AALBORG UNIVERSITY
STUDENT REPORT

PUMP TESTING STAND

EN6t-1-F14

Bachelor Project

Aalborg University Esbjerg
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Title Sheet

Theme:	Thermo Mechanical Energy Systems
Project title:	Pump Testing Stand
Group:	EN6t-1-F14
Semester:	6th semester
Supervisor:	Matthias Mandø
University:	Aalborg Universitet Esbjerg
Initial problem:	Design and construction of a pump testing stand.

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Abstract

Knowledge about pumps and pump performance is an important part of the Thermal Processes and Combustion study program at Aalborg University. To ensure the students have the best learning opportunities, testing facilities should be available. The main purpose of this project is therefore to design and build a testing stand, where standardized pump tests can be performed safe, easy, and in accordance with the Danish Standard ISO 9906.

This project deals with the whole construction process, from designing till finished product. The project involves aspects as structural mechanics, fluid mechanics, thermodynamic, and programming. Appropriate pump theories for the studied model will be considered as well as all the knowledge and understanding taught in the various courses of the Energy Engineering program.

Preface

This project was written in the spring of 2014 as a result of a cooperation between a Danish student enrolled in the Thermal Processes and Combustion study program, in the Department of Energy Technology at Aalborg University Esbjerg and a Spanish student enrolled in Mechanical Engineering at Universidad del País Vasco / Euskal Herriko Unibertsitatea.

According to the curriculum, a Bachelor Project must contain a résumé in a different language than the written report. As the students belong to different nationalities the résumé will be in both Spanish and Danish and it will be on the following pages.

A special thanks goes out to three different companies: Grundfos, Belimo and Granly Diesel for their sponsor, support and help in different ways.

Referencing to the bibliography, which is found in the back of the report on page 45, are enclosed in squared brackets [x]. The number inside the brackets corresponds to the reference number in the bibliography. Figures without references are made by the group and the modified figures are to aid comprehension.

Figures, equations, and tables are numbered continuously throughout each chapter and appendix, where e.g. figure 3.5 refers to the fifth figure in the third chapter.

Resumen

El proyecto redactado y mostrado a continuación, trata del diseño y de la construcción de un banco de pruebas para ensayos de aceptación de rendimiento hidráulico en bombas centrífugas. En la guía docente del programa de la rama de Procesos Térmicos y Combustión incluido en el departamento de Tecnología Energética de la Universidad de Aalborg, se establece que los estudiantes deben trabajar con máquinas de flujo y sus componentes a lo largo del proyecto en el 6º semestre. En concreto, los alumnos del campus de Esbjerg deben profundizar en bombas centrífugas y el diseño de sus rodetes. Para estudiar su funcionamiento real y comparar con las características garantizadas por el fabricante, se deben llevar a cabo ensayos de aceptación en un banco de pruebas apropiado. Dicho proyecto nace fruto de la colaboración entre un estudiante de Ingeniería Energética danés de la propia Universidad de Aalborg y un estudiante español de Ingeniería Mecánica de la Universidad del País Vasco / Euskal Herriko Unibertsitatea.

En primer lugar, se analiza toda la teoría relativa a las bombas y, en especial, las bombas centrífugas, de la misma manera que se estudia la teoría relacionada con los diferentes ensayos de aceptación en bombas. Además, se establecen los requisitos mínimos de la instalación en este proyecto.

En segundo lugar, se acomete con el diseño de la instalación de acuerdo a la normativa internacional ISO 9906 referente a ensayos de aceptación en bombas rotodinámicas. Se realiza un prediseño de la estructura, que se verá modificado a lo largo del proceso de diseño, debido a los requisitos normalizados y a diversos motivos. Se consultaron diferentes catálogos de fabricantes y suministradores para garantizar una instalación óptima. Se dimensionan los diferentes elementos que componen el banco de pruebas considerando el hecho de que están interrelacionados. Se lleva a cabo un análisis de las tensiones en el tanque de agua y los cimientos por medio del software Autodesk; que reafirma el diseño definitivo. Este diseño se realizó teniendo en cuenta que se desea un cambio de rodete de la bomba rápido y sencillo.

Una vez finalizado el diseño se procede a la construcción y el montaje de la instalación. Para ello, se nos facilitaron las instalaciones y el taller de una empresa local, además de contar con la ayuda de un aprendiz de soldador para soldar y cortar de la placa suministrada el acero necesario para el tanque. Se sueldan los diferentes accesorios y tuberías respetando el diseño definitivo. Posteriormente, se desmonta

la estructura para transportarla al taller de la universidad. Allí, se vuelve a montar la estructura uniendo todos los elementos roscados que la componen y procediendo a realizar un test para descartar posibles fugas.

Por último, se acomete con el diseño de un programa para obtener la curva motriz de la bomba en cuestión en ensayos de aceptación. Gracias a un dispositivo myRIO programado con LabVIEW la información necesaria del ensayo puede procesarse y almacenarse. Este dispositivo capta las señales emitidas por las diferentes tomas y elementos, transformándolas en datos manejables. Tiene en cuenta las incertidumbres en las mediciones permitidas por la ISO 9906 a la hora de realizar los ensayos.

Este proyecto es capaz de obtener la curva motriz de una bomba centrífuga a diferentes caudales. Valiéndose del manual adjunto cualquiera podría realizar el ensayo obteniendo alturas de la bomba con diferentes caudales. Estos datos almacenados en un pen-drive pueden ser después tratados con Excel para trazar la curva característica de la bomba en estudio. Se cumple con los requisitos establecidos en un principio.

Para concluir, añadir que dicha instalación se puede mejorar si se trabaja en la futura inclusión de un intercambiador de calor para tener un continuo control sobre la temperatura del fluido que afecta a sus propiedades. En un futuro, esta instalación debería contar con los accesorios y programas necesarios para obtener la curva de potencia, la curva de rendimiento y la curva de la NPSH requerida.

Resume

Projektets formål var at designe og bygge en teststand, til test af den hydrauliske ydeevne for centrifugal pumper. I studieordningen for Energi med speciale i Termiske Processer under Institut for Energiteknik ved Aalborg Universitet, er det angivet at studerende skal arbejde med flow maskiner og komponenter i deres projekt på 6. semester. For studerende på Esbjerg Campus er fokus på pumper og pumpe løbere. Dette projekt er resultatet af et samarbejde mellem en dansk Energi Ingeniør studerende ved Aalborg Universitet og en spansk Maskine Ingeniør studerende ved Universidad del País Vasco / Euskal Herriko Unibertsitatea.

Den første del af projektet fokuserede på de relevante teorier omkring centrifugal pumper og pumpe test. Derudover blev minimums kravene til teststanden opstillet.

I den næste del af projektet blev udformningen af selve teststanden, i henhold til den Internationale Standard ISO 9906, fastlagt. Desuden blev standen designet med henblik på at kunne skifte pumpe løberen hurtigt og effektivt, da dette var et vigtigt krav. Det første udkast til et overordnet design af teststanden, blev ændret igennem forløbet på grund af forskellige krav i den internationale standard. For at sikre det bedste design, blev diverse dataark fra forskellige producenter og leverandører studeret, og de bedst egnede komponenter blev udvalgt. Denne proces var kompliceret, da ændringer i en enkelt komponent, hurtigt kunne betyde ændringer i de andre. Derudover blev der lavet stress analyser i Autodesk Inventor af vandtanken og fundamentet, for at fastsætte holdbarheden.

Efter designet var færdigt, blev der bestilt plade, rør, firkant profil og diverse komponenter i rustfri stål. Derefter blev teststanden svejst sammen på et lokalt firmas værksted, med hjælp fra en svejse lærling. Da systemet var færdigsvejst og tæthedsprøvet, blev det skilt af, transporteret til universitetet og samlet igen.

Den sidste del af projektet havde som fokus at gøre det nemt for studerende og andre at benytte teststanden til opsamling og fortolkning af data. Det var et krav at det ikke måtte kræve specielt software eller hardware at kunne betjene pumpestanden. Derfor blev en myRIO fra National Instruments programmeret ved hjælp af LabVIEW, til at håndtere data opsamlingen. Programmet tager højde for usikkerheder i målingerne i henhold til kravene i ISO 9906 og håndtere alt data fra de forskellige komponenter. Det eneste det kræver, er et USB-stik og et tryk på en knap for at starte testen. Når testen er færdig, kan USB-stikket udtages og dataene kan benyttes direkte til at fremstille en pumpekurve i fx. Excel.

Selvom teststanden kan udføre pumpe test til bestemmelse af drift kurven og dermed opfylde kravet, er der stadig ting der kan forbedres. Der kan programmeres en NPSH eller udholdenheds test ind i myRIO'en, så også disse egenskaber kan testes. Derudover så kan den varmeveksler der er gjort klar til, blive færdiggjort så temperaturen på vandet i teststanden kan kontrolleres og derved teste løberne under andre forhold.

Contents

Introduction

Pumps and pumping system vary in size and shape and the are used in a wide range of applications, from small households to big constructing facilities. The total amount of electricity consumed by pumping system in Denmark, are estimated to be as high as 20 % of the total Danish electricity consumption. In a world where there are a great focuses on CO_2 emission and energy savings, it is therefore important to optimise pump performance and efficiency.

For this reason is a requirement in the curriculum for the Thermal Processes and Combustion study program under the Department of Energy Technology at Aalborg University, that the students must work with flow machines and components during their 6th semester project. For students at the Esbjerg Campus the focus is on centrifugal pumps and impeller designs. To get the actual pump and impeller performance, pump tests must be conducted on a appropriate testing stand.

Building a pump testing stand is subjected to requirements in the Danish Standard ISO 9906. These requirements must be fulfilled to ensure that the results from the pump test are accurate. This project therefore deals with the design and construction of a pump testing stand in accordance with ISO 9906.

CHAPTER 1

Pump and Pump Test Theory

In this chapter the basic knowledge about pumps and pump performance tests is described and analysed. The requirements for the testing stand are also stated at the end of this chapter.

1.1 Pumps

In this section the pump performance will be described, as well as the different groups and types in which they can be classified, deepening into the specific pump type used in the installation.

1.1.1 Pump Definition

A pump, in technological scope, is a device or machine that moves or transfers fluids, gases or liquids, by mechanical action. They can be classified according to different criteria such as the method they use to displace the fluid. In general, they are classified in two main groups: positive displacement pumps and rotodynamic pumps.

Positive Displacement Pumps

Positive displacement pumps move a fixed amount of fluid in each revolution or cycle, providing a close to constant volume flow at a given revolution speed, even with variable system head. The flow rate is nearly constant, as a part of the fluid can leak back to the suction part of the pump, when high pump head is reached. This fact is known as slippage and is caused by the high discharge pressures.

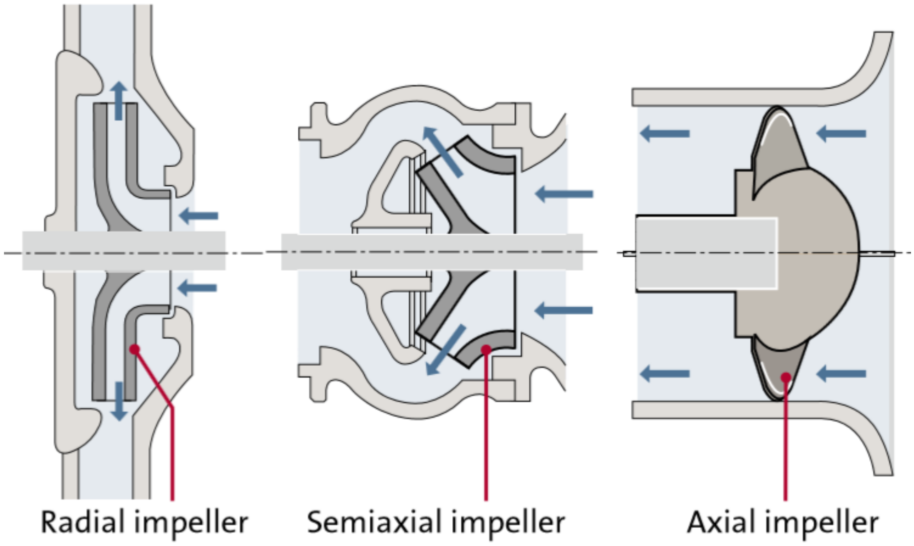

Figure 1.1: Impeller types considering the flow direction. [1]

Rotodynamic Pumps

In these kinetic machines, energy is continuously transferred to the fluid by rotating an impeller. Unlike the positive displacement pumps, rotodynamic pumps do not have a constant flow rate, and it is very depending on the system head. The mechanical efficiency also depends on the system head. Rotodynamic pumps can be of different types, depending on the impeller:

Radial impeller: The flow direction is perpendicular to the rotational axis.

Axial impeller: The flow direction is parallel to the rotational axis.

Semiaxial impeller: The flow direction is a mix between perpendicular and parallel to the rotational axis.

The different types of impellers can be seen in figure 1.1. The type of impeller have an effect on the performance of the pump. This can be seen in figure 1.2, where the head, power, and efficiency is compared between an axial flow pump and a centrifugal pump, which is, in fact, a radial pump. Modifying the flow have larger effect on the head and power for an axial pump, than for a radial pump.

1.1.2 Centrifugal Pumps

Among the different types, the most widely used is the centrifugal pump. In a centrifugal pump the fluid flows in perpendicular direction to the rotational axis, it is therefore considered a radial-flow machine which produces a high head at a low flow rate. Work is done on the fluid by a rotating impeller which, due to the layout

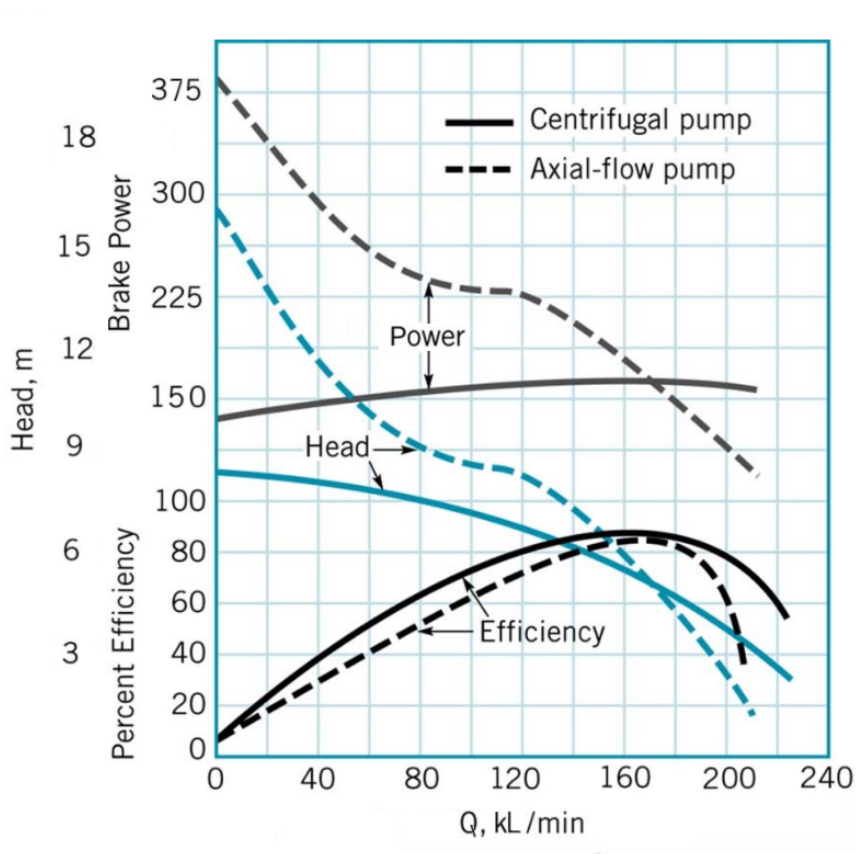

Figure 1.2: Performance characteristics of a axial flow pump and radial flow pump. [2]

of the pump, provokes a pressure increase. The flow coming from the inlet is lead to the centre of the impeller and flows out along the impeller blades. At the impeller eye, vacuum pressure is induced and this sucks the fluid stream into the pump.

In figure 1.3, the names of different components of a centrifugal pump are shown. The relevant components for the pump tests will be described in the next paragraphs.

Inlet Flange and Inlet

The inlet flange is the connection between the system and the inlet, which guides the fluid into the eye of the impeller. The inlet is designed to allow the velocity profile to develop as much as possible, as a fully developed velocity profile in the inlet will contribute to better performance of the pump.

Volute, Diffuser, and Outlet Flange

The fluid coming from the impeller is guided inside the casing, leading it to the outlet flange. By increasing the cross-section area along the flow direction, the velocity is

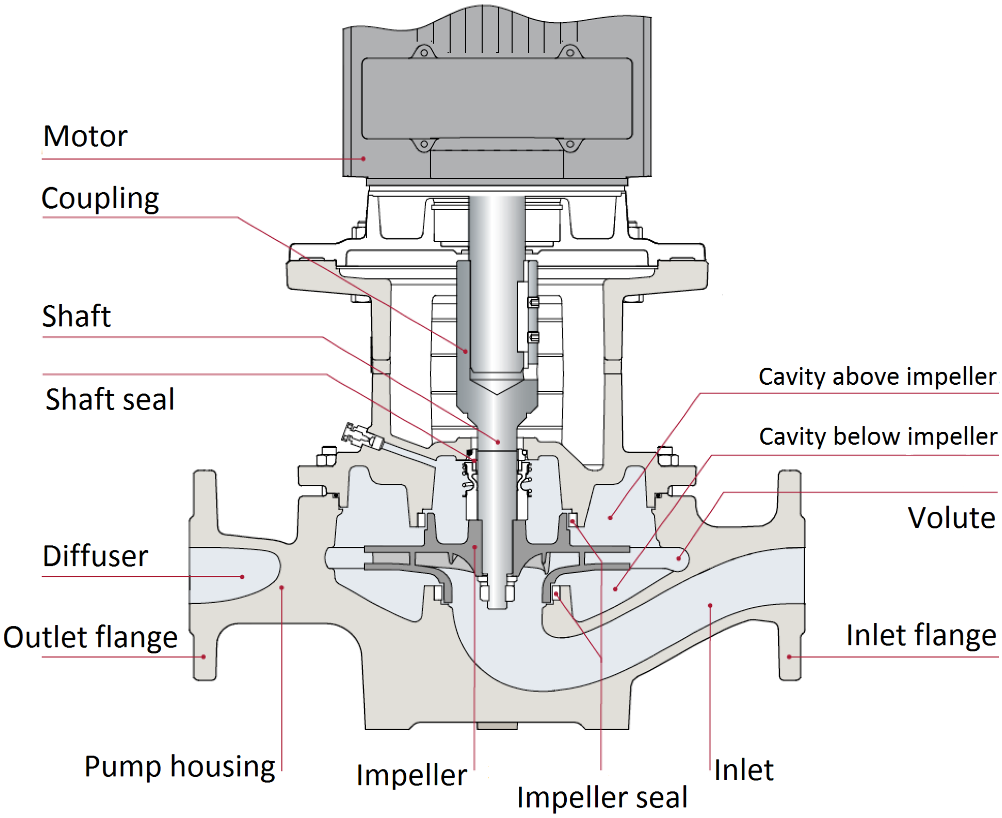

Figure 1.3: Components of a centrifugal pump. [1]

kept close to constant even with increasing volume flow. The volute and diffuser also plays a role in converting the dynamic pressure to static pressure.

Impeller

Inside the casing, at the heart of the pump, the main component regarding pump performance and pump tests is located. It consists of a pair of round plates with curved blades fit inside, and it is called an impeller. When the impeller rotates the centrifugal force will cause the liquid particles to move radially outwards. However, the direction of the flow is modified by the impeller and blade geometry. The shape of the impeller blades, affect the velocity triangles and therefore, the pump performance. The blades have an inlet angle, β_1, and an outlet angle, β_2, and the blades are categorised into the following three different types, depending on the outlet angle:

- Forward Curved Blades. $\beta_2 > 90°$
- Radial Curved Blades. $\beta_2 = 90°$
- Backward Curved Blades. $\beta_2 < 90°$

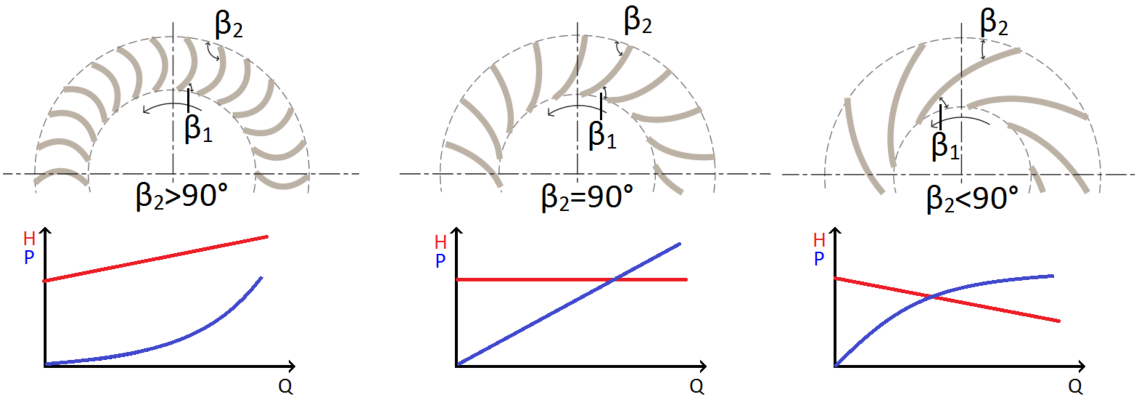

Figure 1.4: Blade shapes according to the blade angle. [1]

Figure 1.4 shows an example for each of three different types of blades, each with the corresponding theoretical head curve and power curve. The head curve is shown in red and the power curve is shown in blue. For the forward curved blades, the head increases linearly and the power increases exponentially with increasing flow. For the radial curved, the head is constant and the power increases linearly. Lastly, for the backward curved head decreases linearly and the power stabilises with increasing flow.

1.2 Pump Performance Curves

This section will describe the different test that are used to create the performance curves for the pump. The performance curves are; head, power consumption, efficiency, and NPSH. They are all functions of the flow. This section also mentions which equipment is needed for the different tests.

1.2.1 Head

The pump head is defined as the difference in head from the inlet flange to the outlet flange of the pump. In mathematical terms this is represented as:

$$H = H_2 - H_1 \tag{1.1}$$

Where the subscript 1 represent the inlet and subscript 2 represent the outlet. As the measurements are made at some distance from the inlet and the outlet, the friction losses need to be subtracted and added accordantly. Figure 1.5 shows a graphical representation of head calculations. The heads marked with a prime are the heads where the measurements are done. With the friction losses, equation 1.1 becomes the following:

$$H = (H'_2 + H_{loss,friction,2}) - (H'_1 - H_{loss,friction,1}) \tag{1.2}$$

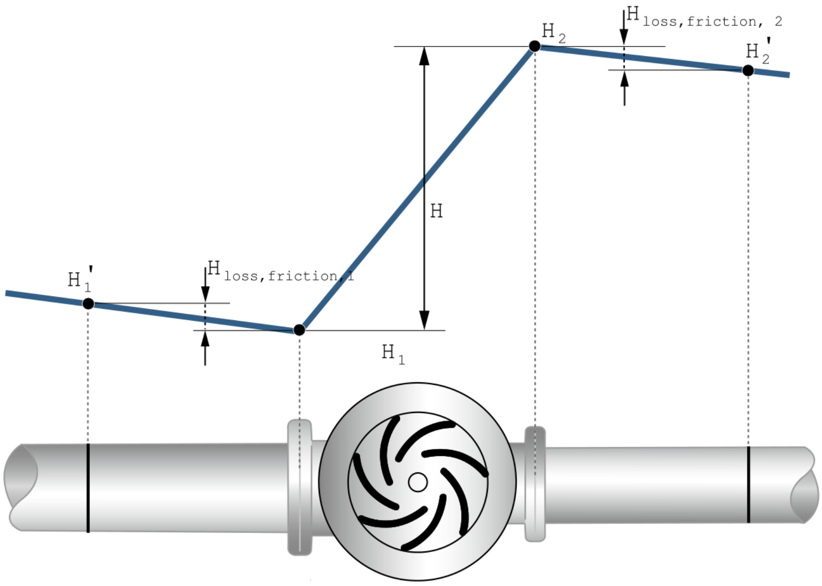

Figure 1.5: Overview of where the head measurements are made. [1]

The head consists of three parts; static head, dynamic head, and elevation head. The static head is from the pressure difference at the inlet and outlet of the pump, the dynamic head is from the difference in kinetic energy of the fluid, and the elevation head is from height difference. In equation form they are:

$$\begin{aligned} H_{static} &= \frac{p}{\rho \cdot g} \\ H_{dynamic} &= \frac{U^2}{2 \cdot g} \\ H_{elevation} &= z \end{aligned} \tag{1.3}$$

where p is the absolute pressure in Pa, ρ is the density of the fluid in kg/m^3, g is the gravitational acceleration in m/s^2, U is the mean velocity of the fluid in m/s, and z is the height above reference in m. Combining and rearranging equation 1.2 and 1.3, while setting the inlet flange as reference height, results in the following equation:

$$H = \frac{p_2 - p_1}{\rho \cdot g} + \frac{U_2^2 - U_1^2}{2 \cdot g} + z_2 + H_{loss,friction,1} + H_{loss,friction,2} \tag{1.4}$$

The head is calculated by equation 1.4 at different flow rates, and the results can be used to plot the head curve. Therefore the pressure has to be measured at the inlet and outlet flanges, and in order to measure the head at different flow rates, the flow has to be variable. Furthermore the mean velocity of the fluid is needed, and this can be found by dividing the volume flow with the cross-section area of the pipe. Therefore two pressure transmitters, a regulating valve and a flowmeter are necessary.

1.2.2 Power Consumption and Efficiency

The power consumption of a pump is found by measuring the electric power supplied to the pump motor. This has to be done at different flows in order to get the power consumption curve. When the power consumption is known, the efficiency can be found by dividing the mechanical energy increase of the fluid by the power consumption. The change in mechanical energy can be found from the following:

$$\Delta E_{mech,fluid} = H \cdot \rho \cdot g \cdot Q \tag{1.5}$$

where $\Delta E_{mech,fluid}$ is the change in mechanical energy of the fluid in W and Q is the volume flow of the fluid in m^3/s.

Taking equation 1.5 into account, the efficiency of the pump with the motor is then:

$$\eta_{total} = \frac{H \cdot \rho \cdot g \cdot Q}{P_{consumption}} \tag{1.6}$$

where η_{total} is the total efficiency and $P_{consumption}$ is the power consumed by the pump motor in W. The results from equation 1.6 can be used to plot the efficiency curve of the pump, but there is a requirement for a watt-meter.

1.2.3 NPSH

NPSH stands for "Net Positive Suction Head" and it is connected to cavitation. Cavitation is when vapour bubbles are created due to pressure locally dropping below the vapour pressure at the given temperature. This occurs where the pressure is the lowest, which is at the impeller eye. If cavitation happens, it will cause the head to be reduced, and thereby reducing the efficiency. Furthermore cavitation can cause noise and vibration which can damage the pump. NPSH is always positive and is measured in metres, making it independent on the type of fluid.

There are two values of NPSH. NPSH$_A$, which is the available NPSH before cavitation occurs, and NPSH$_R$ which is the required NPSH to ensure no cavitation. NPSH$_R$ are also the values used for the NPSH performance curves. The NPSH$_A$ is calculated from the total absolute pressure at the inlet of the pump and vapour pressure in the following way:

$$NPSH_A = \frac{p_{abs,tot,in} - p_{vapour}}{\rho \cdot g} \tag{1.7}$$

where $p_{abs,tot,in}$ is the absolute total pressure at the inlet and p_{vapour} is the vapour pressure. The density and the vapour pressure are dependent on the temperature of the fluid, and therefore the NPSH$_A$ is dependent on temperature. Figure 1.6 shows the NPSH$_A$ as a function of temperature for four different inlet pressures, and water as the running fluid. The graphs shows that the NPSH$_A$ decreases with temperature

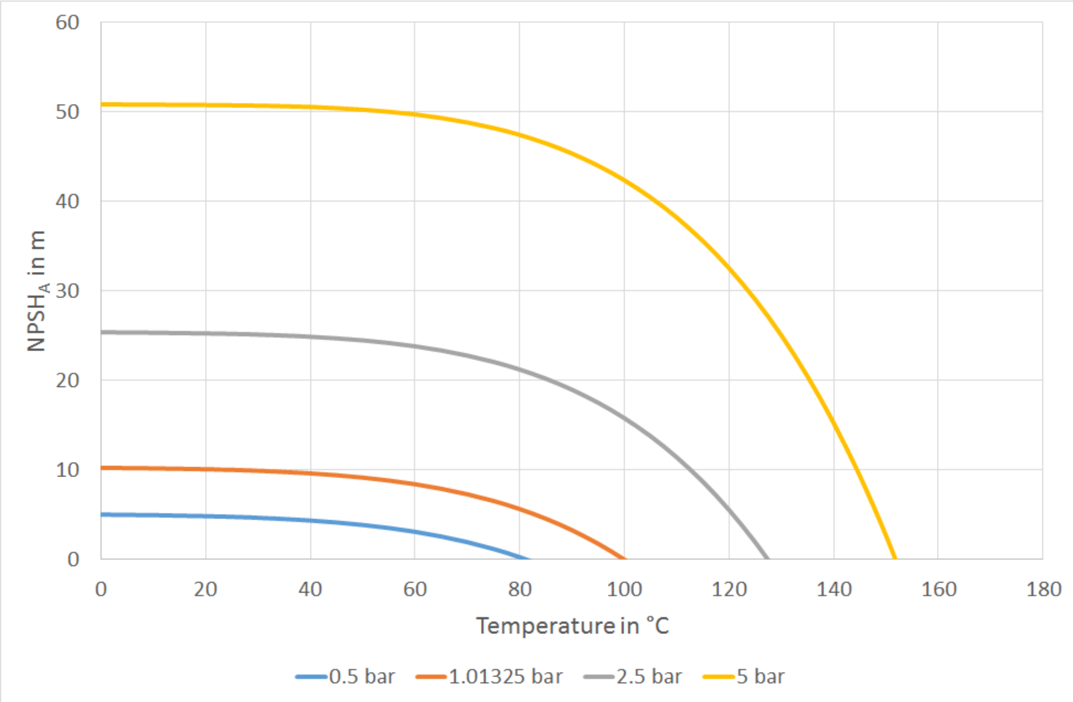

Figure 1.6: $NPSH_A$ as a function of temperature, for four different inlet pressures.

increase, and higher inlet pressures allows higher temperatures in the system. They also show that the rate of $NPSH_A$ change is higher at higher temperatures.

As described above, the head is reduced when cavitation occurs and this is used to establish the NPSH performance curve. According to the Danish Standard "DS/EN ISO 9906:2012" the $NPSH_R$ value is the NPSH value when cavitation have caused the head to be reduced by 3 %, and it is therefore also called $NPSH_{3\%}$. The pressure at the pump inlet, and thereby the NPSH, is reduced gradually until the head have been reduced by 3 % at steady flow. The NPSH at the last point before the 3 % reduction happens, is the $NPSH_R$ at that particular flow. These values can be plotted against the flow to create the NPSH curve for pump.

Modifying the inlet pressure without altering the flow, would require either a changeable water level that is lower than the pump, or a test loop with variable system pressure. To keep the testing stand simple, the pressure reduction will be done with a regulating valve before the pump inlet, which thereby also reduces the flow. The NPSH curve will therefore not cover the entire flow range.

1.3 Requirements

This section describes the requirements of the testing stand.

- The main purpose of the testing stand is to give students and staff at Aalborg University Esbjerg the possibility to test custom impellers, in a predefined pump. The testing is done to create the performance curves for the impeller. As a wide variety of people are going to be conducting the testing, the stand should be easy to use, and should not require extensive amount of training.
- The data acquisition must be electronic and automatic and there should also be no requirements for specific software in order to utilize the data from the testing.
- The testing has to be done in accordance with the Danish standards.
- As the main purpose is testing different impellers, the testing stand has to be constructed in such a way, that changing the impeller is not a complex and time consuming task. It should also be possible to change the impeller without having to empty the water tank, and without spilling too much water.
- The testing stand will initially be placed in the current laboratory, where there are much other equipment, and later it might be moved to the new facilities. To ensure that there is room for everyone, and to make it easy to relocate the testing stand, the stand should be constructed so it is easy to move. This can either be done by mounting it on wheels, or mounting sockets for a forklift. Furthermore, the testing stand should be safe to work with, and the design should ensure that risk of accidents are minimised.
- From experiments and theoretical modelling in a previous project, it is obvious that in a closed loop pump circuit a lot of heat is developed in the pipes. The amount and rate of heat developed is dependent on the size of the pump, the surface area of the pipes and tank, and temperature of the surroundings. As material properties change with temperature, it is favourable if the temperature is kept constant during the tests. Depending on the overall design of the testing stand, it might be a requirement to include a heat exchanger in the tank. This also gives the opportunity to conduct the tests at different temperatures.

CHAPTER 2

Design of Testing Stand

The testing stand is designed in accordance with DS/ EN ISO 9906:2012, which is an International Standard, published in June 2012 and has the status of European and Danish Standard.

2.1 Design Basis

The design took basis partly in the existing testing stand in Aalborg, but mostly in the pump sponsored by Grundfos.

Figure 2.1 shows the first design. There are two pressure gauges to measure the pressure before and after the pump, a regulating valve after the pump to control the flow rate, and a flowmeter in order to measure the flow rate. There is also a regulation valve before the pump to reduce the inlet pressure during NPSH tests. Furthermore, there is a heat exchanger for controlling the temperature, and a valve for emptying the tank.

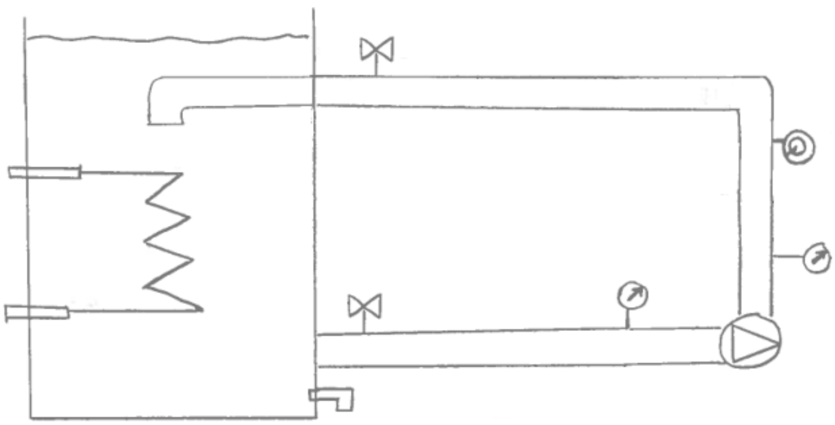

Figure 2.1: The first design of the testing stand.

From the start of the project it was known that the pump would be a NK32-125/142, which is a single stage end-suction pump with an outlet diameter of 32 mm, a nominal impeller diameter of 125 mm, and an actual impeller diameter of 142 mm. However, the pump can be fitted with two different types of motors, a 2-pole or a 4-pole. The motor type has direct effect on the pump performance and dimensions.

Due to some misunderstandings, the information about which type of motor mounted on the sponsored pump, changed as the project moved along. It started as a 2-pole, changed to a 4-pole and then changed back again to a 2-pole. Different parts of the testing equipment are therefore designed after different performance parameters. However, they all live up the parameters of the actual pump.

2.2 Pump Dimensions

As mentioned above, the motor type has an effect on the performance and dimensions of the pump. The main difference is the power of the motor, which means a difference in speed, flow rate, and head. Table 2.1 shows these parameters, which are found from the performance curves, in the data sheet for the pump family.

	Unit	2-pole motor	4-pole motor
Power	[W]	3000	370
Speed	[min^{-1}]	2900	1400
Maximum flow rate	[m^3/h]	37	18
Maximum head	[m]	28.5	7.2

Table 2.1: Pump specifications for the two different motor types for the NK32-125/142. [3]

As the numbers in the table clearly state, the type of motor mounted on the pump has a big impact on the pump performance, and thereby the design parameters.

Furthermore, the type of motor has a small effect on the dimensions of the pump. Figure 2.2 and table 2.2 shows the dimensions of the two types. Two of the dimensions are the most important ones for this testing stand. These are l_1 and b_1, as they dictate the dimensions of the foundation.

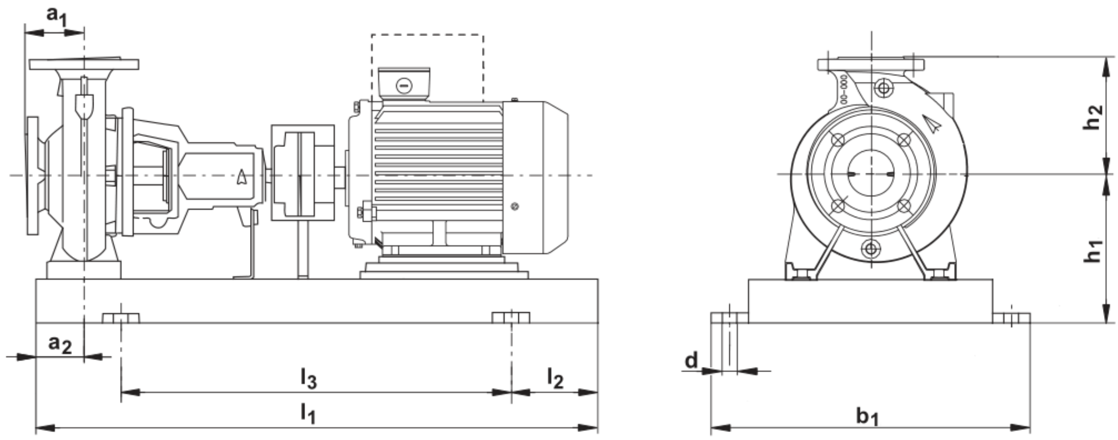

Figure 2.2: Pump dimensions. (Modified from [3])

	Unit	2-pole motor	4-pole motor
a_1	[mm]	80	80
a_2	[mm]	60	60
l_1	[mm]	900	800
l_2	[mm]	150	130
l_3	[mm]	600	540
b_1	[mm]	390	360
h_1	[mm]	177	177
h_2	[mm]	140	140
d	[mm]	19	19
Weight	[kg]	101	71

Table 2.2: Pump dimensions as shown on figure 2.2. [3]

2.3 Water Tank

As the testing stand has to be moveable, all the water necessary for the tests, must be stored in a water tank that is part of the stand. The water tank should be a tall thin structure, in order to reduce the required space in the laboratory. For convenience it should be easy to check the water level inside the container, and the water tank should therefore not be higher than an average person. To avoid water splashing out a cover is also needed.

The water tank will be made in stainless steel, as this material shows high resistance to rust and corrosion that can damage the tank surface. The tank will be in constant contact with water when operating, and therefore corrosion resistance is essential. Furthermore the stainless steel has to be weldable to make the building process easier.

Two shapes, a square and a round, were considered for the water tank. A square tank would be able to hold more water than a round one, if the diameter and height were the same. However, a square tank would also require more welding, and the corners would be subjected to higher stress concentrations, that could probably cause fracture, which is unacceptable. For that reason, a round shape was chosen.

After considering the foundation and the pump dimensions, the bottom plate of the water tank was chosen to be a 500x500 mm squared plate. The height of the tank was chosen to be between 1350 and 1550 mm in order to have the required height for the pump outlet pipe, and still not be higher than an average person when mounted on the foundation.

The stainless steel for the tank was chosen to be cold rolled, as cold rolled stainless steel guarantees higher resistance, harder material, and more accurate dimensions and tolerances than hot rolled steel.

Sanistaal supplied a plate of stainless steel type "1.4404", also known under the grade 316L. 316L has a low carbon content, less than 0.03 per cent, and thereby is more resistant to corrosion. This steel also offers excellent fusion welding performance and its mechanical properties are 200 MPa proof stress and a minimum tensile strength of 500 MPa. [4]

In order to find the necessary thickness of the steel, the future welder of the system was asked, and according to him a thickness of 3 mm would be required in order to weld it manually. Even though stress analysis are outside the curriculum, it was decided to conduct a stress analysis of the water tank in Autodesk Inventor. This was done to get an idea of where the stress is concentrated in the tank, and to establish if a thickness of 3 mm would be sufficient.

In the test, a pressure corresponding to that at the bottom of the tank was applied on the entire inner surface of the water tank. Furthermore, a force equal to the mass of the water and the mass of the water tank was added to the bottom of the tank. Figure 2.3 and 2.4 shows the results of this test.

The figure on the left shows the Von Mises Stress in the water tank in MPa. The highest stress is in the vertical welding where the rolled sheet metal is connected, it is however only 2.07 MPa, which is much lower than the proof strength of the steel. The figure on the right shows the displacement of the water tank under the same load conditions. Again the higher values are along the vertical welding, and the maximum is located at the top, on the inside of the water tank. This value is also very low, as it is only 0.02 mm, which is acceptable.

The final height of the water tank, was chosen to be 1500 mm as the steel plate from Sanistaal had this width. The volume of the water tank is therefore 287 l.

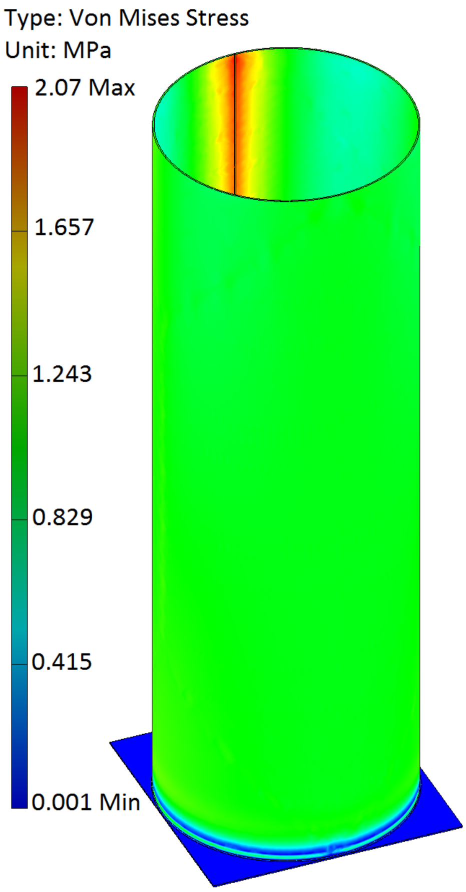

Figure 2.3: Von Mises Stress in MPa in the water tank.

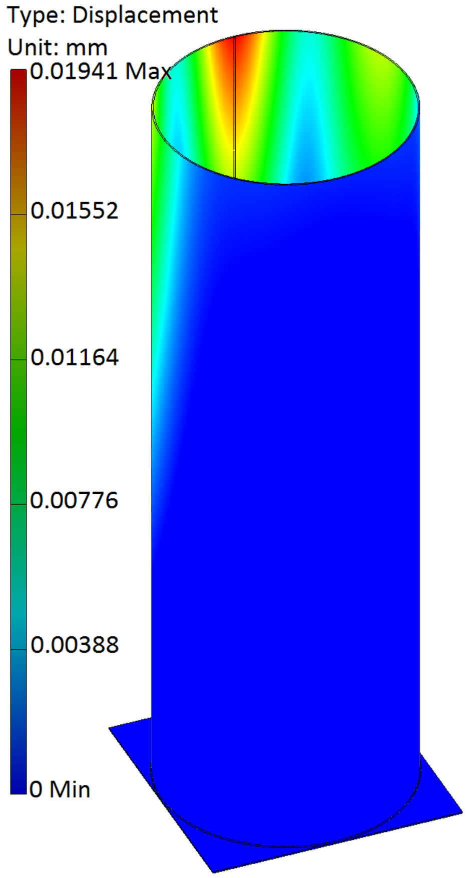

Figure 2.4: Displacement of the water tank in mm.

2.4 Foundation

All of the different parts and accessories of the testing stand have to be mounted on a stiff structure, that are able to be moved around the laboratory. It has to conform to the minimum lengths required by the pipes.

Initially, the predesign of the foundation incorporated rails, in order to satisfy the requirement of an easy and fast impeller change. The rails function was to avoid removing the electric motor every time the impeller needed to be changed. They would allow the electric motor and part of the pump housing with the impeller and the coupling to be pulled back, leaving enough room to change the impeller. However, as shown in the "Grundfos Data Booklet" as well as in the "NK Model B Grundfos Service Video"[1] for the available pump, it is not necessary to remove the motor when changing the impeller.

The pump is a back pull-out design, which means that the dismantling can be performed without affecting the pipework, the housing, or the motor. The impeller

[1] FiXme Fatal: List link in bib

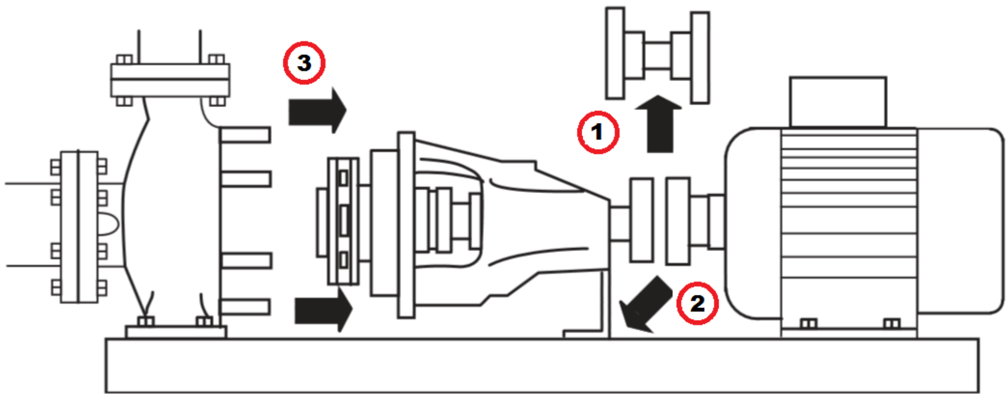

Figure 2.5: Dismantlement of a back pull-out design pump. (Modified from [3])

change can also be performed without any external lifting capability, as the housing is light enough for one person to move it. Changing the impeller consists of three easy steps, which are shown in figure 2.5. The three steps are:

1. Remove the coupling guard and coupling.
2. Unbolt the pump housing.
3. Pull back the pump housing and remove the impeller.

As there is no need for rails, another design of the foundation was made; a rectangular structure composed of squared hollow profiles in stainless steel welded together.

The pump foundation has the width of 390 mm, see figure 2.2 and table 2.2, including the bolting holes. To avoid drilling a hole through the profile from top to bottom, and to avoid that the nuts will be placed below the foundation, it was decided to bolt the pump to two L-shaped steel reinforcements welded from side to side of the structure. The L-shaped profile was chosen over a flat profile, in order to give more stability, and add more welding area at the two ends.

The dimension of the L-shaped profile was decided to be 50 x 50 x 3 mm (base x height x thickness) as there had to be enough width to drill 19 mm holes for bolting the pump foundation. For the squared profile the dimensions were also chosen to be 50 x 50 x 3 mm (base x height x thickness), as the same height as the L-shaped profile is wanted. Both of the profiles have a standard unit length of 6 m. Figure 2.6 and 2.7 shows the meaning of the dimensions of the two profiles, where b is the base, h is the height, and t is the thickness.

With the pump base width and the base on the square profile, the minimum width of the foundation is 490 mm, which is rounded to 500 mm. The excess of

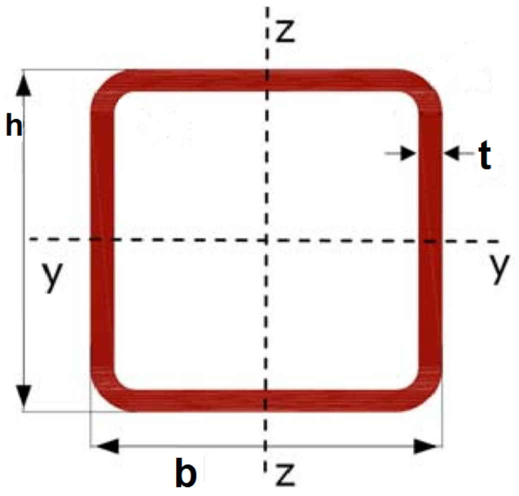

Figure 2.6: Dimension meaning of the square profile. (Modified from [5])

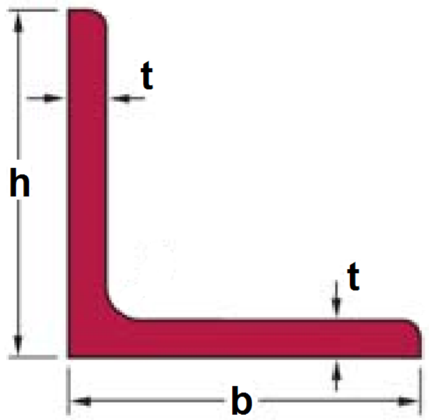

Figure 2.7: Dimension meaning of the L-shaped profile. (Modified from [5])

the 6 meters of squared profile will be used for building the longitudinal sides of the foundation, and they will therefore be 2500 mm each. It will be necessary to cut the square profile in 45° angles at the ends, to give the strongest weld.

To make the foundation moveable, four wheels are added, two fixed wheels and two swivel wheels with brakes. The wheels are not all swivel wheels, as a heavy structure with fixed wheels in one end is easier to manoeuvre for one person. Swivel wheels with brakes are chosen, so that the testing stand can be locked into place when its stationary.

In order to establish if the foundation can withstand the load, a stress analysis similar to the one of the water tank was performed in Inventor. In the test, a load corresponding to the weight of the tank with water is added at one end, and a load corresponding to the weight of the pump is added to the foundation in the other end. Furthermore, the load of gravity is added and the foundation is fixed at the locations of the four wheels.

Figure 2.8 and 2.9 shows the results of the stress analysis. The top figure shows the Von Mises Stress in MPa of the foundation, and the red area indicates where the highest stress is. This highest stress is on the water tank bottom plate, just where there are no longer any support from the frame, and it is 80 MPa. This value is only a third of what the stainless steel can handle.

Figure 2.9 shows the displacement of the foundation in mm, and again the red area indicates the highest values. The highest displacement is at the bottom of the water tank, midway between the two sides of the foundation. It should be noted that the displacement is adjusted to be more visible.

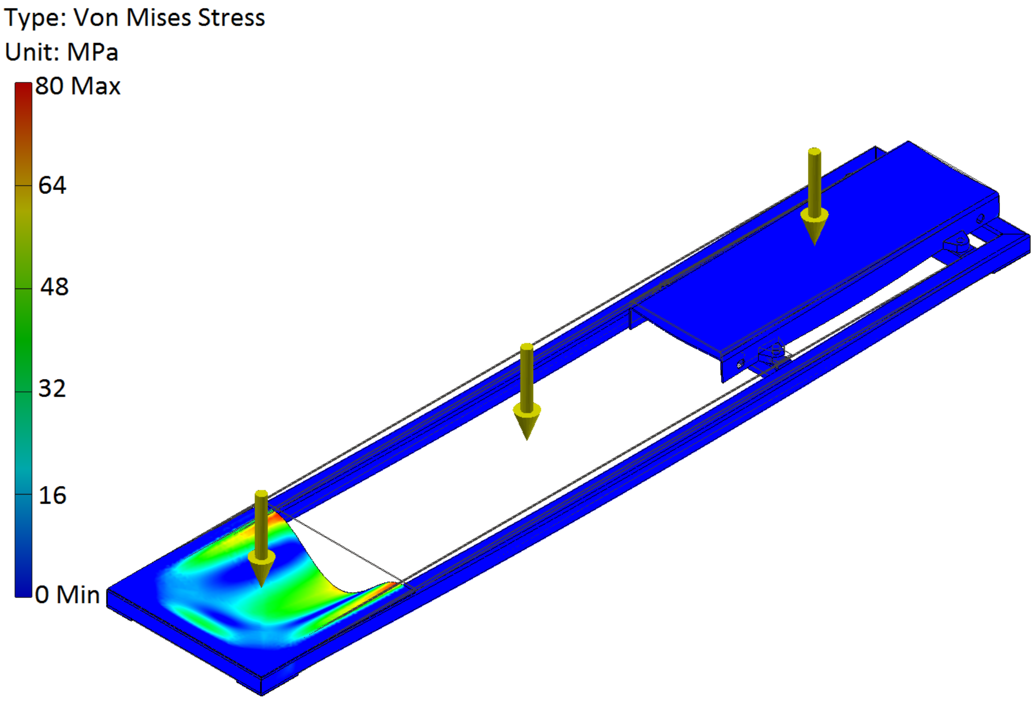

Figure 2.8: Von Mises Stress in MPa of the frame.

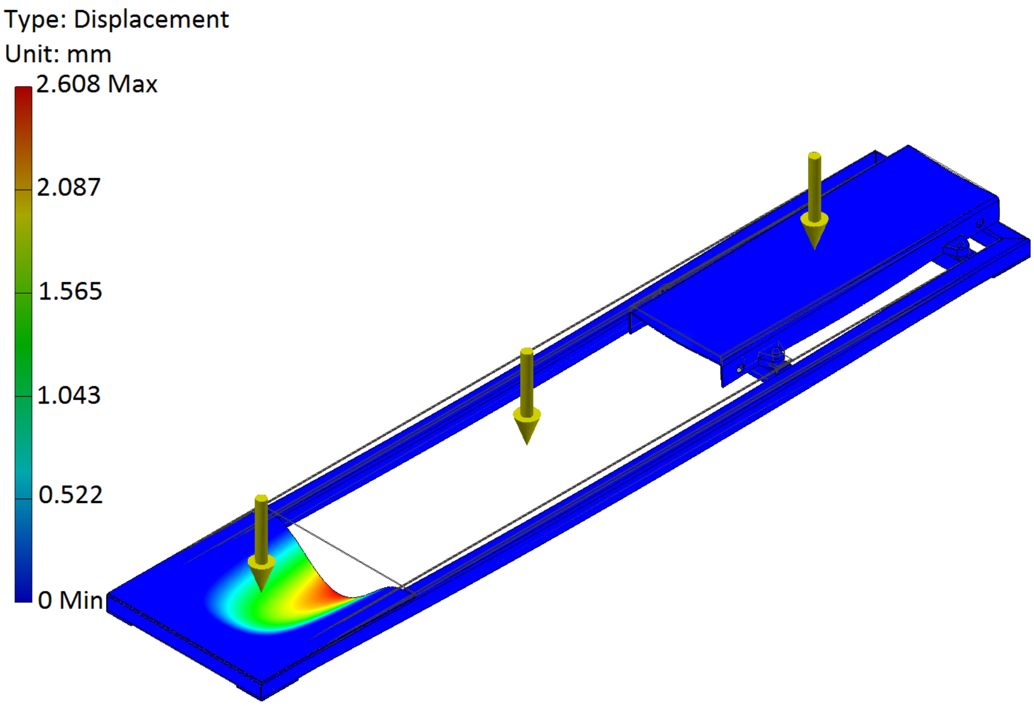

Figure 2.9: Displacement in mm of the foundation.

2.5 Pressure Measurement

A correct and accurate pressure measurement is vital for the calculation of the head. Specific requirements involving pressure are stated in ISO 9906.

First of all, for a correct pressure measurement, a non-rotating and uniform velocity profile of the fluid is needed. That means that all the components of the installation that affect the flow, and thereby the velocity profile, such as valves, bends, and the pump itself, must be placed at a minimum distance from the pressure taps. As established in Annex A of ISO 9906, the inlet pressure tap has to be located upstream from the inlet flange, at a distance of at least two times the diameter. Where the diameter is referring to the internal diameter of the pipe. The outlet pressure tap must be located at least two times the diameter distance downstream from the outlet flange.

The internal diameter of the inlet flange, D_1, of the pump is 50 mm and the internal diameter of the outlet flange, D_2, is 32 mm, therefore the minimum distances are:

$$\begin{aligned} L_1 &\geq 2 \cdot D_1 = 100\, mm \\ L_2 &\geq 2 \cdot D_2 = 64\, mm \end{aligned} \tag{2.1}$$

The lengths calculated in equation 2.1 are the distances between the pressure taps and the flanges, where L_1 is for the inlet and L_2 is for the outlet. There should also be a distance before the inlet pressure tap and after the outlet pressure tap, where there are no flow disturbances. This distance is not described in the ISO 9906, but Grundfos uses distances that are four times the diameter before the inlet pressure tap and two times the diameter after the outlet pressure tap[1]. These minimum distances are therefore:

$$\begin{aligned} L_1' &\geq 4 \cdot D_1 = 200\, mm \\ L_2' &\geq 2 \cdot D_2 = 64\, mm \end{aligned} \tag{2.2}$$

Figure 2.10: The chosen pressure transmitter. [6]

The overall type of pressure transmitter is chosen to be MBS 33 from Danfoss and it can be seen in figure 2.10. Furthermore, the pressure transmitters should measure absolute pressure, and the maximum pressure measurable should exceed the predicted maximum pressure of the system. To find the maximum pressure in the system, the sum of the maximum pump head and the height of the water in the tank, is multiplied with the density of water and the acceleration of gravity. The atmospheric pressure is also added as the absolute pressure is wanted. The maximum pressure in the system is therefore:

$$P_{max,absolute} = (H_{pump} + H_{tank}) \cdot \rho_{water} \cdot g + P_{atm} \tag{2.3}$$

With the actual values the maximum pressure in the system is 3.96 $bar(a)$. Even though there are a pressure transmitter with a range of 0-4 $bar(a)$, the next size, 0-6 $bar(a)$, is chosen. This is done as the maximum pressure of the system is very close to full scale on the 0-4 $bar(a)$ transmitter, and an impeller design which would increase the maximum head by a small amount, would push it out of the scale and thereby giving inaccurate readings.

The MBS 33 from Danfoss can withstand temperatures up to 85°C.

2.6 Flow Measurement

The different tests requires flow measurements. According to section D.3 in Annex D of ISO 9906, any flow measurements can be used as long as is complies with the following:

- All flow passing through the pump must also pass through the flowmeter.
- The instrumental uncertainty should not exceed $\pm 1.5\%$.

A magnetic inductive flowmeter from Isoil was chosen, which can be seen in figure 2.11.

For the first point, as long as there is only one pipe, all the flow passing through the pump will pass through the flowmeter. Figure 2.12 shows the instrumental uncertainty of a Isomag MS 2500 sensor with a ML 51 converter attached. The figure indicates that the MS2500-ML51 complies with second point from Annex D of ISO 9906. Furthermore, the calibration report from Isomag can be seen in Appendix A. It shows that the uncertainty of the actual flowmeter lies between the indicated lines.

Figure 2.12 also shows that the lower and upper limit for fluid velocity, taking the 1.5 % error into account, is 0.166 m/s and 10 m/s respectively. This means that the flowmeter needs to have a minimum diameter in order to measure the maximum flow rate of the pump, and the smallest possible diameter should be chosen.

Figure 2.11: Isomag MS 2500 flowmeter. [7]

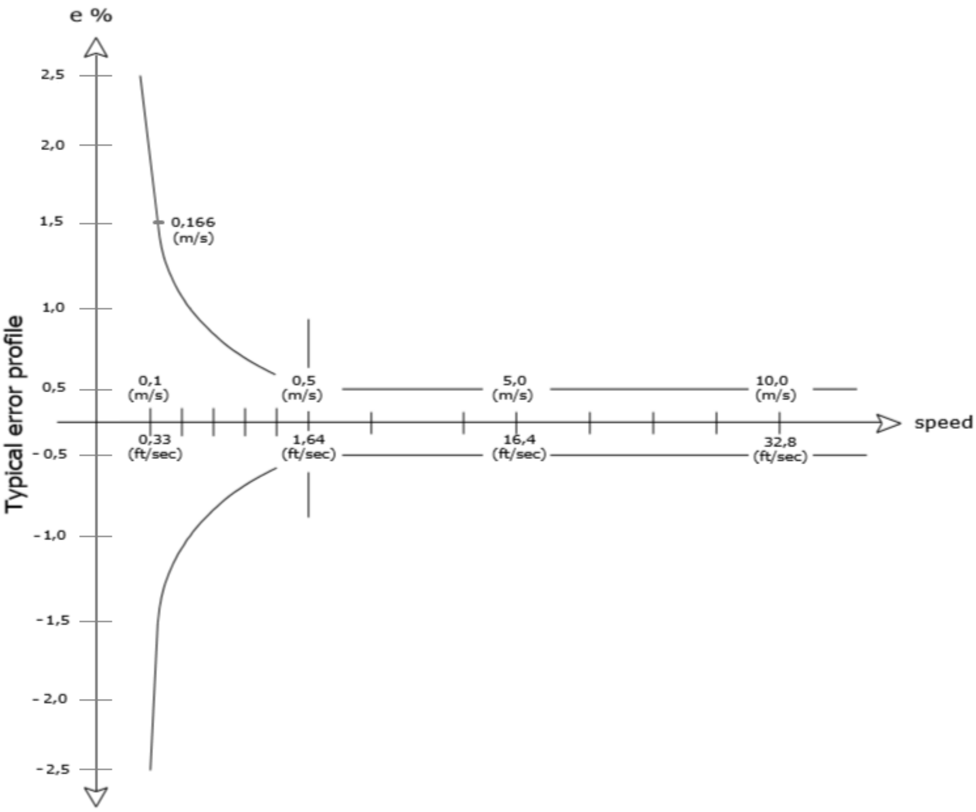

Figure 2.12: Accuracy table for a Isomag MS 2500 sensor with a ML 51 converter attached. (Modified from [7])

The minimum and maximum flow rate can be calculated by multiplying the velocity with the cross section area, or in equation form:

$$
\begin{aligned}
Q_{min} &= V_{min} \cdot \frac{D^2 \cdot \pi}{4} \cdot 3600 \\
Q_{max} &= V_{max} \cdot \frac{D^2 \cdot \pi}{4} \cdot 3600
\end{aligned}
\tag{2.4}
$$

where Q_{min} and Q_{max} are the minimum and maximum flow rates in m^3/h, V_{min} and V_{max} are the minimum and maximum fluid velocities in m/s, and D is the internal diameter in m.

The initial design, figure 2.1 on page 11, puts the flowmeter on the outlet side of the pump, where the diameter is 32 mm. A flowmeter with this diameter, give a minimum and maximum flow rate measurable of 0.48 m^3/h and 28 m^3/h respectively. The maximum flow rate measurable is lower than 37 m^3/h, which is the maximum flow rate of the pump, found in table 2.1, and a flowmeter with a diameter of 32 mm is therefore too small.

The next possible diameter size is 40 mm, and the minimum and maximum flow rate measurable are 0.75 m^3/h and 45 m^3/h respectively. As the maximum flow rate measurable is above the maximum flow rate of the pump, a flowmeter with a diameter of 40 mm is chosen.

The highest accuracy of the flow measurements are when the flow is fully developed and free of swirl. For this reason, there are some requirements in ISO 9906 regarding the length before and after the flowmeter, where there should be no flow disturbing equipment. These lengths are a function of the internal diameter of the pipe, just as the length requirements for the pressure transmitters. The distance before the flowmeter has to be ten times the diameter, and the distance after has to be five times the diameter. As a flowmeter with an internal diameter, D_3, of 40 mm is chosen, the minimum lengths are:

$$
\begin{aligned}
L_3 &\geq 10 \cdot D_3 = 400\ mm \\
L_3' &\geq 5 \cdot D_3 = 200\ mm
\end{aligned}
\tag{2.5}
$$

where L_3 is the length before the flowmeter, and L_3' is the length after the flowmeter.

These minimum lengths gave reason to concern regarding the placement of the flowmeter. The sum of the minimum lengths, the length of the equipment installed in the vertical pipe, and the height of the pump outlet flange, is approximately 1400 mm. This means that with a water tank height of 1500 mm, there are only 100 mm from the top of the upper horizontal pipe, to the top of the water tank, making the assembly tolerances small. Therefore the location of the flowmeter is moved to the upper horizontal pipe.

The maximum temperature the flowmeter can withstand is 100 °C.

2.7 System Temperature

As water is pumped around in the testing stand, heat will build up in the form of a temperature rise. To prevent this temperature rise to reach critical levels, it is important to have the ability to cool the water. The amount of cooling required depends on the pump power and the surface area of the tank and pipes. These two properties are also the deciding factor when the maximum temperature without cooling has to be established.

To establish the maximum temperature and the rate of temperature rise, a simple model of the energy build up, can be set up as a differential equation of the amount of energy going into the system, minus the amount of energy going out of the system. Where the system in this case consists of:

- The steel in the water tank, the pipes, and the pump housing.
- The water in the tank and pipes.

For this system, the amount of energy going into it, is the power supplied to the pump. The energy leaving the system, is the heat transfer in convection form. Put into equation form, this is:

$$\begin{aligned} \frac{dE_{sys}}{dt} \approx \frac{\Delta E_{sys}}{\Delta t} &= \dot{E}_{in} - \dot{E}_{out} \Leftrightarrow \\ m_{sys} \cdot c_{p,sys} \cdot \frac{\Delta T_{sys}}{\Delta t} &= W_{pump} - Q_{convection} \Leftrightarrow \\ (m_{water} \cdot c_{p,water} + m_{steel} \cdot c_{p,steel}) \frac{\Delta T_{sys}}{\Delta t} &= W_{pump} - h_\infty \cdot A_s \cdot (T_{sys} - T_\infty) \Leftrightarrow \\ \frac{\Delta T_{sys}}{\Delta t} &= \frac{W_{pump} - h_\infty \cdot A_s \cdot (T_{sys} - T_\infty)}{m_{water} \cdot c_{p,water} + m_{steel} \cdot c_{p,steel}} \end{aligned} \tag{2.6}$$

where:

- T_{sys} is the temperature of the system in $^\circ C$.
- W_{pump} is the power supplied to the pump in W.
- h_∞ is the heat transfer coefficient to the ambient air in $W/m^2\ ^\circ C$.
- A_s is the surface area in m^2.
- m_{water} and m_{steel} is the mass of the water and mass of the steel in kg.
- $c_{p,water}$ and $c_{p,steel}$ is the specific heat capacity of water and steel in $J/kg\ ^\circ C$.

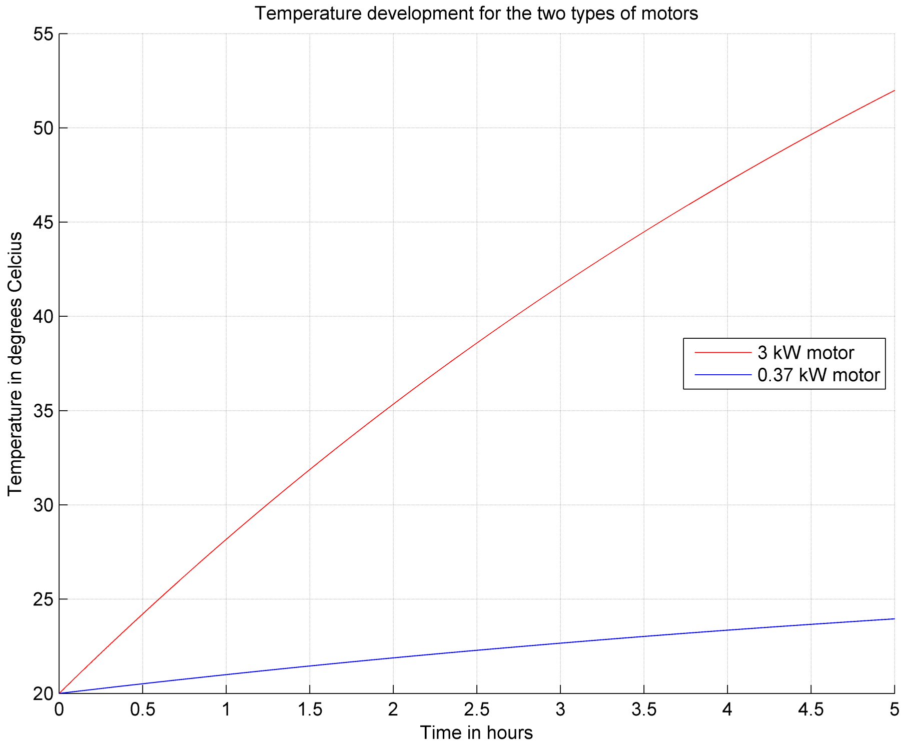

Figure 2.13: Temperature development in the system.

Figure 2.13 shows the theoretical temperature development in the system. The blue graph shows the temperature of the system with a 4-pole pump motor. The temperature increases about four degrees in five hours, and there is not much need for cooling with this type of motor. However, the red graph shows the temperature development with the 2-pole motor. This temperature increases about 32 degrees in five hours. For a system with a 2-pole motor, there is a need for a heat exchanger in the tank.

Figure 2.13 is the solution to equation 2.6, solved numerically in MATLAB. The MATLAB files can be seen in Appendix B. The following approximations are used:

- The water has a mass of 290 kg and an initial temperature of 20 $°C$.
- The surface area of the tank and pipes are 3 m^2, with a heat transfer coefficient of 15 $W/m^2\ °C$.
- The ambient air has a temperature of 20 $°C$.
- The steel has a mass of 100 kg and an initial temperature of 20 $°C$.
- The steel and the water have the same temperature.

Apart from the first five hours of temperature increase, the maximum temperature reached was also found. This was done by setting the change in temperature to zero, and solve for the temperature. The results are 86.7 $°C$ and 28.2 $°C$ respectively.

As the temperature rise in the first five hours is not critical, and as the tests are not designed to run constantly, it is decided that a heat exchanger will not be designed at this point. The design of a heat exchanger was also postponed, as the 4-pole motor does not require a heat exchanger. It is however decided that two pipe pieces with shut-off valves should be mounted on the tank, to give the possibility to include a heat exchanger at a later point. A thermometer was added at the bottom of the tank, so that the properties of water needed for the head calculations, could be a function of temperature.

2.8 Valves

In order for the testing stand to fulfil its primary purpose, creating a head curve, a valve capable of reducing the flow is necessary. This valve should be located after the pump outlet, to ensure the inlet pressure does not drop below vapour pressure. However, there should also be a valve before the pump inlet to reduce the inlet pressure for NPSH tests. The valves should be electronically operated to make the testing stand easier to use. Nevertheless, it should be possible to close off the pipes manually, in case of malfunction, or when the impeller has to be changed. Therefore, there is also a need for two shut-off valves with a handle.

The valves and the motors for the electronically controlled ones, were sponsored by Belimo. The supplied motors can go from opened to closed in 90 seconds and are able to provide location feedback. Figure 2.14 shows the electric motor for controlling the valves.

Figure 2.14: Electronic motor for valve control. [8]

The two valves at the pump inlet section, should be the same diameter as the pipe to minimise the pressure loss. The two valves at the outlet section could either be the same diameter as the outlet pipe, or as the flowmeter. Due to the length requirements before and after the flowmeter, there is no room to mount the two valves in the upper horizontal pipe, and they must therefore be mounted in the vertical pipe with the same diameter as the pump outlet.

2.9 Pipes and Components

In order to connect the different components, three different sizes of pipes are needed; 50, 40 and 32 mm. The pipes should be made of stainless steel as the water tank and foundation, they are ordered from Sanistaal as well. The required length for each of the pipe sizes is around 1 m, but they are only sold in standard length of 6 m. From the beginning it was the intention to cut all the pipe parts from the 6 m pipe and create the thread at the ends, but due to the fact that stainless steel is very hard, cutting thread into it requires special equipment. Therefore barrel and welding nipples were ordered in the wanted lengths.

Apart from the pipes, barrel nipples, and welding nipples, there is also a need for a number of flanges, bends, and small parts for connecting the pressure and temperature transmitters. Expansion from the outlet pipe to the flowmeter pipe is done in the 90° bend where the vertical pipe is connected to the upper horizontal pipe. All these items are supplied by Sanistaal.

2.10 Final Design

To sum up all the design process, this section will offer an overall view of the definitive design. Along the design process some parts of the stand had to be modified due to different criteria.

Figure 2.15 shows the final design and figure 2.16 lists some of the pictograms used. This design considers the minimum lengths required for the pressure and flow measurements described in section 2.5 and 2.6. The necessary shut-off valves for the heat exchanger described in section 2.7, is also added to the design. Furthermore, manually operated valves have been added next to the electronically controlled ones. The flowmeter has been moved and a temperature transmitter has been added at the bottom of tank. For that reason, the vent to empty the water tank has been moved slightly. All the dimensions in the figure are shown in millimetres.

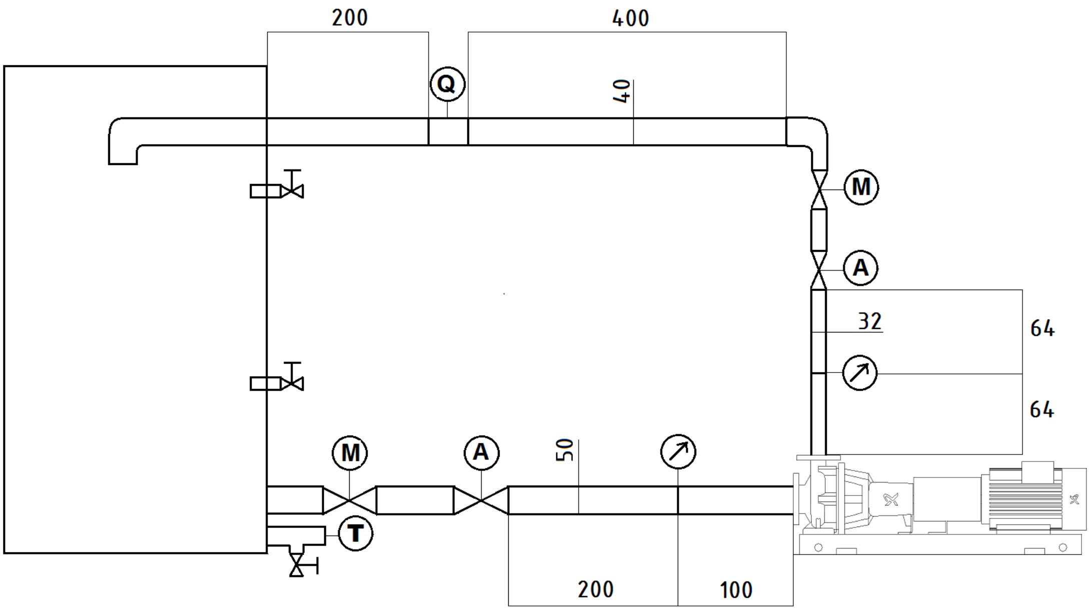

Figure 2.15: Final design of the testing stand.

Component	Symbol
Flowmeter	Q
Manually controlled valve	M
Electronically controlled valve	A
Pressure transmitter	↗
Temperature transmitter	T
Shut-off valve	

Figure 2.16: Pictograms used in figure 2.15.

CHAPTER 3

Construction of Testing Stand

The construction of the testing stand was performed at Granly Diesel; a local company that repairs ship engines. One of the junior welders offered to help with the construction, and the company put their facilities at disposal. Therefore all of the steel was delivered at Granly Diesel's workshop at Esbjerg Harbour.

3.1 Welding at Granly Diesel

First step was cutting the plate for the water tank and thereafter roll it into a cylinder. It was carried out at another company workshop with the necessary and appropriate equipment. Meanwhile, the square profile was cut into two 500 *mm* parts and two 2500 *mm* rods with 45° cuts at the ends. Figure 3.1 is a picture of

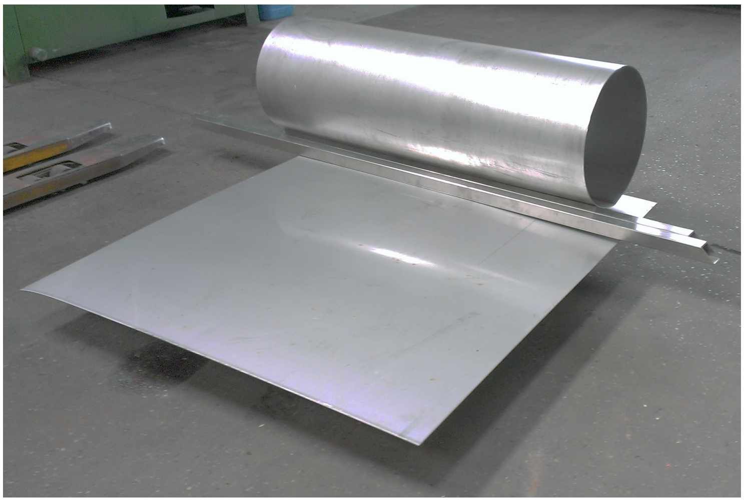

Figure 3.1: Picture of the water tank, the leftover sheet metal, and the long foundation parts with 45° cut at the ends.

the water tank, the leftover sheet metal, and the two side parts for the foundation. The 45° cuts can be seen on the right side in the picture.

Next step was to weld the foundation together and add the wheels. At the same time, the bottom plate for the water tank and the L-shaped pump supports were cut out. A top cover for the water tank was also cut out from the remaining sheet metal. It was fitted with a handle, a rim, and a hanger to make it easy to remove. Figure 3.2 is a picture of the foundation with mounted wheels. In the upper part of the picture, a pump support can be noticed. Holes were drilled into the four corners of the tank bottom and into the pump supports. The pump supports were then welded to the foundation and also the bottom plate was welded to the tank.

Figure 3.2: Picture of the foundation with mounted wheels.

Next, the pump and the water tank were mounted on the foundation and the required length of the inlet pipe was measured and cut out. The outlet pipe was cut out in the correct length as well. Both pipes were fitted with a flange at one end and a welding nipple at the other end. Furthermore, a hole for the inlet pipe and a hole for the temperature transmitter were drilled in the tank. Figure 3.3 is a photo of the pump and water tank mounted on the foundation. On the left side of the picture the hole drilled for the inlet pipe can be seen. The small pipe welded on the inlet pipe is the mounting piece for the inlet pressure transmitter. A similar one is also welded on the outlet pipe, that can be seen standing up in the front of the picture.

The last thing to be cut out and welded together, were the two parts of the upper horizontal pipeline. One of these parts were assembled like the two previous pipes, with a flange at one end and a welding nipple at the other end. The other part of the upper horizontal pipe is mounted with a flange at one end and a 90° elbow at the end going into the tank. This bend's purpose is to direct pumped water downwards and thereby reduce probable splashing. Figure 3.4 shows a picture of the water tank with the mounted upper horizontal pipe. In addition the holes for

Figure 3.3: Picture of the pump and water tank mounted on the foundation.

Figure 3.4: Picture of the upper horizontal pipe and holes for the heat exchanger.

Figure 3.5: Picture of the leakage test with mounted heat exchanger valves.

where the shut-off valves for the future heat exchanger will be placed can also be seen on the picture. Figure 3.5 is a picture of the last task accomplished. It shows the water tank while it was filled with water, to conduct a leakage test. Also, it was tested and checked that the welding can withstand the pressure applied by the water.

3.2 Reassembling at the University

After the successful leakage test, the testing stand was dismantled and transported to the university for rebuilding. During the reassembling process, the pipe joints were packed with packing yarn and joint paste to ensure the joints were tight. In addition to the pipes, bends, and valves, the flowmeter and pressure transmitters were added. Once again the tank was filled with water but this time to conduct a leakage test of all the joints.

Figure 3.6 shows the testing stand once it was assembled. That green box mounted in the middle of the upper horizontal pipe is the flowmeter. The pressure transmitters can barely be seen, as they are pointing into the picture. The manual operated vales for the inlet and outlet are the ones equipped with a black handle. Next to them, the regulating valves without the electric motor are located.

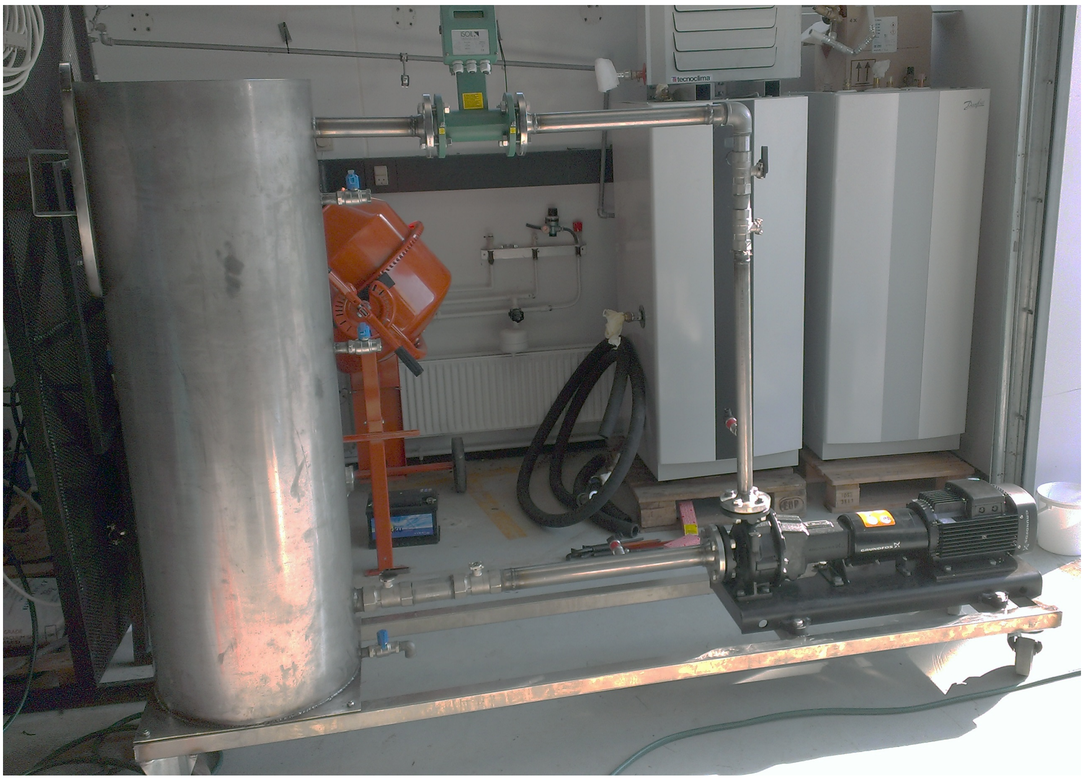

Figure 3.6: Picture of the assembled testing stand.

Figure 3.7: Picture of completely assembled testing stand.

Once the second leakage test was done, all that was left was to mount the electric motors for the valves and connect all of the equipment to the required power sources. All electric components were gathered into a water resistant plastic casing, which was set up on a small table created from the leftover steel sheet. This table was built over the pump motor, by bolting the table legs onto the pump foundation. In this location, the table does not interfere with the changing of the impeller.

Figure 3.7 is a picture of the whole assembled testing stand with the table mounted. The water resistant plastic casing is placed on top of the table in the left side of the photo and the cables between the casing and the equipment have been sip-tied together. The electric motors for the regulating valves can also be seen in the picture.

CHAPTER 4

Data Acquisition

Among the requirements for the testing stand, was an easy to use and automatic data acquisition that would not demand additional software. For that reason it was decided to program a myRIO from National Instruments to handle the data acquisition. A myRIO is a measuring and testing device that can handle a lot of different inputs, have on-board features like buttons and LEDs that can be programmed by the user, and it can be programmed to launch an application on start-up. Figure 4.1 shows pictures of five out of six sides of the myRIO.

4.1 Connecting Equipment

In order to measure and log the data from the different equipment, they have to be connected through the analogue ports to the myRIO. In total, there is need for seven input channels and two output channels. Table 4.1 shows the distribution and signal type of these connections.

The 2-10 V signals can be connected directly to the myRIO, but the 4-20 mA signals have to be converted to a voltage. This is done by connecting a 250 Ω resistor between the signal and ground, thereby creating a 1-5 V signal instead. Figure 4.2 shows an electric circuit diagram of signal conversion. The circle with the "e" is

Equipment	**Input/Output**	**Signal**	**Total channels**
Pressure transmitter	Input	4-20 mA	2
Temperature transmitter	Input	4-20 mA	1
Flowmeter	Input	4-20 mA	1
Watt-meter	Input	4-20 mA	1
Valves	Input	2-10 V	2
Valves	Output	2-10 V	2

Table 4.1: Types of connections the different equipment needs.

Figure 4.1: Pictures of five sides of a myRIO.

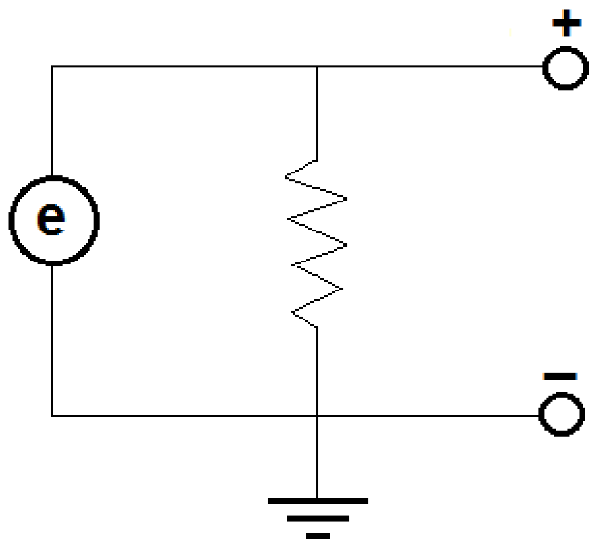

Figure 4.2: Electric circuit diagram of the signal conversion.

the equipment giving of the 4-20 mA signal and the plus and minus circles on the right, is where the 1-5 V signal is measured. The 4-20 mA signal are converted to a 1-5 V signal instead of a 2-10 V signal, as the myRIO has only two ± 10 V but eight 0-5 V analogue channels. The ± 10 V channels are used for the valves as they already emit a voltage signal in that range.

After the signals have been converted to voltage signals and measured by the myRIO, they must be transformed to the corresponding unit. This is done by the following equation:

$$Value = (U - O) \cdot K \tag{4.1}$$

where U is the measured voltage in V, O is the offset in V and K is a transformation coefficient. The transformation coefficient is dependent on the voltage range and equipment measuring range, where the range means the highest value minus the lowest one. The transformation coefficient can be found in the following way:

$$K = \frac{measurement\ range}{voltage\ range} \tag{4.2}$$

To control the closing of the valves, a 2-10 V signal is used. The voltage required for a specific position in degrees, can be found by isolating U in equation 4.1:

$$U = \frac{Value}{K} + O \tag{4.3}$$

The transformation coefficient, K, is the same as the one needed in equation 4.1. The measurement scale, the voltage range, the offset, and the transformation coefficient can be seen in table 4.2.

Measurement	Scale	Range	Offset	Coefficient
Pressure	0-6 bar	4 V	1 V	1.5 bar/V
Temperature	0-100 °C	4 V	1 V	25 °C/V
Flow	0-12.8 l/s	4 V	1 V	3.2 l/s/V
Valve position	0-90 °	8 V	2 V	11.25 °/V
Power	0 - 3100 W	4 V	1 V	775 W/V

Table 4.2: List of the different values from equation 4.1 and 4.2.

4.2 LabVIEW Programming

LabVIEW is a graphical programming software that allows the user to create applications, called VI's, with blocks and wires. These blocks can also be customised to fit the actual needs. The customised blocks are called SubVI's and they are also used to give a better overview, reducing larger code into a single block.

4.2.1 Measurement SubVI's

A SubVI is created for each of the different type of equipment, containing a block for reading the voltages, some code for transforming the values, and a block for directing the signal out of the SubVI. Figure 4.3 shows the SubVI for the pressure measurements, where the blue block on the left reads the voltages, the two orange blocks on the right direct the signal out of the SubVI, and the stuff in-between transforms the values. This SubVI handles both pressure transmitters at the same time.

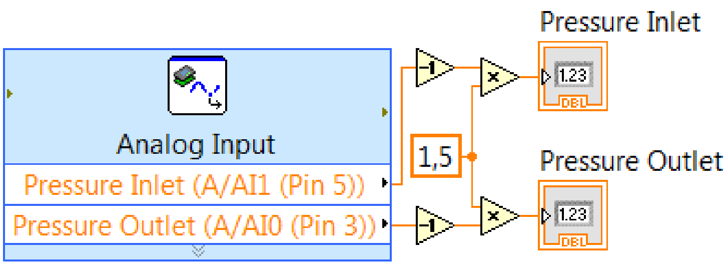

Figure 4.3: SubVI for measuring, transforming, and directing the pressure.

In the flow SubVI there are code similar to the code in the pressure SubVI, but there are also code to convert the flow to velocity in the pipes. This is simply accomplished by dividing the flow with the internal cross-section area of the pipes. The four different signals are directed out of the SubVI. In the valve control SubVI, the code is turned around to convert the wanted valve position to a voltage.

The temperature SubVI is stuffed inside another SubVI called "Material Properties". In this SubVI the density and viscosity are calculated as a function of temperature. These functions are a third-order and fourth-order polynomial, created using the trend line function in Excel. The data used are the properties of water between 10°C and 90°C from the program "Engineering Equation Solver". These functions are:

$$\begin{aligned}\rho(T) &= \left(1\cdot10^{-5}\right)T^3-\left(5.5\cdot10^{-3}\right)T^2-\left(5.5\cdot10^{-3}\right)T+1000.4\\ \mu(T) &= \left(3\cdot10^{-11}\right)T^4-\left(7\cdot10^{-9}\right)T^3+\left(8\cdot10^{-7}\right)T^2-\left(5\cdot10^{-5}\right)T+0.0017\end{aligned} \tag{4.4}$$

Note that these functions are only valid in the temperature range of 10-90°C.

4.2.2 Head Calculation SubVI

The calculation of the head is obtained by translating equation 1.4 into a SubVI. This SubVI can been seen in figure 4.4.

Each of the different parts of equation 1.4 can be seen different places in figure 4.4. In the top of the figure the static head is calculated, in the middle the dynamic head is calculated, and in the bottom the head loss from friction is calculated in two SubVI's. In these SubVI's, the Reynolds number are first calculated with the water

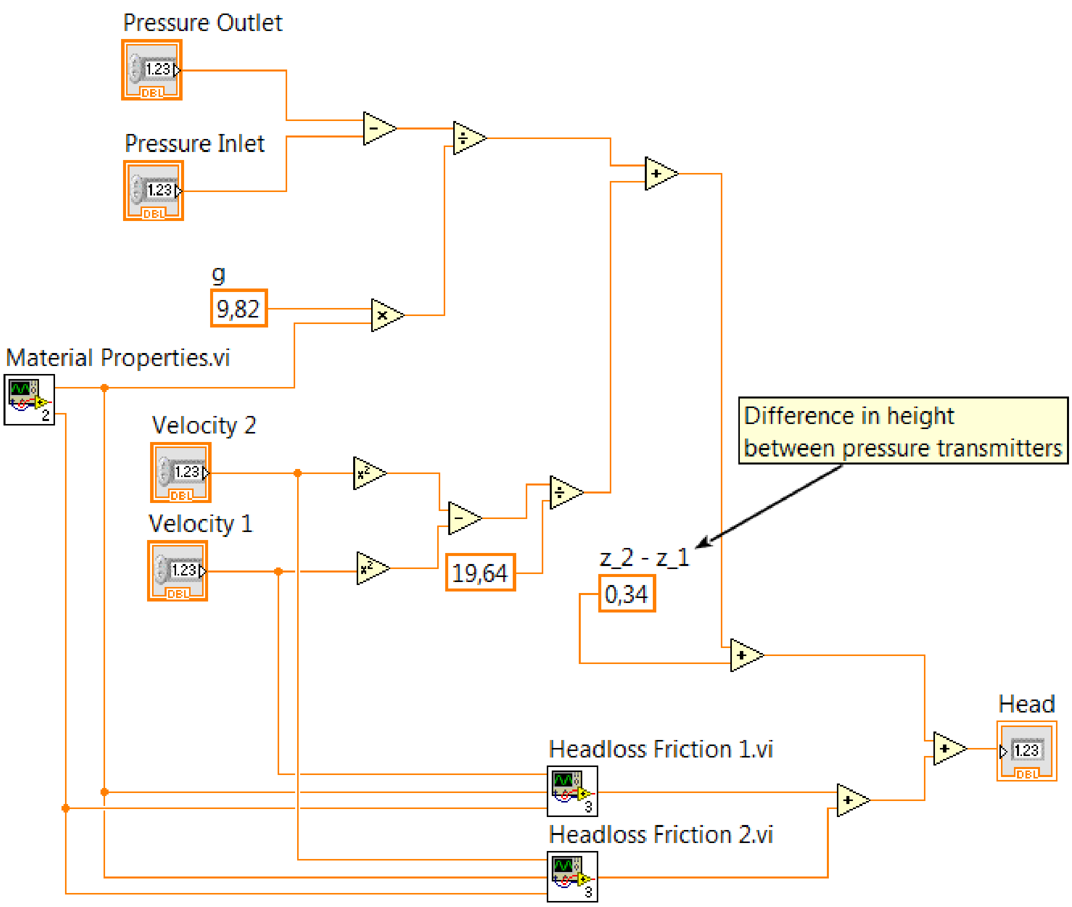

Figure 4.4: Head calculation SubVI.

properties at the current temperature, which is then used to find the friction factor using Colebrook's Equation. Colebrook's Equation is solved numerically using Fixed Point from the following rewritten equation:

$$f = \frac{1}{\left(-2\log\left(\frac{\epsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)\right)^2} \tag{4.5}$$

It is solved to an accuracy of 10^{-10}, and this is achieved in ten or less iterations.

4.2.3 Performance Test

To test the performance of the pump and impeller, a performance test is set up. This test calculates the head, power, and efficiency at different flow rates. As the head calculation is dependent on different factors, which can cause fluctuating in the calculation, some precautionary measures are taken to minimise the effect of the fluctuation. The head calculations are therefore made in the following sequence:

1. The valve position is changed 2.5°.
2. The flow is allowed to settle for ten seconds after the valve movement is done.
3. The flow and power is measured and the head and efficiency is calculated 100 times at a frequency of 10 Hz.
4. The mean and standard deviation for the flow, head, power, and efficiency are found and stored in an array.
5. Step 1-4 is repeated until the valve position have gone from 0° to 65° and back to 0°.
6. The values from step 4 are saved as a csv file on a connected USB-stick. csv stands for "Comma Separated Variables" and the file can be opened in a wide variety of programs, including Excel. Table 4.3 is an example, with fictional values, of how the csv file could look after a performance test.

$\bar{Q}$	s_Q	$\bar{H}$	s_H	$\bar{P}$	s_P	$\bar{\eta}$	s_η
23.422	0.255	22.615	3.003	2976	0.079	56.72	2.820
22.587	0.157	24.349	2.710	2989	0.134	55.68	1.543
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table 4.3: Example of csv file.

The mean values in step 4 are calculated form the following equation[9]:

$$\bar{x} = \frac{1}{n}\sum x_i \tag{4.6}$$

where x_i is the i-th reading and n is the number of readings.
The sampled standard deviation, also found in step 4, is calculated by the following equation[9]:

$$s = \sqrt{\frac{1}{n-1}\sum (x_i - \bar{x})^2} \tag{4.7}$$

Equation 4.6 and 4.7 are both from ISO 9906.

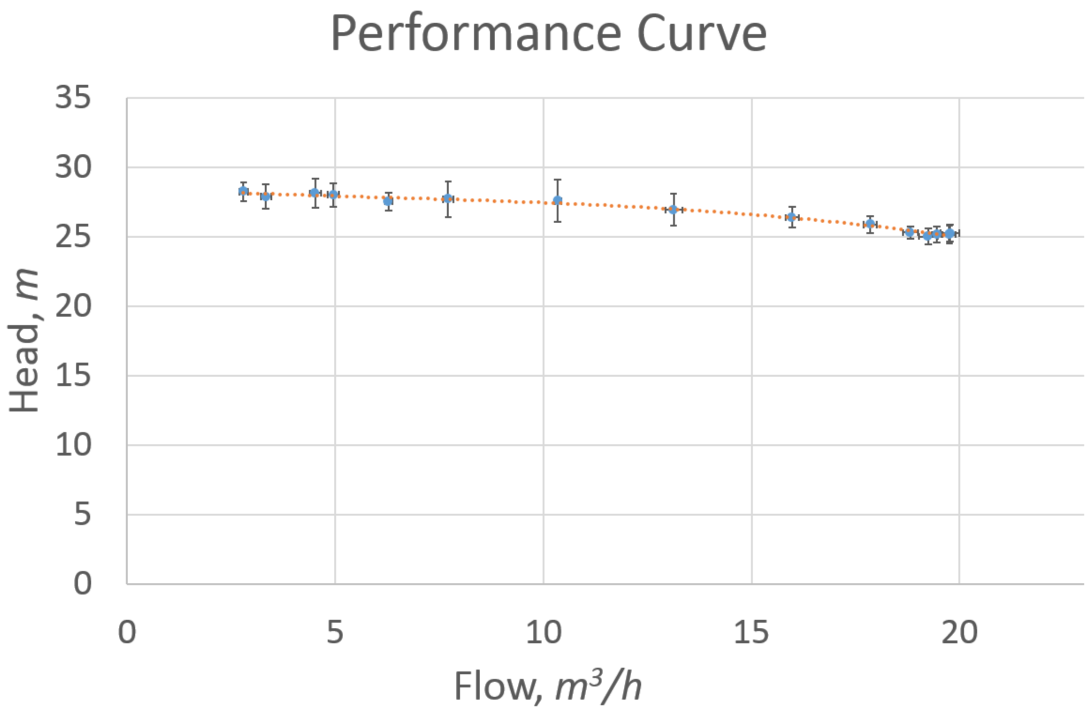

Figure 4.5: Performance curve created with data from a performance test.

The values from the csv file can be used to create a performance curve for the pump. Figure 4.5 shows a head performance curve for an impeller that was delivered with the pump. The small vertical and horizontal black lines are error bars around the different mean values.

4.2.4 Program Execution.

The performance test does not require any inputs while it is running, however it demands a start-up input. To avoid the need for users to connect a laptop with LabVIEW to the myRIO in order to start the application, it is loaded onto the myRIO and set to run on start up. As there are going to be more than one test to run, the on-board button are programmed to handle inputs from the user. The four LEDs on the front of the myRIO named “LED0”, “LED1”, “LED2”, and “LED3” are programmed to indicate different things. The meaning of the different LEDs are the following:

LED0: Ready state. Indicates if the myRIO is ready.

LED1: Sub-program 1. Connected to the first sub-program on the myRIO, which is reserved for endurance test.

LED2: Sub-program 2. Connected to the performance sub-program.

LED3: Sub-program 3. Connected to the last sub-program, reserved for NPSH test.

When the myRIO is turned on, the start-up sequence is around 30-60 seconds and after that time, the main program will be running on the myRIO. The program will start by setting the valve position to fully open. To indicate that the myRIO is working, LED0 will blink slowly. When the valves have been fully opened, LED0 will go from blinking to being on consistently.

The user can then choose between three different tests or sub-programs by operating the on-board button. Each time the button is pressed an LED will light up and five seconds after the button has been last pressed, the sub-program connected to the active LED, will execute. The corresponding LED will start blinking to indicate that the myRIO is executing that sub-program.

While a sub-program is running, LED0 will be off. When LED0 turns back on, the sub-program is done and the USB-stick with the data can be removed, or another test can be started. The data that are saved in the different test are numbered continuously, so that the previous data will not be lost when a new test is started.

Conclusion

The main goal of this student project has been the successful design and construction of a testing stand for a predefined centrifugal pump. This structure complies with the requirements established in the hydraulics performance acceptance tests for rotodynamics pumps in Danish Standards. These standardized tests intend to ensure the performance of the pump and to compare the results with the manufacturer's guarantee.

The first part of the project was to specify the requirements for this testing stand. This required an understanding of the pump types, deepening into centrifugal ones, and theory about the different test that can be performed with a centrifugal pump.

In the second part, the testing stand was designed in accordance with the International Standard for rotodynamic pump tests, ISO 9906. The design also took into account the changeability of the impeller and a safe working environment. Data sheets and properties of the different equipment were studied and analysed. The dimensioning of different parts of the testing stand were linked together, so changing any of them affected the rest. Stress analysis simulation of the water tank and foundation, using Autodesk Inventor, confirmed the design. After the design was finalised, the testing stand was built from sheet metal and steel rods.

The last part of the project dealt with programming a myRIO in LabVIEW, to be able to execute a pump test. The myRIO device measures the readings of the different equipment and converts it to manageable data. It also takes into account the measurements uncertainties according to ISO 9906 in the form of a sampled standard deviation.

A manual for conducting the performance test was created and attached to the testing stand. The manual can be seen in Appendix C.

Future Work

The main requirements of the testing stand are fulfilled, but there are still improvements to be made.

One of the main things to add to the testing stand, could be a heat exchanger. This allow the users to conduct tests with constant temperature and at different temperature levels, thereby establishing the connection between temperature and performance. An inlet and outlet for a heat exchanger have already been added, leaving only the need for a coil inside the water tank.

Another thing to add, could be the possibility to conduct different test. For example a NPSH test for obtaining the NPSH curve. The valve needed to reduce the inlet pressure is present and the only thing missing is the LabVIEW sub-program.

Furthermore, to ensure the durability of the installation some improvements could be done to avoid the water hammer effect. Water hammer is a phenomenon that occurs when a valve is suddenly closed or when the pump has a sudden stop. The fluid running along the pipeline is forced to stop, creating a shock wave that causes an overpressure because of its inertia. This can be noticed as a loud banging, similar to a hammering noise. The overpressure could damage the pipes, even breaking them if the pressure is high enough. Possible solutions could be modifying the stand to include e.g. non-return valves or a surge tank.

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List of Figures

List of Tables

APPENDIX A

Flowmeter Calibration Results

The next page shows the calibration results of the flowmeter, done by a calibration laboratory in Italy. The results shows that the flowmeter lives up to the accuracy profile supplied by the manufacturer.

Via f.lli Gracchi 27
20099 Cinisello Balsamo (Mi)
Tel. ++0039-2-660271
Fax ++0039-2-6123202

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Test Report Of Electromagnetic Flow Meter ISOMAG™ Series

Riferimento interno *(Internal Reference)* **: 340513** Linea di taratura *(Calibration Line)* **: 4**
Conferma d'ordine *(Order Confirmation)* **n°: OC14-00968**

DATI SENSORE / SENSOR DATA

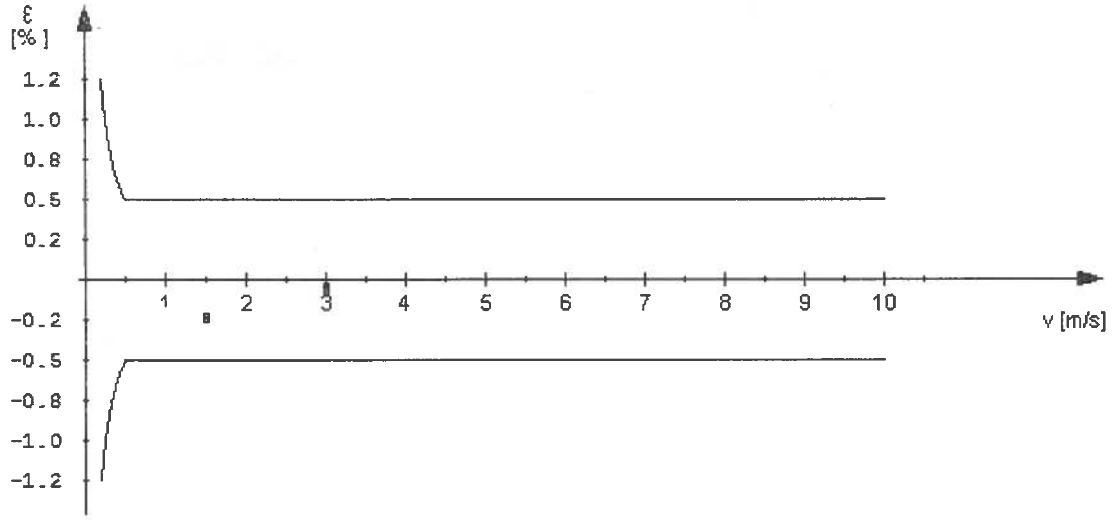
Modello Sensore *(Sensor Model)*	**MS 2500-P40-B1A2A**
Numero di Serie *(Serial Number)*	**04R4797**
Diametro Nom. *(NominalDiameter)*	**40**
Fondo Scala *(Full scale)*	**12,8 dm3/s**
Coefficiente Ka *(Coefficient Ka)*	**+1.4986**
Coefficient Kz *(Coefficient Kz)*	**+0**

DATI CONVERTITORE / CONVERTER DATA

Modello Convertitore *(Converter Model)*	**ML 51-B1A**
Numero di Serie *(Serial Number)*	**45S003374**

RISULTATI DELLA TARATURA / CALIBRATION RESULTS

N°	Campione di Riferimento *Reference Meter*	Durata Prova *Test Time*	Velocità nominale(DUT) *Nominal Test Speed (DUT)*	Temperatura ambiente *Ambient Temperature*	Temperatura acqua *Water Temperature*	Portata Riferimento *Reference Flow rate*	Portata DUT *Measured Flow rate(DUT)*	Errore *Deviation*
	Unità/*units*	s	m/s	°C	°C	dm3/s	dm3/s	%
1	L04M001	100	3,000	21,9	18,3	3,8403292	3,8377633	-0,07
2	L04M001	100	2,999	21,9	18,3	3,8381622	3,8365582	-0,04
3	L04M002	100	1,504	21,9	18,3	1,9257994	1,9209858	-0,25
4	L04M002	100	1,498	21,9	18,3	1,9179204	1,9136040	-0,23



Rapporto *(Report)* **n°: LSTA02183S** **Data stampa** *(Print. Date)* **:14/04/2014**

Approvato da *(Approved by):* Vittorio [signature] **Codice** *(Code)* **: 02**

END OF REPORT

Calibration laboratory : HEMINA S.p.A. div. LIBRA - via Piemonte , 2 35044 Montagnana (PD) – ITALY
All the calibration procedure are according to internal Technical instruction n. IT176 and according to standard ISO 17025.
The Laboratory Traceability to national standards is guarantee by periodic calibration

APPENDIX B

MATLAB files

This appendix contains the MATLAB files used to solve the temperature development in section 2.7.

B.1 Pumpsolve

The first file is called *Pumpsolve.m* and it is the main file used to solve for the temperatures. It invokes a function called *Pumptest.m*, this function is a custom function, and it is shown in B.2.

```
clc
clear
clf

T_start = 20; % Start temperature of the produced water in degrees celcius.
T_inf = 20;   % Temperature of the ambiant air in degrees celcius.
h_inf = 15;   % Heat transfer coefficient of the ambiant air i W/m^2-K.
A_s = 3;      % Surface area of tank and pipes in m^2.
mass_W = 290; % Mass of the water in kg.
cp_W = 4100;  % Specific heat capacity of water in J/kg-K
W_p = 3000;   % Electric power of 2-pole motor.
W_p_2 = 370;  % Electric power of 4-pole motor.
mass_S = 100; % Mass of the steel in kg.
cp_S = 500;   % Specific heat capacity of steel in J/kg-K

runtime_s=24*3600; % Run time in seconds.
step_size = 1;     % Step size in seconds

syms x

options = optimoptions('fsolve','Display','off');
```

```
steps = runtime_s/step_size;            % Total number of steps.
tspan = 0:step_size:runtime_s;          % Time vector.

% Fetching coefficients.
a(1) = W_p;
a(2) = h_inf*A_s;
a(3) = mass_W*cp_W + mass_S*cp_S;
a(4) = T_inf;

a_2=a;
a_2(1)=W_p_2;

temperature_initial = T_start;          % Initial temperatures.

% Solution.
[t,X_1] = ode45(@(t,x)Pumptest(x,a),...
    tspan,temperature_initial,options);
T_1_max=double(solve(Pumptest(x,a)==0,x));

% Solution.
[t,X_2] = ode45(@(t,x)Pumptest(x,a_2),...
    tspan,temperature_initial,options);
T_2_max=double(solve(Pumptest(x,a_2)==0,x));

% Plotting the results.
figure(1)
hold on
plot(t/3600,X_1,'-r')
plot(t/3600,X_2,'-b')
axis([0 5 20 55])
xlabel('Time in hours');
ylabel('Temperature in degrees Celcius');
title('Temperature development for the two types of motors');
legend('3 kW motor', '0.37 kW motor', 'Location', 'East');

% Displaying the maximum temperatures.
format bank
disp('The maximum temperature for the 2-pole motor in degrees Celcius is:')
disp(T_1_max)
disp('The maximum temperature for the 4-pole motor in degrees Celcius is:')
disp(T_2_max)

% Printing the results to figure.
print(figure(1),'-dpng','TemperatureDevelopment.png','-r600');
```

B.2 Pumptest

The next file is called *Pumptest.m*, and it is the function used to solving the temperature development and maximum temperature.

```
function output = pumptest(x,a)

dx(1) = (a(1)-a(2)*(x(1)-a(4)))/a(3);

output = dx;
```

APPENDIX C

Manual

The next pages contains the manual for operating the pump testing stand. It is also included on the CD-ROM.

Testing Stand Manual

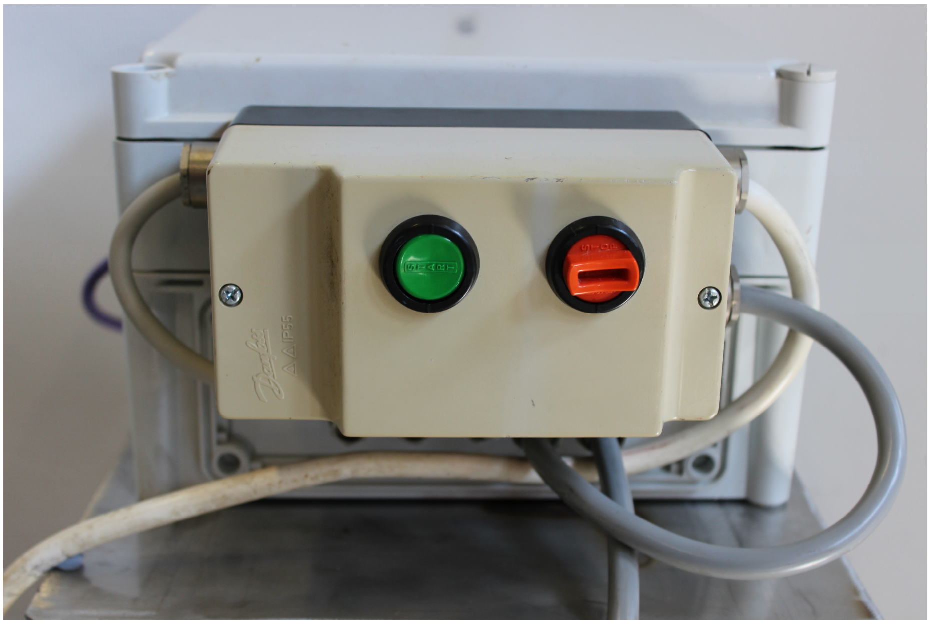
Requirements

1 USB-stick

Approach

1. Insert the USB-stick into the myRIO in the USB-port marked with a red circle.

2. Start the pump by pressing the green button.



Turn page

3. Press the left button on the myRIO, until the LED corresponding to the wanted test lights up.
   - **LED1:** Not used.
   - **LED2:** Head performance test.
   - **LED3:** Not used.

   The corresponding LED will start blinking.

4. When LED0 lights up, the test is complete and the USB stick can be removed. Stop the pump by pressing the red button next to the green one. The data on the USB-stick will for the performance test look like the following:

$\bar{Q}$	s_Q	$\bar{H}$	s_H	$\bar{P}$	s_P	$\bar{\eta}$	s_η
23.422	0.255	22.615	3.003	2976	0.079	56.72	2.820
22.587	0.157	24.349	2.710	2989	0.134	55.68	1.543
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

Turn page

APPENDIX D

CD-ROM content

The content on the CD-ROM listed with a small description.

Data Sheets

This folder contains data sheets for the different equipment.

- **Aalco Metals - Stainless Steel - 14401 Bar:**
  Specifications for commercial stainless steel 316.
- **Belimo - Motor - NR24A-SR:**
  Data sheet for the outlet valve motor.
- **Belimo - Motor - SR24A-SR:**
  Data sheet for the inlet valve motor.
- **Danfoss - Pressure Transmitter - MBS 33:**
  Data sheet for the two pressure transmitters.
- **Grundfos - Pump - NK, NKE:**
  Data booklet for the NK and NKE pump family.
- **Isoil - Flowmeter Converter - ML 51:**
  Data sheet for the ML 51 converter, attached to the flowmeter.
- **Isoil - Flowmeter Sensor - MS 2500:**
  Data sheet for the MS 2500 sensor, attached to the flowmeter.
- **National Instruments - myRIO-1900:**
  User guide and specifications for the myRIO.

LabVIEW

- **Colebrook:**
  SubVI used to calculate the friction factor with Colebrook's Equation.
- **Efficiency:**
  SubVI used to calculate the efficiency of the impeller.
- **Head Calculation:**
  SubVI used to calculate the head for the impeller.
- **Headloss Friction 1:**
  SubVI used to calculate head loss from friction in the inlet pipe.
- **Headloss Friction 2:**
  SubVI used to calculate head loss from friction in the outlet pipe.
- **Main:**
  The main VI that contains the ground layer of code.
- **Material Properties:**
  SubVI used to calculate the water properties as a function of temperature.
- **Power Consumption:**
  SubVI used to obtain the power consumed by the pump.
- **Pressure:**
  SubVI used to obtain the pressure at the inlet and outlet.
- **Pump Test:**
  LabVIEW project file.
- **Reynolds:**
  SubVI used to calculate Reynolds number.
- **Valve Control Value:**
  Position control SubVI for the valves.
- **Valve Control:**
  On/Off control SubVI for the valves.
- **Valve Read:**
  SubVI used obtain the position of the valves.
- **Volume Flow (Velocity):**
  SubVI used to obtain the flow rate and velocity of the water.

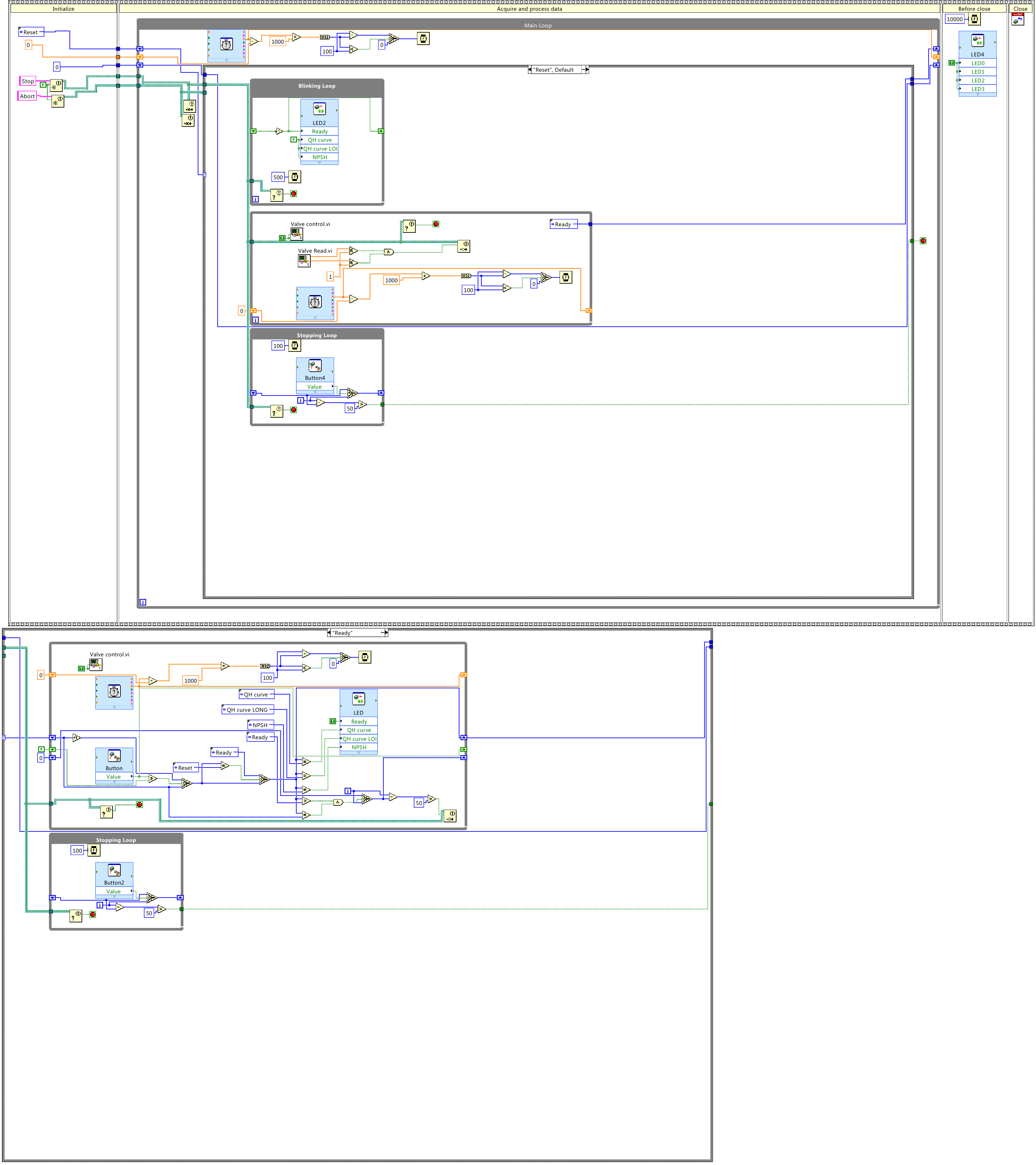
Other Files

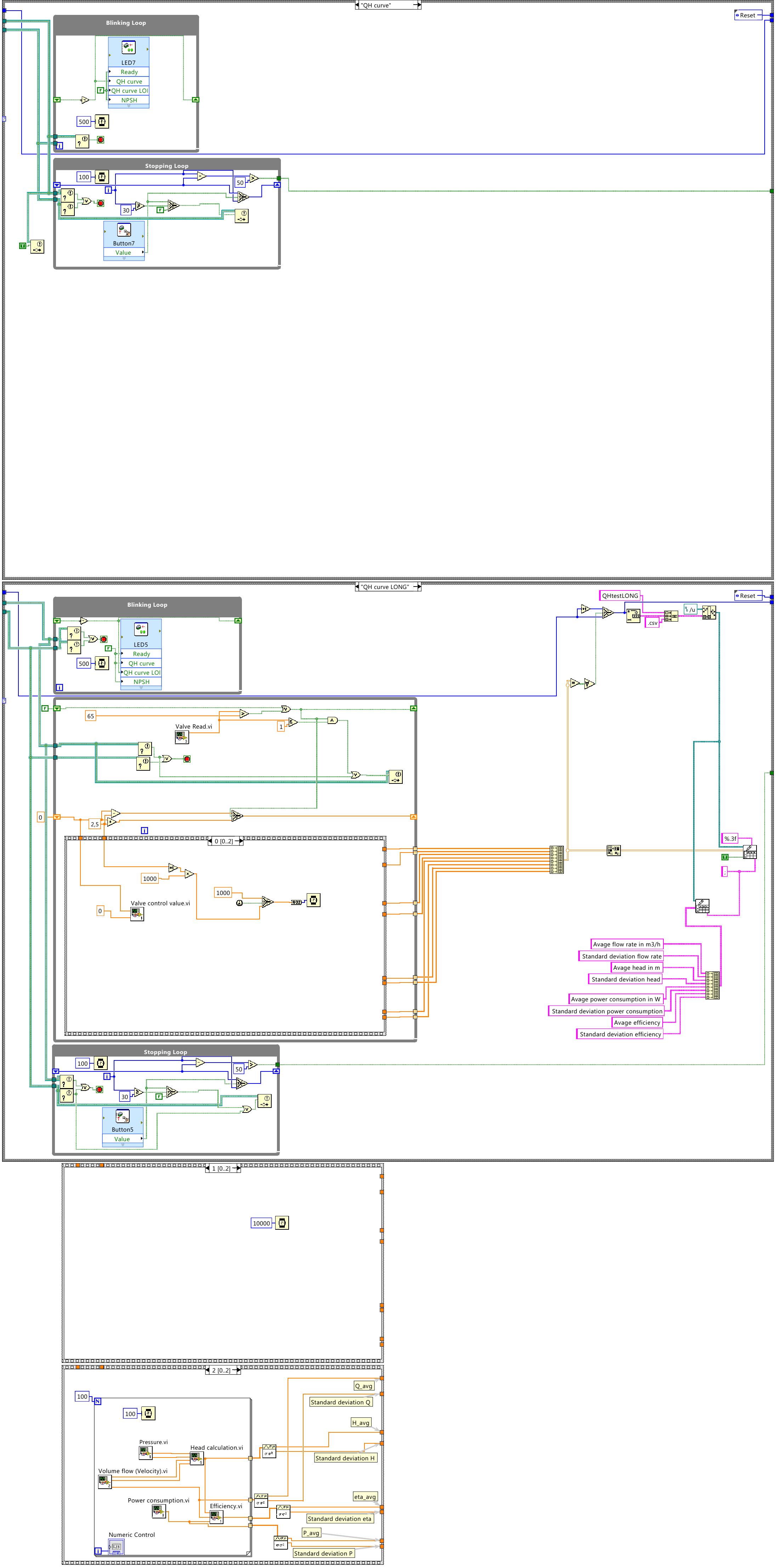
- **Manual:**
  The manual for operating the testing stand.
- **Pump Testing Stand:**
  The complete written report.
- **Water Properties:**
  Excel spreadsheet used to create the viscosity and density polynomials.

APPENDIX E

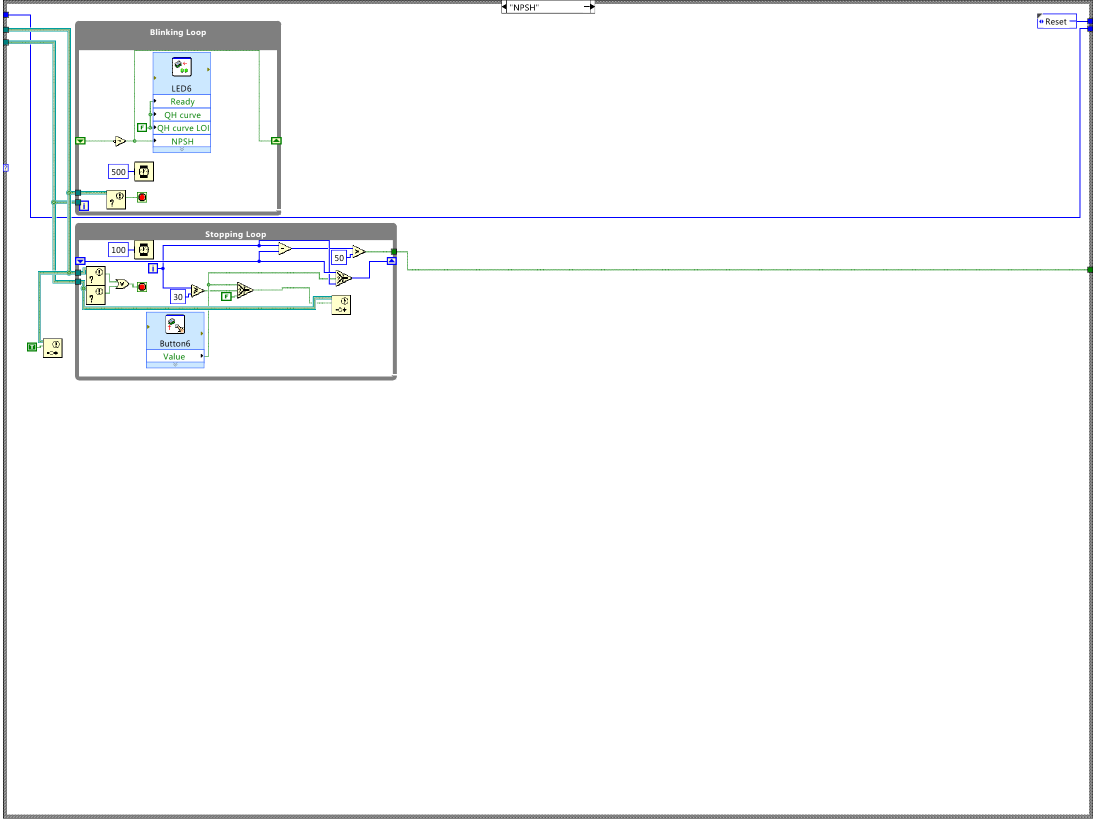
LabVIEW Code

The next pages will include a printout of the LabVIEW code.


Initialize
Acquire and process data
Before close
Close
Main Loop
Reset
Stop
Abort
1000
100
"Reset", Default
Blinking Loop
LED2
Ready
QH curve
QH curve LOI
NPSH
500
Valve control.vi
Valve Read.vi
Ready
Stopping Loop
Button4
Value
50
10000
LED4
LED0
LED1
LED3
"Ready"
QH curve LONG
LED
Button
Button2



"QH curve"
Reset
Blinking Loop
LED7
Ready
QH curve
QH curve LOI
NPSH
500
Stopping Loop
100
50
30
Button7
Value
"QH curve LONG"
QHtestLONG
.csv
%.3f
Blinking Loop
LED5
Ready
QH curve
QH curve LOI
NPSH
500
65
Valve Read.vi
0
2,5
0 [0..2]
1000
1000
Valve control value.vi
0
Avage flow rate in m3/h
Standard deviation flow rate
Avage head in m
Standard deviation head
Avage power consumption in W
Standard deviation power consumption
Avage efficiency
Standard deviation efficiency
Stopping Loop
100
50
30
Button5
Value
1 [0..2]
10000
2 [0..2]
100
100
Q_avg
Standard deviation Q
H_avg
Pressure.vi
Head calculation.vi
Standard deviation H
Volume flow (Velocity).vi
eta_avg
Power consumption.vi
Efficiency.vi
Standard deviation eta
P_avg
Numeric Control
Standard deviation P


"NPSH"
Blinking Loop
LED6
Ready
QH curve
QH curve LOI
NPSH
500
Stopping Loop
100
50
30
Button6
Value
Reset