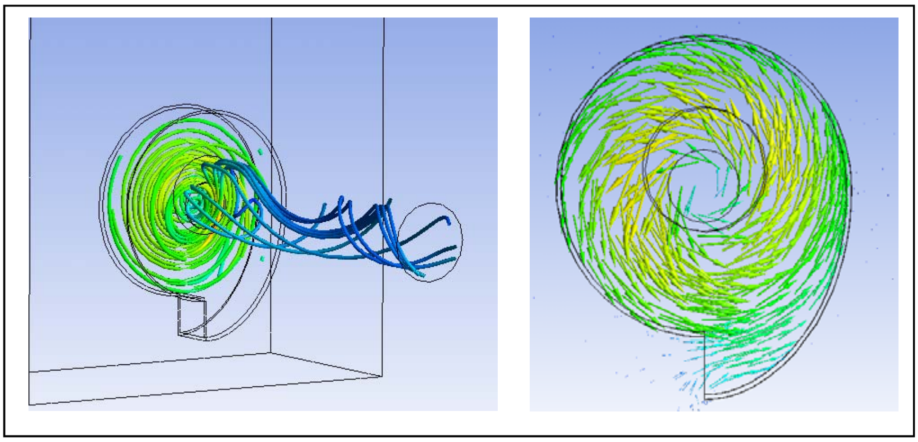

Figure 4.25 – CFD Streamlines and Vectors

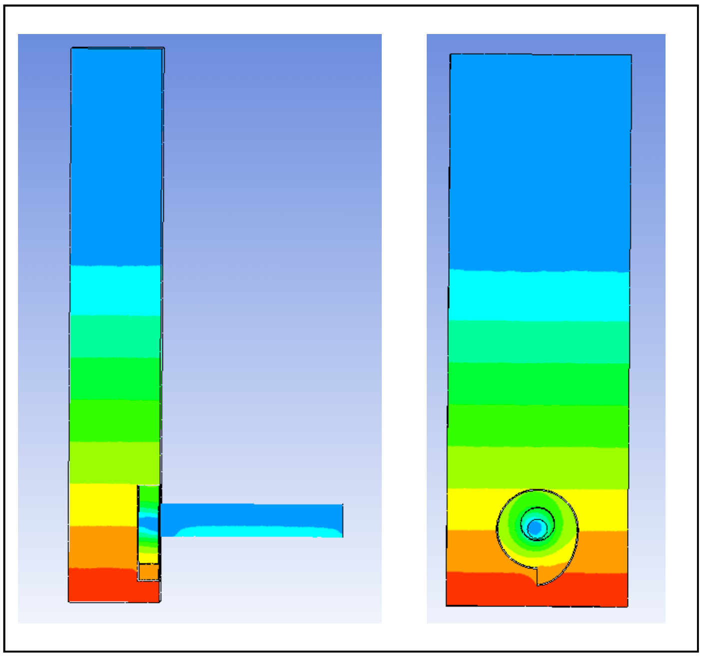

Figure 4.26 – CFD Pressure Plot

4.9.2 CFD Verification

Verification is one of the most important steps in a CFD analysis, it is the process of optimising the model to accurately predict the results of known calibrated lab test. The lab test results obtained during full scale testing were used to validate and verify the CFD model.

The initial prototype geometry was used to optimise the model so the performance curves generated by both the software and the full scale lab tests were correlating to within 5% or less. The first number or runs of the software showed large fluctuations as the head height increased as can be seen in figure 4.27 below, this can be attributed to the turbulent flow above the kickback point.

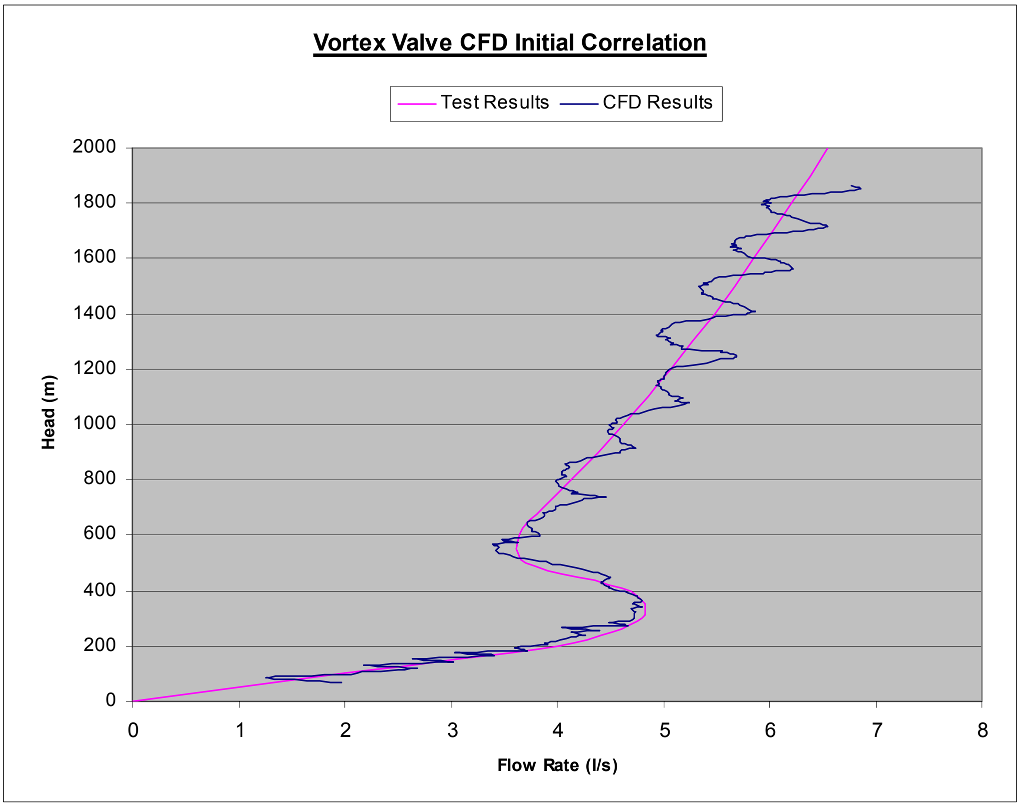

Figure 4.27 – Initial CFD Correlation

The mesh was refined to a smaller size as shown in table 4.9 and the kappa coefficient increased to 0.8 to try an improve correlation. The results can be seen in figure 4.28 below which show very good correlation to within 5%.

	Vortex Chamber	Manhole Walls	Outlet Pipe	Manhole Opening	Outlet Pipe
Angular Resolution (°)	15	30	15	30	15
Max. Edge Length (mm)	24	50	24	50	24
Min. Edge Length (mm)	8	10	8	10	8

Table 4.9 – Modified Mesh Settings

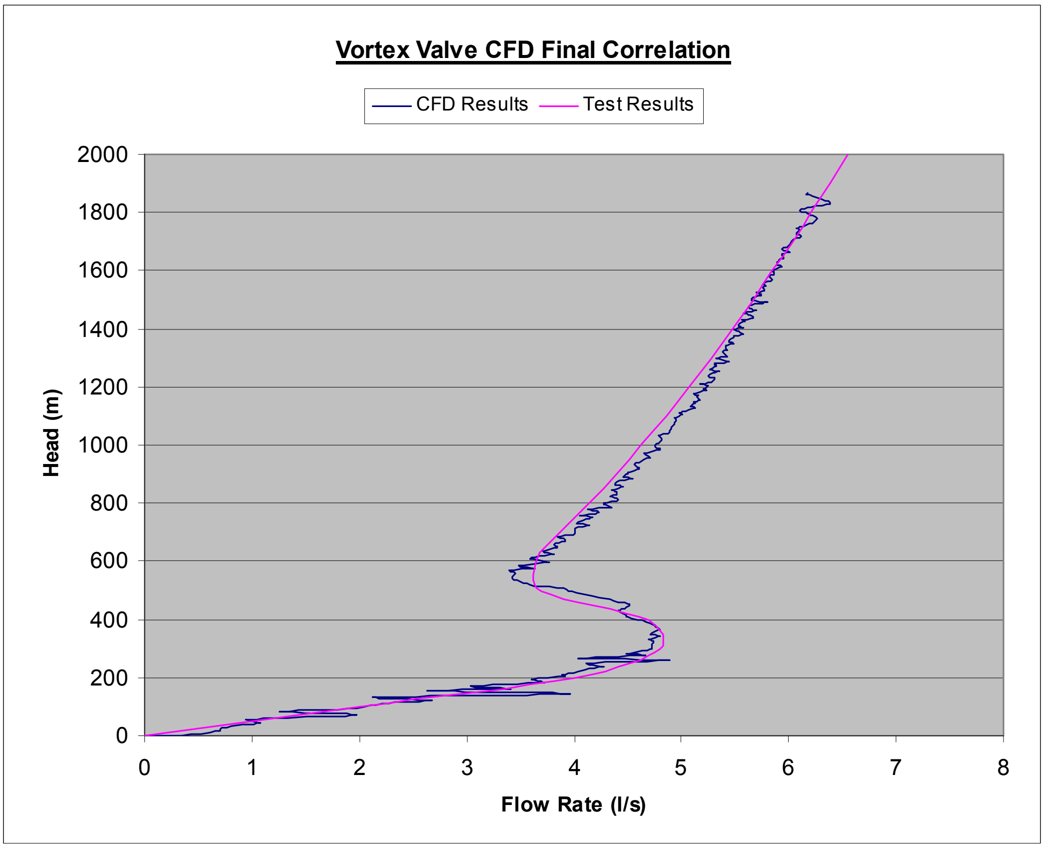

Figure 4.28 – Final CFD Correlation

CFD is a very useful tool in simulating fluid flow through the vortex valve and can be accurately used to predict the performance of the flow control device. It does however have some downsides in that solution time was approximately between 7 – 8 hours for good correlation. The software is difficult to learn and an in-depth knowledge of fluid mechanics and CFD is required for selecting the appropriate settings and options during model set up. However it gives the designer great flexibility to investigate "what if" design changes to the geometry and once the model is set up the same settings can be used for various geometries.

5.0 Conclusion

Following a review of all current vortex flow control valves it was found that they all required a flat face manhole for installation whereas a standard storm water manhole is a circular shape of 1.2meters internal diameter. Three mounting concepts were developed to allow for easy installation in a standard 1.2meter storm water manhole, the concepts evolved from one to the next with concept 3 chosen as the model to develop into a detailed design. The vortex chamber was redesigned to allow for more efficient material usage and to optimise the manufacturing process.

A detailed design was developed using mounting concept 3 and the redesigned vortex chamber to provide the final over all design. The mounting coupler was rotationally moulded from polyethylene due to its intricate design, the vortex chamber was fabricated from polyethylene because of its simple geometry. The final design was manufactured from polyethylene plastic which provided big advantages over the current units on the market in the areas of cost of materials, cost of manufacture and simplified installation.

A full scale test rig was designed and developed to test the relationship between the geometric variables of the vortex valve, namely the outlet opening diameter, the width of the vortex valve, the inlet height and the swirl diameter. An over ground high density polyethylene manhole was used to install the vortex valve, water was supplied to the manhole to simulate hydrostatic head from a header tank. The flow through the vortex valve was measured by keeping the head constant and weighing the volume of water that passed through the valve over a period of thirty seconds. The weight increment in kg's divided by thirty provided the mass flow rate in kg/s and therefore l/s assuming a water density of 1000kg/m^3.

A prototype vortex valve was tested to provide its performance curve of hydrostatic head in meters versus flow rate in litres per second. The curve followed the general "S" shape of vortex flow control devices and clearly showed its flush flow point, kickback point and design flow range. The kickback part of the curve was found to be the extra hydrostatic head required to initiate the vortex due to the air pocket trapped in the top of the vortex chamber.

The first geometric variable varied was the outlet opening diameter, this showed a linear increase in design flow, kickback flow and flush flow as the diameter was increased. It showed a linear decrease in the head height required to reach the flush flow and kickback flow points due to the smaller air pocket trapped in the vortex chamber as the outlet opening diameter increased.

Increasing the width of the vortex valve linearly increased the design flow, kickback flow and flush flow. It showed a non linear increase in the head height required to reach the flush flow and kickback flow points.

Increasing the inlet height of the vortex valve linearly increased the design flow, kickback flow and flush flow. It showed a non linear decrease in the head height required to reach the flush flow and kickback flow points.

The optimum relationship between the geometric variables that satisfies the design objectives is a ratio of 4:1 between the swirl diameter and the outlet opening diameter which provided an outlet opening CSA 4 times that of an orifice plate. A ratio of 4:1 was also used with the width and inlet height as it provided the minimum chance of blockage with similar sized inlet and outlet openings while maximizing the flow through the vortex valve to minimise storage requirements.

Varying the swirl diameter while keeping a constant relationship with the other variables linearly increased the design flow above the kickback point but non linearly increased the flush flow and kickback flow points. It approximately linearly increased the head height required to reach the kickback and flush flow points.

A model was built to determine the required geometry of the vortex valve for a given flow rate and head height specification based on all the testing results. Two models were then developed to predict the performance curve of a specific geometry vortex valve, the first model used a unique swirl diameter for each specification with the second model using the nearest available standard size vortex valve and modifying the outlet opening diameter to provide the required specification. The first model could accurately predict the performance curve above the kickback point but not below it, the second model could accurately predict the entire performance curve by varying the outlet opening diameter of a standard size unit.

A CFD model was developed to simulate the flow through the vortex valve using Ansys CFX software, the model set up was complex but once developed it did accurately model the performance of the vortex valve and was correlated using full scale test results. To obtain good correlation a solution time of 7 - 8 hours was required on a high performance computer

5.1 Recommendations

The following recommendations are outlined for future work in the subject.

- To use computational fluid dynamics to determine the optimum geometric relationship for flow rates above 20 l/s that will fit in a standard Ø1.2m storm water manhole.
- To design a conical flow control device for a standard Ø1.2m storm water manhole.
- To perform the same set of tests on a conical vortex flow control device to identify geometric relationships and build geometric and performance models.
- Investigate further if computational fluid dynamics can be used to model the fluid flow through the vortex valve in under one hour to enable designers to quickly consider the influence of design changes.

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