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Testing of RPT in pumping mode of operation

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Submission date: Januar 2013
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NTNU

Norges teknisk-
naturvitenskapelige universitet

Institutt for energi- og prosessteknikk

EPT-M-2012-134

MASTEROPPGAVE

for

Stud.techn. Andrea Stranna

Høst 2012

Testing av reversibel pumpeturbin i pumpedrift

Testing of RPT in pumping mode of operation

Bakgrunn og målsetting

Reversible pumpeturbiner har, som det fremgår av navnet, to hovedsakelige driftsmoder, turbindrift og pumpedrift. Det er nettopp avsluttet et PhD arbeid som omfatter karakteristikker og stabilitet i turbindrift. En turbinmodell ble designet og tester utført i Vannkraftlaboratoriet. Pumpedrift ble kun overfladisk undersøkt.

For å teste pumper, må den hydrauliske energien drepes. Den vanligste metoden er å ta ut energien ved å kjøre matepumpen som turbin. Dette er fullt mulig å gjøre i Vannkraftlaboratoriet, men fordi våre pumper ikke har ledeapparat, er vannføringen lite regulerbar. Vi har defor måtte se oss om etter andre løsninger. Vannkraftlaboratoriet har nylig anskaffet en energidreper for dette formålet. Imidlertid viser det seg at det også er mulig å drepe energien ved å kjøre matepumpen som pumpe, dvs at vannføringen går feil vei gjennom denne pumpen.

Målet er å fremskaffe pumpekarakteristikkene for den reversible pumpeturbinen ved bruk av energidreperen og/eller kjøre matepumpene med negativ vannføring. For Vannkraftlaboratoriet er det viktig å få teste ut systemet slik at reversible pumpeturbiner kan testes i begge driftsmodi.

Oppgaven bearbeides ut fra følgende punkter

1 Sette seg inn i hvordan testing av pumpekarakteristikker foregår i alminnelighet
2 Analysere strømningen i systemet når den hydrauliske energien fjernes ved
a) Energidreper,
b) ved bruk av matepumpen i pumpedrift.
3 Gjennomføre tester for å fremskaffe pumpekarakteristikkene
4 Lage prosedyre for utføring av pumpetester i Vannkraftlaboratoriet

" - "

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Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

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NTNU, Institutt for energi- og prosessteknikk, 22. august 2012

Olav Bolland
Instituttleder

Torbjørn K. Nielsen
Faglig ansvarlig/veileder

Medveileder(e)

Preface

The following report describes the project conducted as my master's thesis after 5 years of study at NTNU. The project was carried out for the Waterpower Laboratory at the Department of Energy and Process Engineering.

It has been a pleasure to get to work on my master thesis in the Waterpower Laboratory at NTNU. After many hours in the lab and in the study hall this thesis is finally finished. I would like to thank my supervisor, Torbjørn Kristian Nielsen, for helping me get through it. Running the Francis rig in pump mode has been challenging and I would like to thank Grunde Olimstad for hleping me getting started. I would also like to thank Bård Brandstø and the guys in the lab for helping me with the practical implementation of the tests, and Joachim Gogstad and Bjørn Winter Solemslie for helping me with everything else.

Andrea Stranna
Trondheim, January 22, 2013

Abstract

In this project two pump mode tests has been carried out on a model RPT in the Waterpower Laboratory at NTNU. The measurement set up and execution of the tests were the same, except for the method of dissipating energy in the system. In the first test one of the feed pumps in the basement was used as energy dissipator. In the second test a throttle valve was used as energy dissipator.

The objective has been to see how the Waterpower Laboratory is suited for such a test. It was also important to test the two different dissipation methods and evaluate which should be preferred when performing a pump mode test.

During the tests it was observed that the guide vane angle kept changing. When the results were processed it became evident that the variations in guide vane angle during the tests had a big influence on the measured pump curves. Variations in guide vane angle has not previously been observed during turbine mode testing. It is presumed that the variation in guide vane angles is due to play in the guide vane system and the design of the guide vanes. The guide vanes are Francis vanes, and not RPT vanes. It is assumed that it is the sharp trailing edge of the guide vanes that causes turbulence over the vanes in pump mode, thus making the guide vanes move about within the play of the guide vane system. It is suggested that the guide vane system is replaced with an RPT guide vane system for further testing in pump mode.

The two dissipation methods tested were both effective. The throttle valve works best for achieving 0 flow, while the feed pump is easier to regulate. None of the methods showed signs of high noise or vibrations, and both may be used for future tests.

Sammendrag

I dette prosjektet har det blitt gjennomført to tester i pumpemodus på et RPT modellhjul i Vannkraftlaboratoriet på NTNU. Måleoppsettet og utførelsen av testene var de samme, bortsett fra måten energien i systemet ble drept. I den første testen ble energien drept ved bruk av en av matepumpene i kjelleren. I den andre testen ble energien drept gjennom en strupeventil.

Målet har vært å se hvordan Vannkraftlaboratoriet er skikket for en slik test. Det har også vært viktig å få testet de to energidrepingsmetodene og evaluere hvilken som er best å bruke i fremtidige tester i pumpemodus.

Under testene ble det observert at ledeskovlåpningen forandret seg. Da resultatene ble bearbeidet kom det frem at variasjonen i ledeskovlåpning under kjøringen hadde stor påvirkning på de målte pumpekurvene. Det har ikke tidligere vært observert variasjon i ledeskovlåpningen under kjøring i turbinmodus. Det antas at variasjonen i ledeskovlåpning er grunnet slark i ledeskovlsystemet samt designet av ledeskovlene. Ledeskovlene er Francis-ledeskovler, ikke RPT-ledeskovler. Det antas at det er den skarpe skovlavløpskanten som forårsaker turbulens over skovlene i pumpemodus, og på den måten beveges skovlene innenfor slarket i ledeskovlsystemet. Det foreslåes å bytte ut ledeskovlsystemet med RPT-ledeskovler for videre testing i pumpemodus.

Begge metodene for energidreping som ble testet fungerte bra. Strupeventilen er best å bruke når man ønsker 0 flow, mens matepumpen er enklere å regulere. Ingen av metodene viste tegn til høy lyd eller vibrasjoner, og begge kan brukes i fremtidige tester.

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Nomenclature

Symbols

Symbol	Description	Unit
A	Area	m^2
c_p	Spesific heat	kJ/kgK
g	Acceleration of gravity	m/s^2
H_e	Effective head	m
H_{np}	Pump mode head	m
H_{nt}	Turbine mode head	m
H_{st}	Static head	m
m	Mass	kg
n	Rotational speed	rpm
P	Power	W
P_h	Hydraulic power	W
P_{Lm}	Mechanical power loss	W
P_m	Mechanical power	W
Δp	Differential pressure	Pa
Q	Volumetric flow rate	m^3/s
Q_H	Heat	J
T	Torque	Nm
ΔT	Temperature difference	$^\circ C$
W_G	Generator work	J
W_P	Pump work	J

Greek symbols

Symbol	Description	Unit
α	Guide vane opening angle	$^\circ$
η_h	Hydraulic efficiency	-
η_{hmax}	Maximum hydraulic efficiency	-
ρ	Density	kg/m^3
ω	Angular velocity	rad/s

Abbreviations

CFD	Computational Fluid Dynamics
IEC	International Electrotechnical Commission
NTNU	Norwegian University of Science and Technology
PLS	Programmable Logic Controller
RPT	Reversible Pump Turbine
rpm	Revolutions per minute

1 Introduction

Reversible pump turbines (RPT's) are an important part of the future of hydropower. The ability to pump water up to the reservoirs when the power supply is greater than the power demand is cruscial for implementing new renewable energy such as wind power into the power grid[1]. A big part of turbine design improvement lies in model testing. When testing a reversible pump turbine it is important to test it in both turbine and pump mode. The Waterpower Laboratory at NTNU, as it is today, is fully equiped for testing Francis turbines and RPT's in turbine mode, but there has not been done any tests in pump mode.

In order to test an RPT in pump mode the energy introduced to the system needs to be dissipated. The most common way to do this is by running the feed pumps as turbine. The feed pumps in the Waterpower Laboratory can be run as turbines, but because they are not equipped with a guide vane system there is little room for controlling flow and system head. Therefore the Waterpower Laboratory has invested in a throttle valve for this purpose. After the throttle valve was installed it has been discovered that running the feed pumps against the flow from the RPT will dissipate the energy and make it possible to control flow and head. Thus there are now two possible methods for dissipating energy during a pump test in the Francis rig.

The main objective of this thesis was to run through a measurement series in pump mode and produce a pump characteristic for an RPT model. Then evaluate how the Waterpower Laboratory is suited for this type of test. Testing the two different dissipation methods and evaluate which should be preferred when performing a pump mode test was also important.

2 Background

The Waterpower Laboratory at NTNU is situated at Campus Gløshaugen. It is one of the oldest buildings on campus and was put into operation as early as 1917. Since then it has played an important part in the development of Norwegian hydropower, through educating new engineers and facilitating research. It has been used for model testing of Francis turbine model runners for several years, and fulfills the IEC requirements for Francis model testing [2]. However the laboratory has not been used for testing of reversible pump turbines in pump mode, even though this is theoretically possible.

The IEC (International Electrotechnical Commission) is a worldwide organization for standardization. The object of the IEC is to promote international co-operation on questions concerning standardization in the elctrical and electronic fields [3].

2.1 IEC standard for model acceptance tests

The *IEC 60193 Hydraulic turbines, storage pumps and pump-turbines, Model acceptance tests* covers the arrangements for model acceptance tests to be performed on hydraulic turbines, storage pumps and pump-turbines to determine if the main hydraulic performance contract guarantees have been satisfied [3]. In this thesis the model runner that has been tested, the *Olimstad reversible pump turbine* (henceforth called the *Olimstad RPT*) does not have a prototype counterpart or a customer waiting for guarantees to be met. However it is desirable to comply with the IEC standard as far as possible and establish if the laboratory can bee used for a guarantee test of a reversible pump turbine in the future.

2.2 The Olimstad RPT model

The RPT model in the Waterpower Laboratory at NTNU was designed by Grunde Olimstad as a part of his Ph.D thesis "Characteristics of Reversible-Pump Turbines" [1]. Designing a model runner enabled comparison between CFD analyses and tests done in the lab. A 3D representation of the final turbine design can be seen in figure 2.1.

The objective of the thesis was to study stability design criteria for reversible pump turbines, so the model was deliberately designed to have steep characteristics and areas of instability [1].

2.2.1 Previous testing of the turbine

The Olimstad RPT was tested in turbine mode at the waterpower laboratory at NTNU in the spring of 2012, as part of the project thesis *Hydraulic performance of a high head Francis turbine*. The model RPT was tested at 20 meter head, and the the best efficiency achieved was 90% [4]. The resulting efficiency and Hill diagram can be seen in figure 2.2 and 2.3.

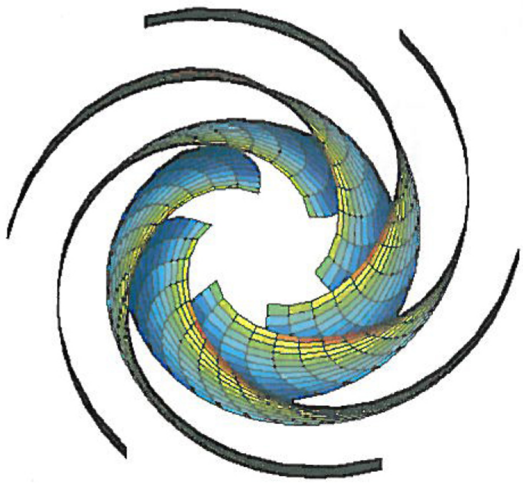


Figure 2.1: 3D representation of the Olimstad RPT design [1].

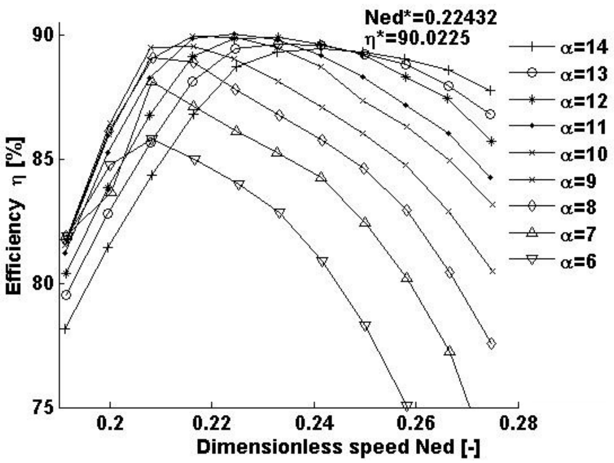


Figure 2.2: Efficiency measurements on the Olimstad RPT model in turbine mode [4].

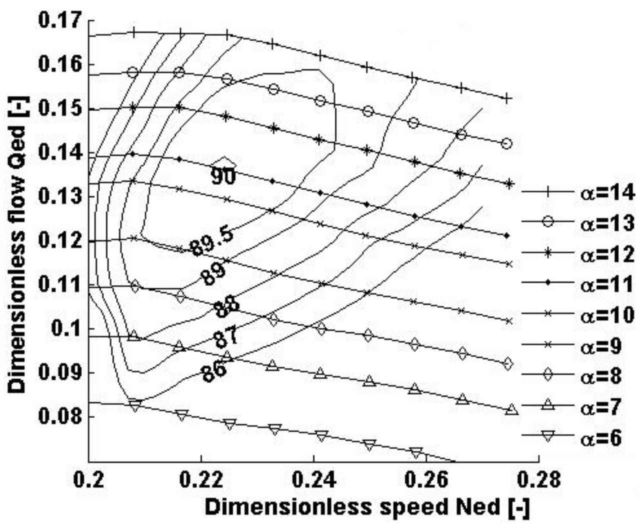


Figure 2.3: Hill diagram for the Olimstad RPT model in turbine mode [4].

3 Theory

3.1 Francis turbines

The Francis turbine is one of the most common hydropower turbines and is used for hydraulic heads of up to 700m [5]. The Francis turbine is a reaction turbine. A reaction turbine is defined as a turbine where about half of the specific energy at the inlet is kinetic energy and the other half is pressure energy, and the working fluid gets a spin before the runner inlet [5]. Reaction turbines have a pressure difference from the inlet to the outlet of the runner, and the water flows from the high pressure to the low pressure side. Part of the specific energy converted to mechanical energy through the turbine is converted from this pressure drop, and this is the reaction part of the energy conversion [6]. When in operation, the Francis runner must be completely submerged at all time.

3.1.1 Physical structure of a Francis turbine [5]

As shown in figure 3.4 the Francis turbine consists of spiral casing (1), guide vanes (2), runner (3) and draft tube (4). The spiral casing distributes the water through the stay wanes in the spiral casing and onto the guide vanes, making the flow conditions as smooth as possible around the circumference of the guide vanes. The guide vanes are adjustable and regulates the flow onto the turbine. They also give the water coming from the spiral casing a rotation with the right flow angle onto the runner. The runner converts the specific energy of the water to mechanical energy. The runner is connected to the shaft and is the rotating part of the turbine. The blades of a Francis runner are fixed and can not be adjusted. The draft tube is shaped as a cone, where the velocity of the flow is reduced towards the outlet to convert the remaining kinetic energy in the drain into pressure energy.

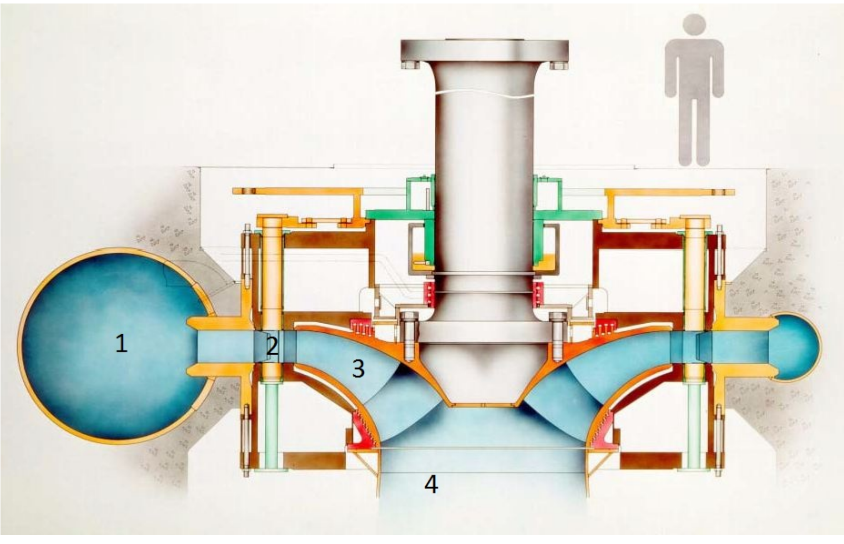


Figure 3.4: Cross section of a francis turbine.

3.1.2 Relative velocities

The velocity triangles, figure 3.5, describes the flow at the inlet and outlet of a runner vane. Here the red arrows c_1 and c_2 describes the flow velocities relative to the spiral casing, a stationary reference point. The black arrows w_1 and w_2 describes the flow velocity relative to the runner vane. The blue arrows u_1 and u_2 describes the runner velocity at inlet and outlet.

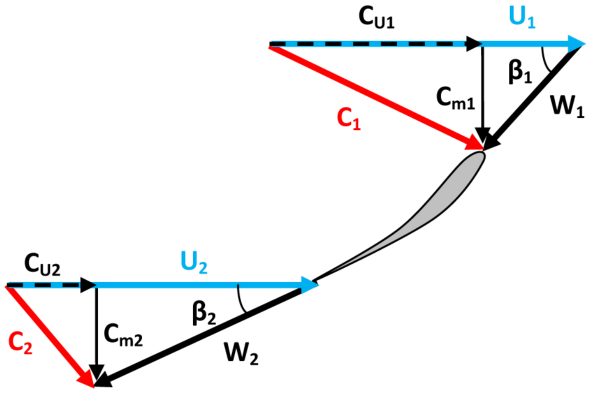


Figure 3.5: Velocity diagrams for a Francis runner blade.

3.2 Centrifugal pumps

Centrifugal pumps lift liquids or generate pressure by a rotary motion of one or several impellers [7]. They are very similar to Francis turbines in design, but rotate in the opposite direction leading the flow through its runner from low pressure at the inlet to high pressure at the outlet.

3.2.1 Physical structure of a centrifugal pump

The pumps consists of two main components, the impeller and the pump casing. The impeller forces the the liquid into a rotary motion, while the pump casing both directs the liquid onto the impeller and leads it away again under high pressure. The action of the impeller causes the liquid to leave the impeller at a higher velocity and pressure than it had when entering the impeller. Further, in the pump casing, part of the velocity the liquid has from the impeller is converted to pressure through diffusion as the cross section area of the casing increases. As seen in figure 3.6 some centrifugal pump casings have got a channel provided with vanes, as in a Francis turbine, and in these cases this is where most of the diffusion takes place [7].

3.3 Reversible pump turbines

Reversible pump turbines, RPT's, are a combination between a Francis turbine and a centrifugal pump. The RPT is made to work as a turbine in one rotational direction

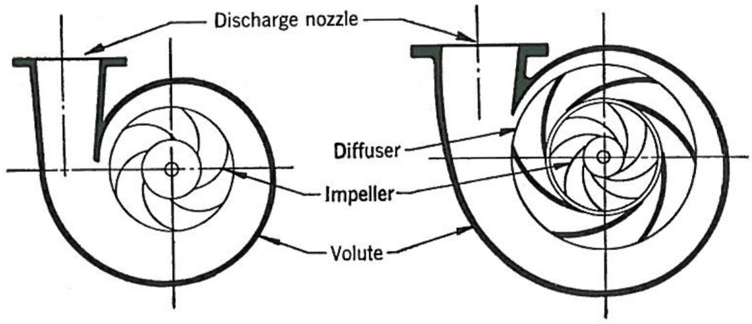


Figure 3.6: Centrifugal pump with and without diffusor vanes [7].

and as a pump in the opposite rotational direction. Thus the design of the runner must be a compromise between optimal pumping and optimal power production. The biggest difference lies in the runner, where blade design needs to be optimized for both pumping and producing. The spiral/volute casing and the guide vane and stay vane system works the same way as in a Francis turbine, except for the design of the guide vanes. The guide vanes are designed with a rounded trailing edge (turbine direction), in order to create less turbulence past the vanes when the water flows in pump direction.

Figure 3.7 shows the cross section of a pump turbine. It is illustrated how power is supplied to the shaft in pump mode, and extracted from the shaft in turbine mode. The direction of the flow through the runner for each mode is also shown.

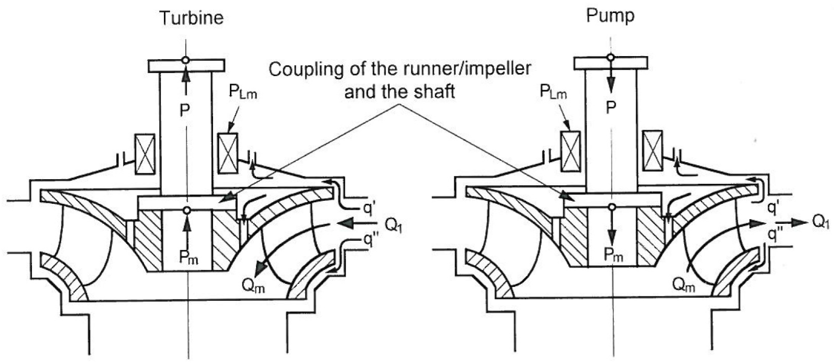


Figure 3.7: Cross section of a reversible pump turbine [3].

3.3.1 Blade curvature and outlet diameter

Due to head losses in the penstock and draft tube the head the pump works against will be bigger than the head the turbine works with. The static head is the same in both cases, but in pump mode the conduit losses are added to the static head and in turbine mode they are subtracted from the static head. This is illustrated in figure 3.8 where H_{st} is the static head and H_{nt} and H_{np} are the effective heads for turbine mode and pump mode respectively.

This means that compared with a turbine with given head, flow and speed of rotation,

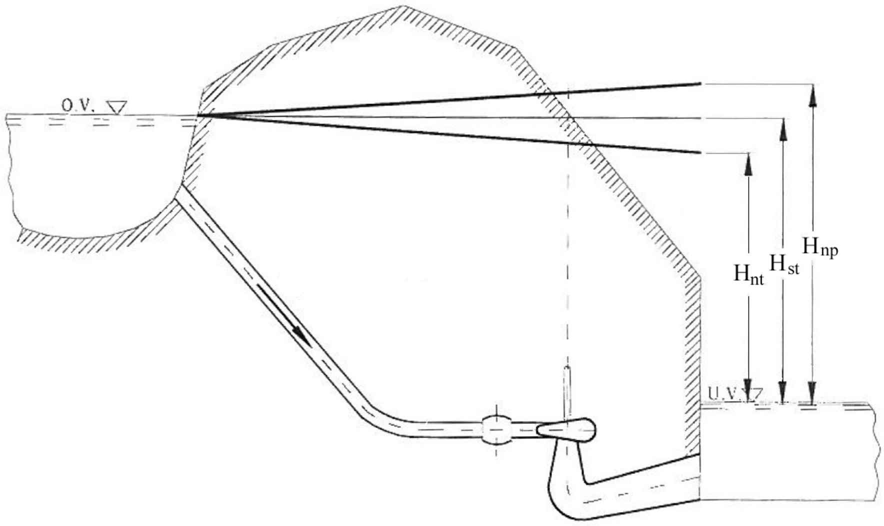


Figure 3.8: Visualisation of the difference in turbine head and pump head for an RPT [6].

the outlet diameter of a pump runner must be increased to be able to pump the same flow back up to the reservoir [1], as shown in figure 3.9.

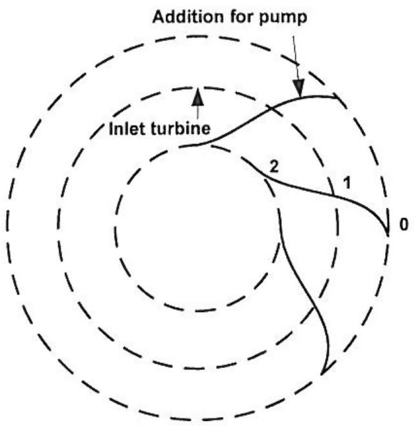


Figure 3.9: Design principle for an RPT. 0 marks inlet RPT, 1 marks inlet for a comparable Francis turbine and 2 marks outlet [1].

For an RPT the inlet and outlet velocity diagrams in turbine and pump mode will look something like those in figure 3.10.

3.3.2 Four quadrant characteristic

The correlation between the direction water flows through the turbine/pump, the rotational direction of the runner and whether power is put into or extracted from the system can be described by a four quadrant characteristic. The most complete characteristic for a pump/turbine is found when it is tested in all four quadrants. However, turbines

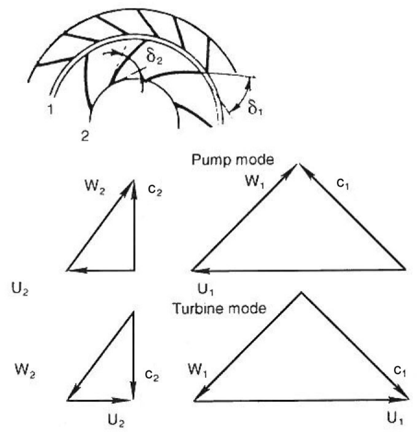


Figure 3.10: RPT velocity triangles [8].

usually only operates in the turbine mode quadrant and pumps only operate in the pump mode quadrant and they are thus tested in only these quadrants. If a RPT operating in pump mode losses power the water being pumped up to the reservoir will start flowing back through the RPT and the RPT will eventually end up in turbine mode, at runaway speed. The four quadrant pump characteristic makes it possible to predict the behavior of the pump turbine in the transition from pump mode to turbine mode.

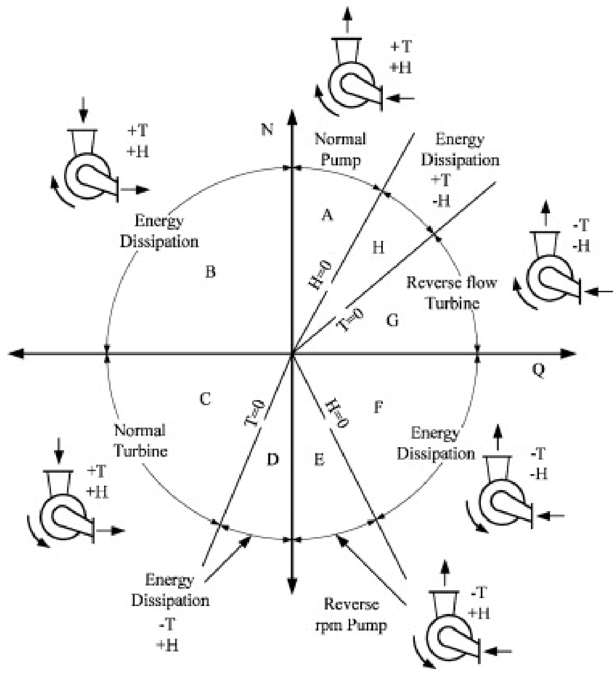


Figure 3.11: Description of the operating modes of the four quadrants [7].

3.4 Model testing

Since most hydropower machinery prototypes are too big to be tested in a lab, and on site testing is difficult and costly, tests on downscaled models of the prototypes are done instead [9]. A model test will also give greater flexibility to test different operation points [10], as well as highlighting issues that can be fixed before the prototype is manufactured. When testing a pump the main objective is to find the pump characteristics, or pump curves. This is defined as the variation of the head with capacity at a constant speed [7]. Another important part of the pump characteristics is the hydraulic efficiency of the pump.

Hydraulic efficiency of a pump, η_h, is by the IEC [3] defined as:

$$\eta_h = \frac{P_h}{P_m} = \frac{\rho g Q H_e}{P + P_{Lm}} \tag{3.1}$$

Here, P_m is the mechanical power transmitted through the coupling of the runner and the shaft, and P_h is the hydraulic power available for producing power. P is the power delivered from the turbine shaft and P_{Lm} is the losses in the shaft bearings. Q is the volumetric discharge through the turbine, H_e is the effective head, g is the acceleration of gravity and ρ is the density of water.

Thus, in order to find the pump characteristics and efficiency we have to measure Q, H_e, P and P_{Lm}.

Q is measured directly by a flow meter, while H_e is found by measuring the pressure difference over the runner and the change in velocity over the runner:

$$H_e = \frac{\Delta p}{\rho g} + \frac{Q^2(\frac{1}{A_1^2} - \frac{1}{A_2^2})}{2g} \tag{3.2}$$

Here, Δp is the pressure difference, A_1 is the runner inlet area and A_2 is the runner outlet area.

P and P_{Lm} are found by measuring the corresponding torques and multiplying by the rotational speed of the turbine:

$$P = T\omega \tag{3.3}$$

$$P_{Lm} = T_{Lm}\omega \tag{3.4}$$

3.4.1 Energy dissipation

In order to test a pump, the energy introduced to the system by the pump needs to be dissipated somewhere else. The feed pumps in the waterpower laboratory could be run as turbines, and thus dissipating the energy introduced by the RPT. However, because the feed pumps do not have any guide vane system, it would not be possible to control the head and flow in the system this way. Therefore the Waterpower Laboratory has invested in a throttle valve for this purpose.

After the throttle valve was installed it has been discovered that running the feed pumps against the flow from the RPT will dissipate the energy and make it possible to control flow and head. Thus there are now two possible methods for dissipating energy during a pump test in the Francis rig.

3.4.2 Water temperature

According to the IEC standard for model acceptance tests [3], the temperature of the water should not vary significantly during the test. The standard states "The water temperature should in principle not exceed 35°C and should not vary significantly during the test (e.g. 5°C per day)."

Since the temperature of the lab is relatively stable during a day, this should not affect the water temperature. However we also have to take into account the increase in water temperature due to the dissipation of hydraulic energy in the system. This energy will mostly be converted to heat taken up by the water and thus increasing the water temperature. A rough estimate of the increase in water temperature will help make sure that the temperature variation during testing does not exceed the IEC recommended value.

The highest increase in water temperature will occur when the feed pump is used as energy dissipator, since extra work is put into the system by the feed pump. Thus dissipation through the feed pump rather than through the throttle valve will be considered for this estimation.

Assuming that all the work put into the system by the both the generator and the feed pump is converted to thermal energy increasing the water temperature, we can say that the heat, Q_H[1], is is the sum of the generator work, W_G, and pump work, W_P.

$$Q_H = W_G + W_P \tag{3.5}$$

Further the increase in water temperature can be expressed as [11]:

$$Q_H = mc_p\Delta T \tag{3.6}$$

The water reservoir in the laboratory holds around 600 m^3 of water and a calculated guess gives us about 100 m^3 in the closed loop system. Estimating the energy is a bit more tricky, since the power of both the generator and the feed pump is varied continuously throughout the testing. We are however only looking for a rough estimate so if we assume both generator and feed pump operate at an average of 15 kW for 10 hours straight, we should at least not estimate a too small temperature increase compared to reality. We will use the following values:

Q_H	1 080 MJ	Heat as estimated from W_G and W_P
m	100 000 kg	Mass of water in the closed loop
c_p	4.178 kJ/kgK	Specific heat of water

Put into equation 3.6 this gives an increase in temperature of $\Delta T = 2.6°C$. This is within the limits stated by the IEC as well as it is a conservative estimate. The real values when testing ought to be smaller.

[1]Heat is here denoted as Q_H rather that Q so as not to confuse it with the volumetric flow rate.

4 Setup of the lab

4.1 The Francis rig

[2] The Francis part of the Waterpower laboratory is built around a main pipe system, the artery of the lab. In the basement there are two main feed pumps that can be run one at a time, or connected in series or parallel, depending on whether high pressure or high volume flow is required. By different combinations of pump settings and pipe loops a variety of operational modes are obtainable. Both open loop, closed loop and running from an open water reservoir is possible.

The main water reservoir in the lab, the lower reservoir, is situated under the floor in the lab, and is commonly known as the sump. The capacity of the reservoir is 450 m^3. In the reservoir the flow velocity is reduced, so that particles in the water sink to the bottom and may be removed by a water purifier. The floor and walls of the reservoir is made from reinforced concrete and is coated with a layer of strong polymer composite.

There is a second reservoir in the lab, the upper reservoir, which is situated on the top floor of the building. It consists of two large tanks with a u-shaped channel between them. The upper reservoir is used when running an open loop and gives a constant head of about 16 meters.

A special feature of the NTNU Waterpower Laboratory are the two main tanks, one high pressure and one low pressure tank, situated upstream and downstream of the Francis rig, respectively. The high pressure tank upstream the rig, hereinafter referred to as the pressure tank, is used as a pressure reservoir when running a closed and open loop, dampening pump effects and delaying the influences on the turbine from changes in pump speed. When running the rig from the upper reservoir, the pressure tank will also have the potential to function as an air cushion (for example for start/stop measurements). The low pressure tank downstream of the Francis rig, hereinafter referred to as the draft tube tank, acts as the tail water in the system. A vacuum pump is mounted on the tank giving the possibility to regulate the submergence of the turbine when running a closed loop.

The turbine is installed with a vertical shaft below a 352 kW DC-generator by Siemens. The generator can be run as a motor, thus enabling running an RPT runner in pump mode.

Figure 4.12 shows the structure of the Francis rig with upper and lower reservoirs, pressure tanks and pumps.

4.1.1 Feed pumps

The feed pumps are situated in the basement of the Waterpower Laboratory, slightly below the lower reservoir. The feed pumps are double suction radial impeller centrifugal pumps with a volute casing (no diffuser vanes), of the type *KSB RDLO 400-665* [12].

[2]Translated and edited with basis in *Modelltest av Francis turbin i Vannkraftlaboratoriet ved NTNU* [2].

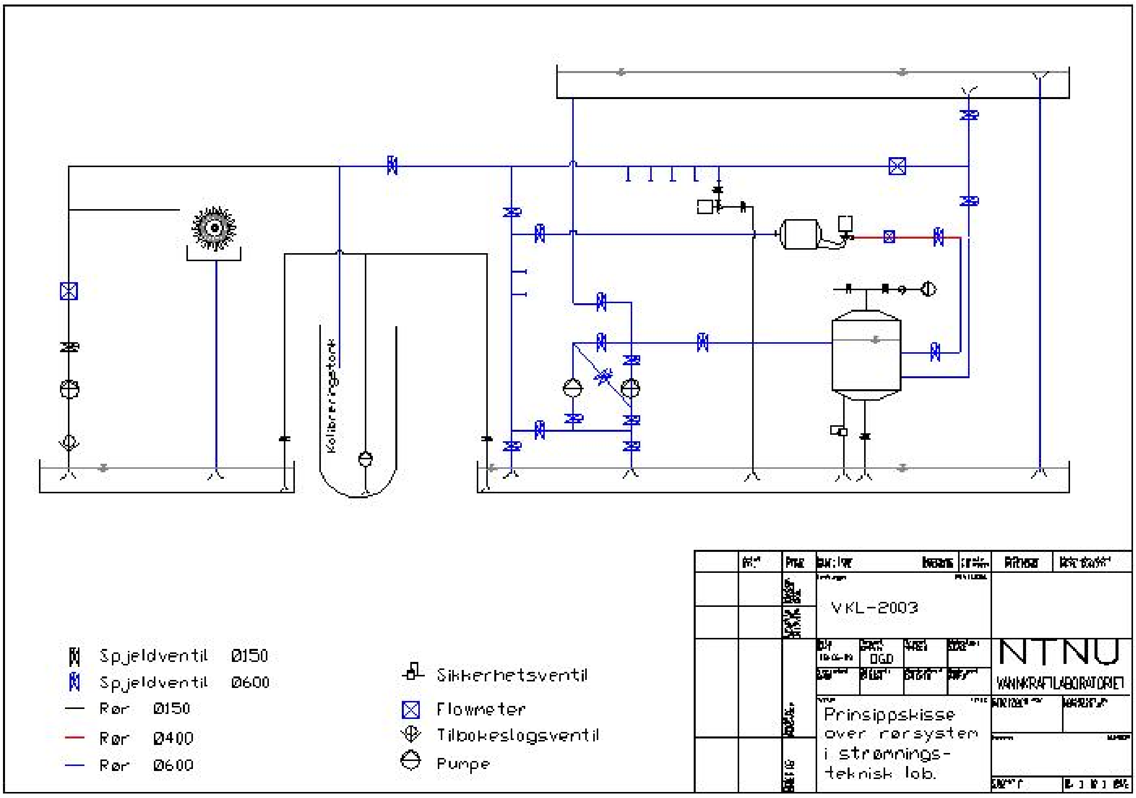


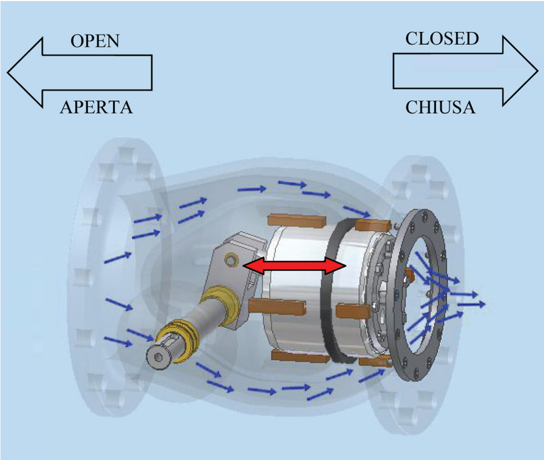
Figure 4.12: Principle drawing of the Francis rig pipe system in the Waterpower Laboratory.

The inlet and outlet diameter of the pumps are 500 mm and 400 mm respectively. Each pump is run by a non-synchronous electromotor with an ABB frequency converter and a maximum output of 315 kVA. The pumps are rpm-regulated and controlled by a PLC (Programmable Logic Control) system. If run connected in series, a pressure equivalent to 100 meters water column is obtainable. The maximum volume flow obtainable is 1 m^3/s, when the pumps are connected in parallel. Figure 4.13 shows one of the pumps installed in the basement of the Waterpower Laboratory.

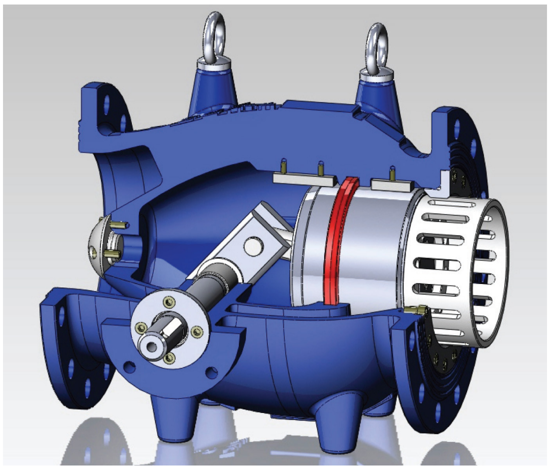
Figure 4.13: One of the feed pumps in the Waterpower Laboratory.

4.1.2 Throttle valve

The throttle valve is a needle valve of type *FA7800500, Needle Valve PN16 slott K50*. It is manually operated by a handwheel on the side of the valve. The handwheel moves a piston inside the valve, controlling the valve opening, as seen in figure 4.14a. The valve is installed below the high pressure tank and forms a closed loop with the Francis rig turbine.The valve is equipped with an anticavitation slotted cylinder at the outlet, as shown in figure 4.14b.



(a) Flow pattern through throttle valve.



(b) Anticavitation cylinder at outlet.

Figure 4.14: Throttle valve [13]

4.2 Measurements on the Francis turbine test rig

A more detailed description of the measurement setups can be found in appendix C.

4.2.1 Torque

Torque is measured at two places on the rig: The torque on the generator shaft and the friction torque on the axial bearings. The sum of the power calculated from the generator and friction torque is the power delivered by the turbine runner.

4.2.2 Pressure

Preassure is measured several places on the rig. The inlet pressure is measured just in front of the spiral casing, and the differential pressure over the turbine is measured between the inlet and the outlet at the end of the draft tube.

4.2.3 Flow

The volume flow measurements are done with an electromagnetic flow meter. The flow meter is situated a few meters upstream of the Francis rig.

4.2.4 Rotational speed

The rotational speed is measured on the shaft, just above the upper labyrinth seal.

4.2.5 Water temperature

The water temperature is measured immediately downstream of the pressure tank in front of the Francis rig.

4.2.6 O_2 level

The oxygen level in the water is measured in the feed pipe to the main pumps in the basement.[3]

[3] The IEC recommends monitoring O_2 levels and keeping them as low as possible, especially when performing cavitation tests. What is most important is to record the O_2 level so that it might be identified as a source of error if tests done with different O_2 levels are to be compared. During the fall of 2012, when this thesis was written, the O_2 sensor in the Waterpower Laboratory was faulty. However this is not of much importance for the sake of this thesis, but should be noted by students who might use measurements from these tests in the future.

5 Execution

5.1 Calibrations

The measurement instruments on the Francis rig were calibrated before testing of the RPT started. The instruments calibrated were:

- Inlet and differential pressure transducer used to calculate head.
- Flow meter, used to measure flow.
- Weighing tank, necessary for calibrating flow meter.
- Generator torque load cell.
- Friction torque load cell.

The calibrated values were entered into the LabView logging program before testing started. For calibration methods and results see appendix C.

5.2 Setup

Two different loop set ups were used. One where the energy in the system was dissipated through the feed pumps in the basement, and one where the energy was dissipated through the energy dissipating throttle valve under the pressure tank. The head, flow and torque measurement points were the same for both loop set ups.

5.2.1 Feed pump loop

A closed loop, the same as when running the rig in turbine mode, was set up for this test. Only one of the feed pumps were used, since this gave a sufficient system head. The pump was run in normal pump mode, meaning it pumped against the RPT in the Francis rig. As the RPT pumped, the flow moved from high pressure to low pressure side through the feed pump. This means the feed pump was operating in the second quadrant in the pump characteristics diagram, figure 3.11, the energy dissipation quadrant. The loop set up can be seen in figure 5.15.

5.2.2 Throttle valve loop

The throttle valve is situated underneath the pressure tank. It is possible to set up valves to fill a closed loop from the Francis rig through the pressure tank, throttle valve, suction tank and back through the Francis rig. The loop set up can be seen in figure 5.16, and a detailed procedure of how to adjust and fill this loop can be found in appendix B.

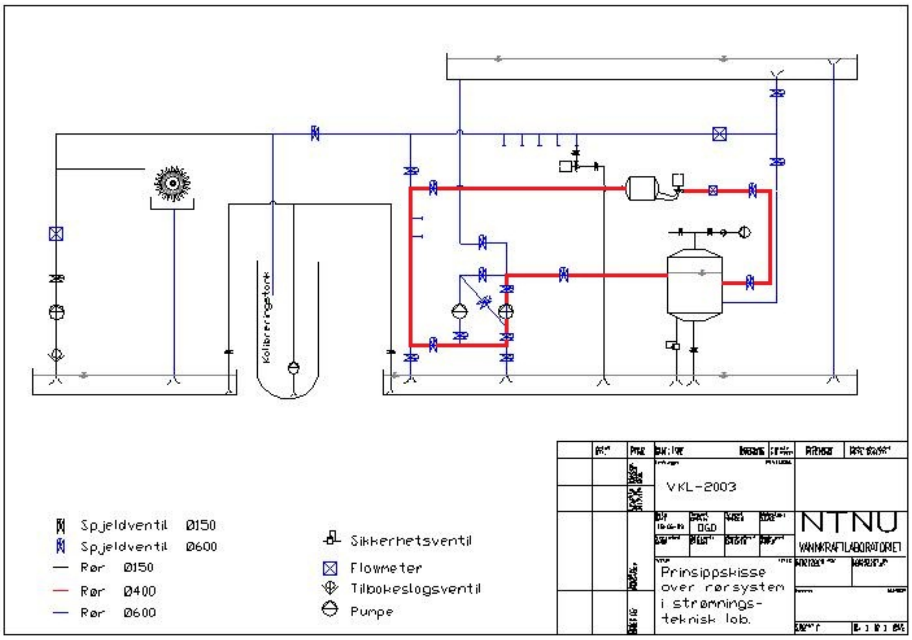


Figure 5.15: Loop set up with feed pump as energy dissipator.

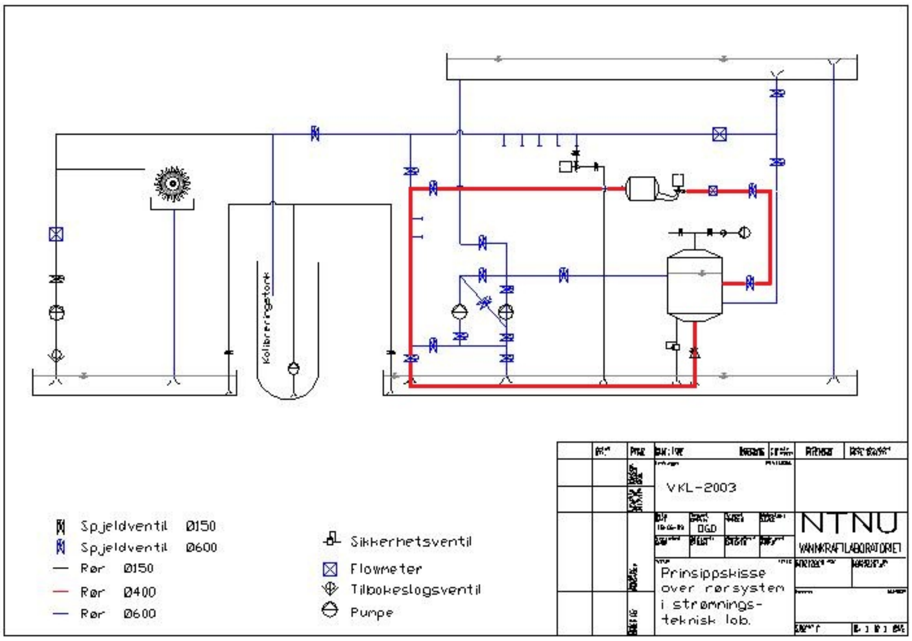


Figure 5.16: Loop set up with throttle valve as energy dissipator.

5.3 Taking measurements

Since the goal was to measure pump curves of head-flow variation at constant speeds, measurements were taken for series of constant RPT rpm's. The same RPT rpm's were tested when using the two different dissipation methods. The sample time for each measurement point was 30 seconds. Table 5.1 shows the RPT speeds the measurement series were taken for, and the correlating number of measurement points for each series.

RPM series	Number of measurement points	
	With feed pump	With throttle valve
290	15	17
320	15	19
350	15	21
380	19	22
410	19	25
440	19	27
470	19	29
500	19	31
530	19	34
560	19	36

Table 5.1

5.3.1 Feed pump

To change the head and flow and move from one measurement point to another, the rotational speed of the feed pump was adjusted. The jump in speed varied between 10, 20 and 30 rpm, small steps if the change in head and flow was large, and larger steps if the change was small.

The feed pumps are controlled from the control room in the lab. The entire test with feed pump dissipation was carried out from the control room, except for occasional check up rounds through the lab.

5.3.2 Throttle valve

Adjusting the opening of the throttle valve, and thus the head and flow, is done by turning the handwheel on the valve. The handwheel was turned once or twice between each measurement point depending on the change in head and flow between points.

Since the throttle valve is situated underneath the pressure tank and is manually operated 25 steps had to be descended and ascended for each measurement point. With over 150 measurement points this turned out to be quite a workout.

For details of the measurement methods see appendix A.

5.4 Processing data

When recording a point in the LabView logging program, the data from the measurement point is dumped in an Excel sheet. A set of small MatLab scripts were used to process the results and visualize them. Examples of the scripts can be found in appendix D.

6 Results

The main objective of this thesis was to run through a measurement series and produce a pump characteristic for the *Olimstad RPT*, and then evaluate how the Waterpower Laboratory is suited for this type of test. Testing two different dissipation methods and evaluate which should be preferred when performing a pump mode test was also important.

For all figures, the red lines describes results from the measurements done with throttle valve as energy dissipator and the blue lines describes the results from the measurements done with feed pump as energy dissipator.

6.1 Pump characteristics

The H-Q curves for the *Olimstad RPT* are presented in figure 6.17 and 6.18. Figure 6.17 shows the characteristics obtained with the feed pump as energy dissipator, and figure 6.18 shows the characteristics obtained with the throttle valve as energy dissipator.

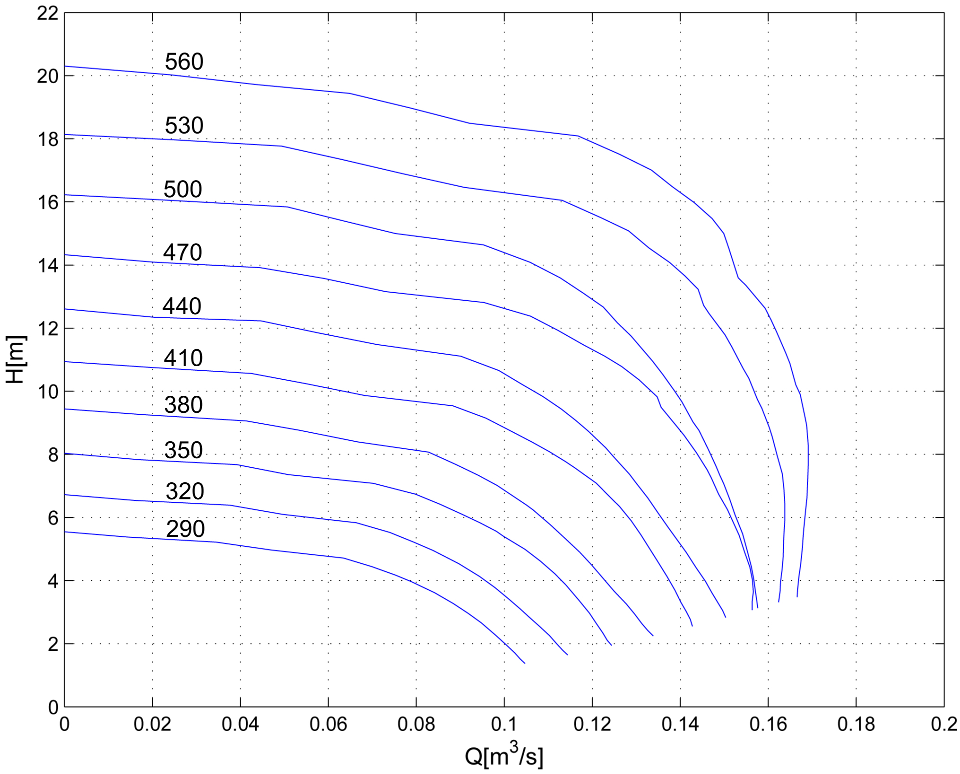


Figure 6.17: The pump curves obtained for the RPT model when run against the feed pumps. Each curve is for a constant RPT rpm

In theory the method of energy dissipation ought not to have an effect on the RPT pump characteristics, other than difference in the head loss through the pump/valve at highest possible volume flow, as it is natural that the head loss through the stationary pump is greater than that through the open valve. In figure 6.19 the characteristic curves are compared.

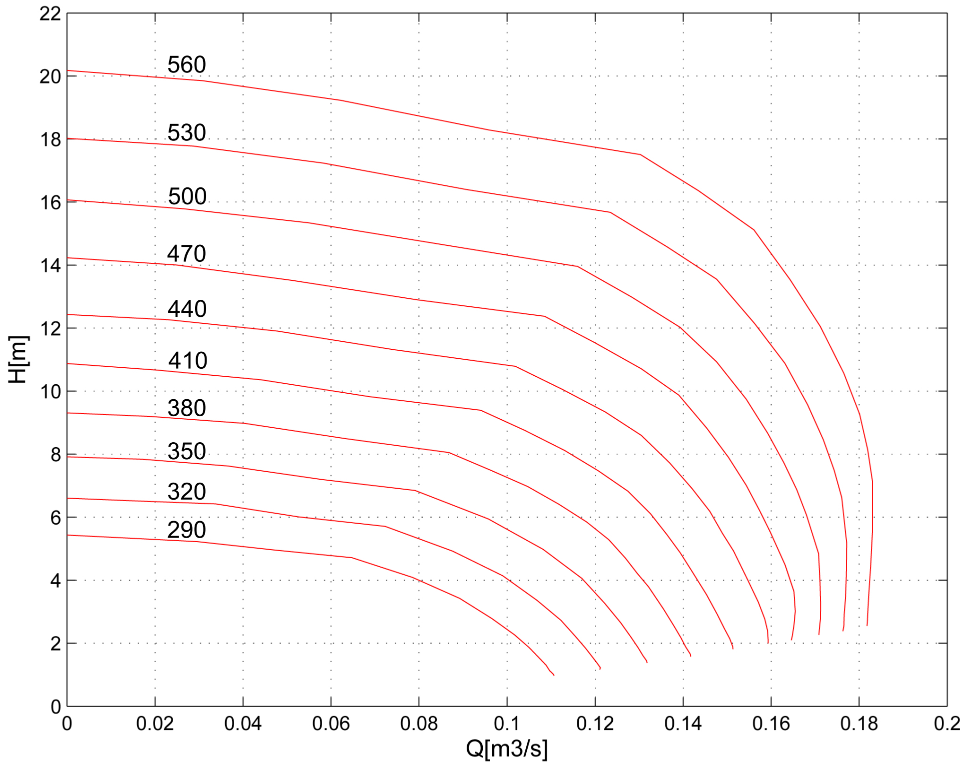


Figure 6.18: The pump curves obtained for the RPT model when run against the energy dissipater. Each curve is for a constant RPT rpm

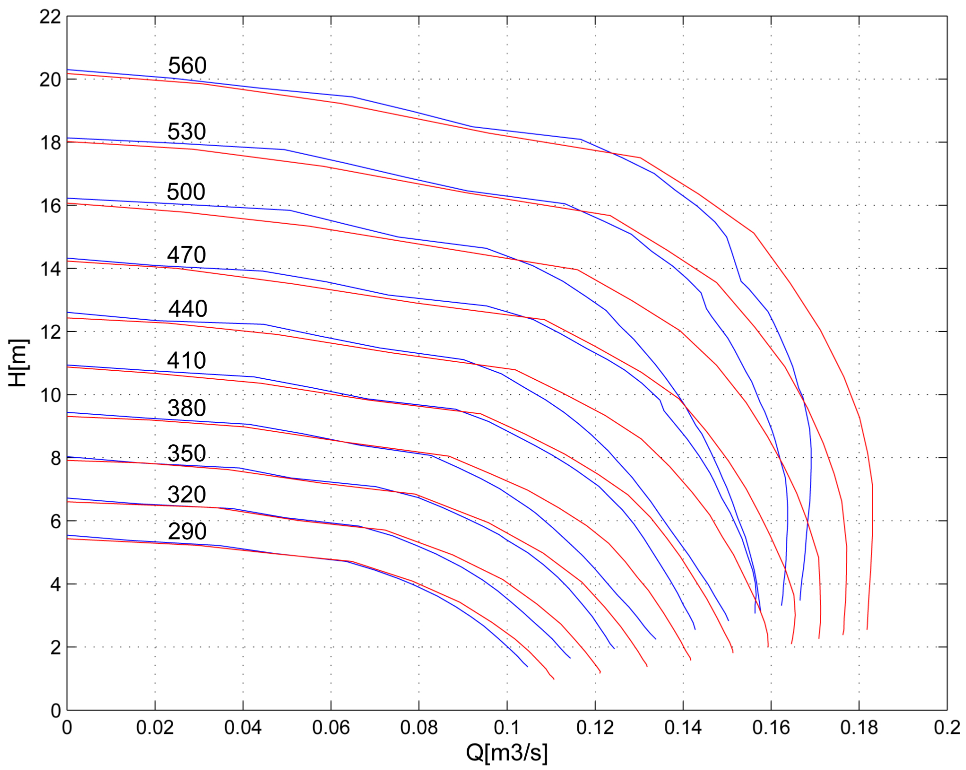


Figure 6.19: Comparison of the pump curves.

6.2 Guide vane opening

The guide vane opening was set to a starting value of $\alpha = 6.855°$ for both test series. During both tests the guide vane opening was seen to vary up and down between measurements without any influence from the controller. The subsequent figures shows the behavior of the guide vanes during the tests.

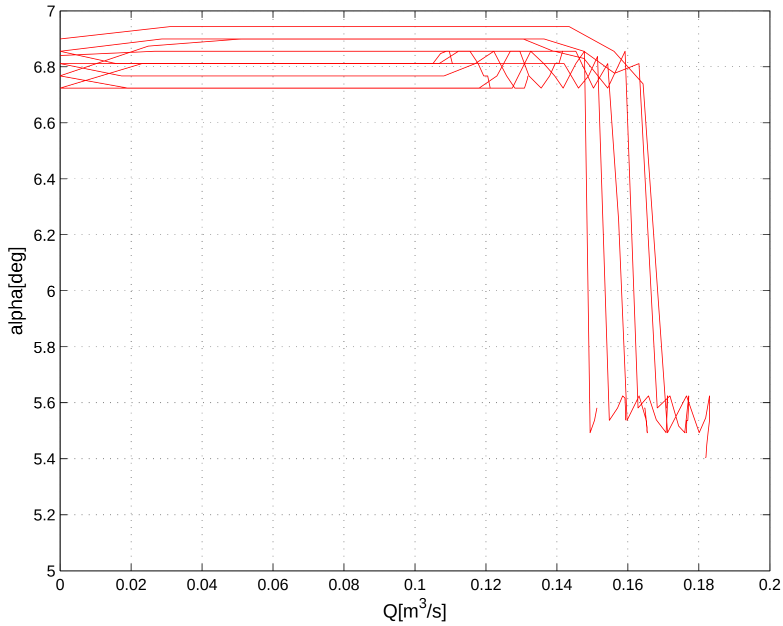


Figure 6.20: Variation in guide vane opening for the complete throttle valve measurements.

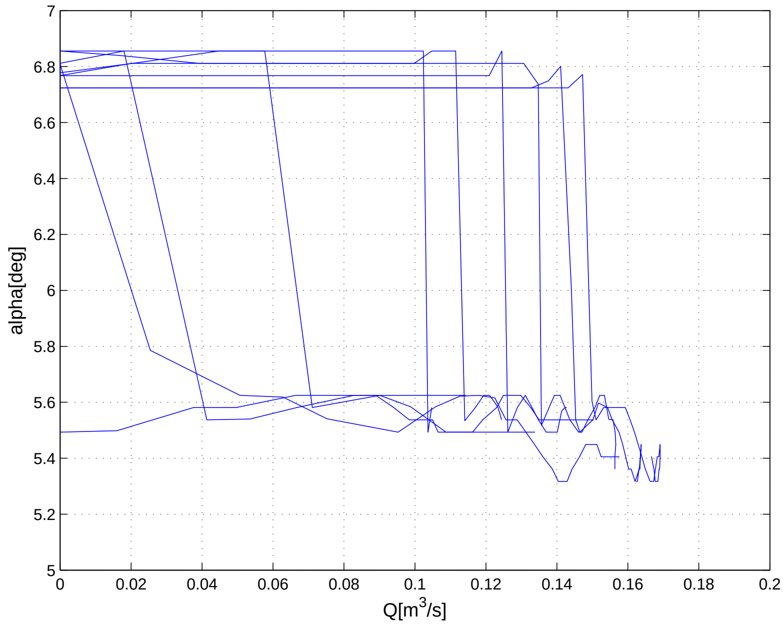


Figure 6.21: Variation in guide vane opening for the complete feed pump measurements.

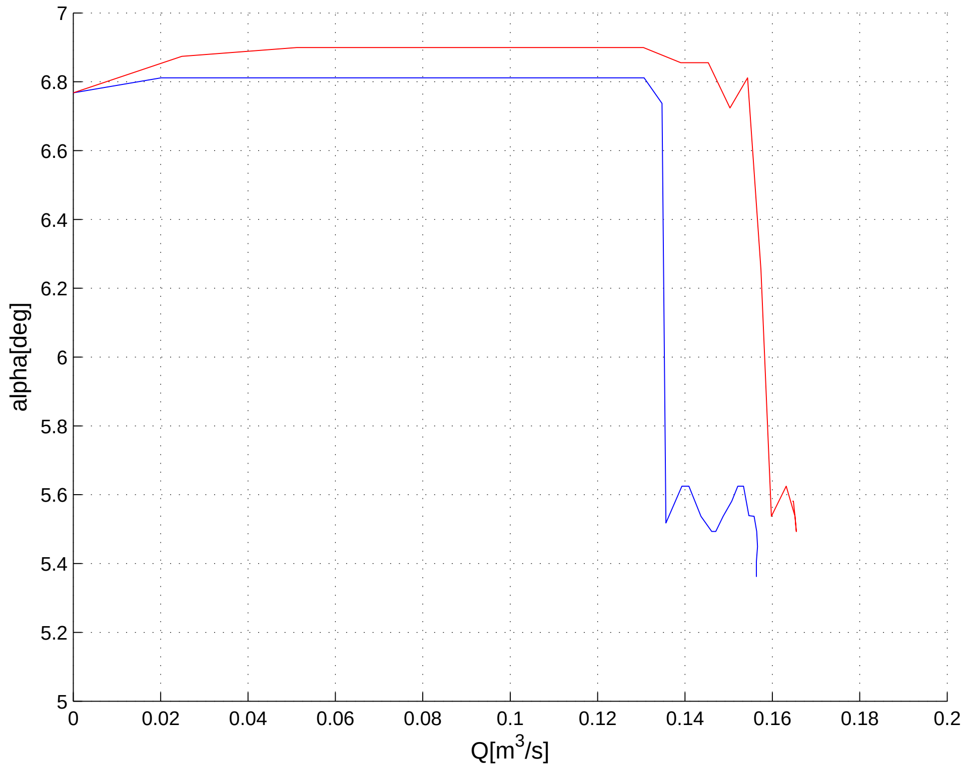


Figure 6.22: Variation in guide vane opening for the 470 rpm series.

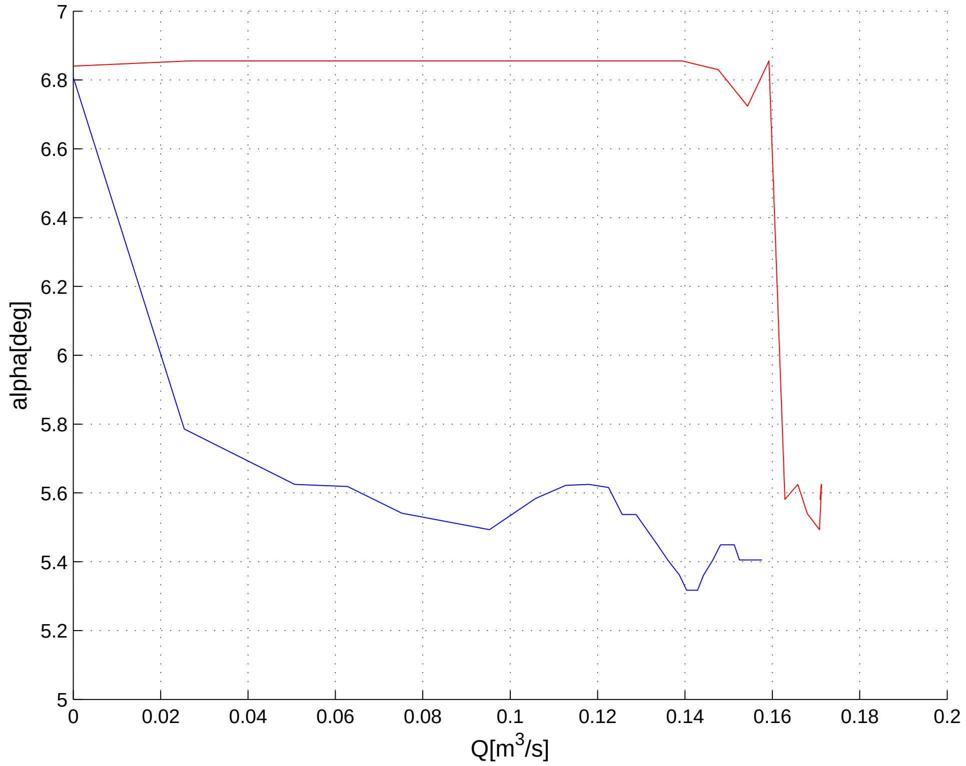


Figure 6.23: Variation in guide vane opening for the 500 rpm series.

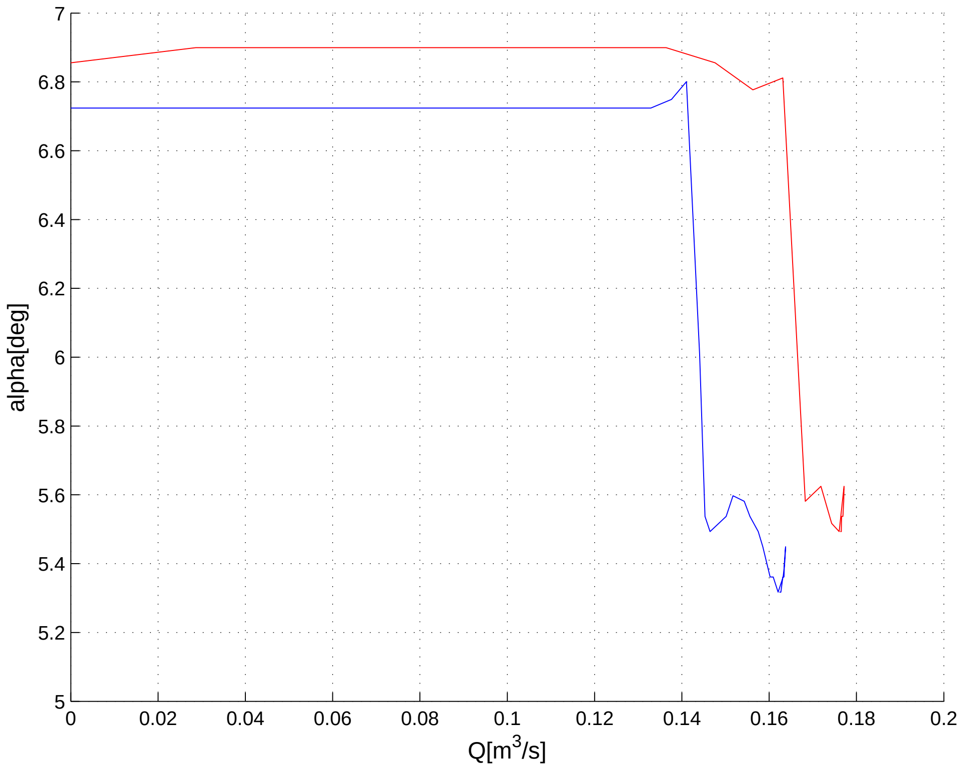


Figure 6.24: Variation in guide vane opening for the 530 rpm series.

6.3 Hydraulic efficiency

The maximum hydraulic efficiency, η_{hmax}, was achieved at 560 rpm's for both test methods. The variation in maximum hydraulic efficiency from the two tests was quite large, more than 2%. The efficiencies for the two test methods can be seen in figure 6.25 and 6.26.

η_{hmax} with feed pump	74.5%
η_{hmax} with throttle valve	77.0%

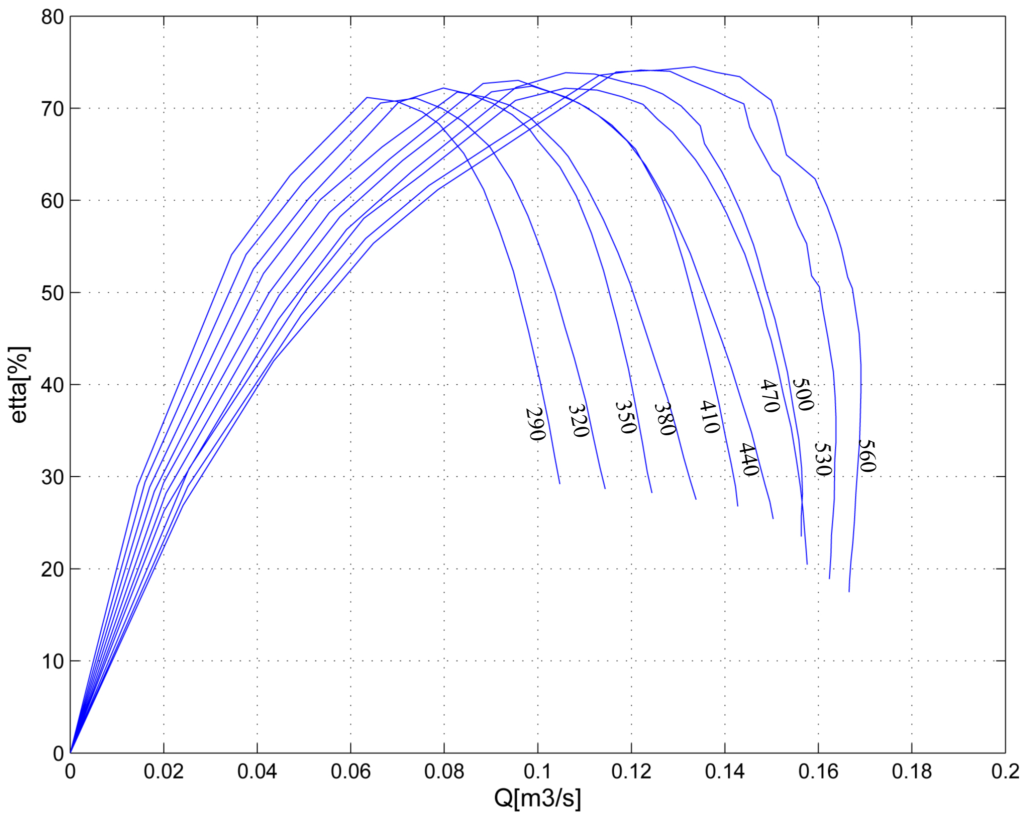


Figure 6.25: Efficiency curves for constant RPT rpm's with feed pump as energy dissipator.

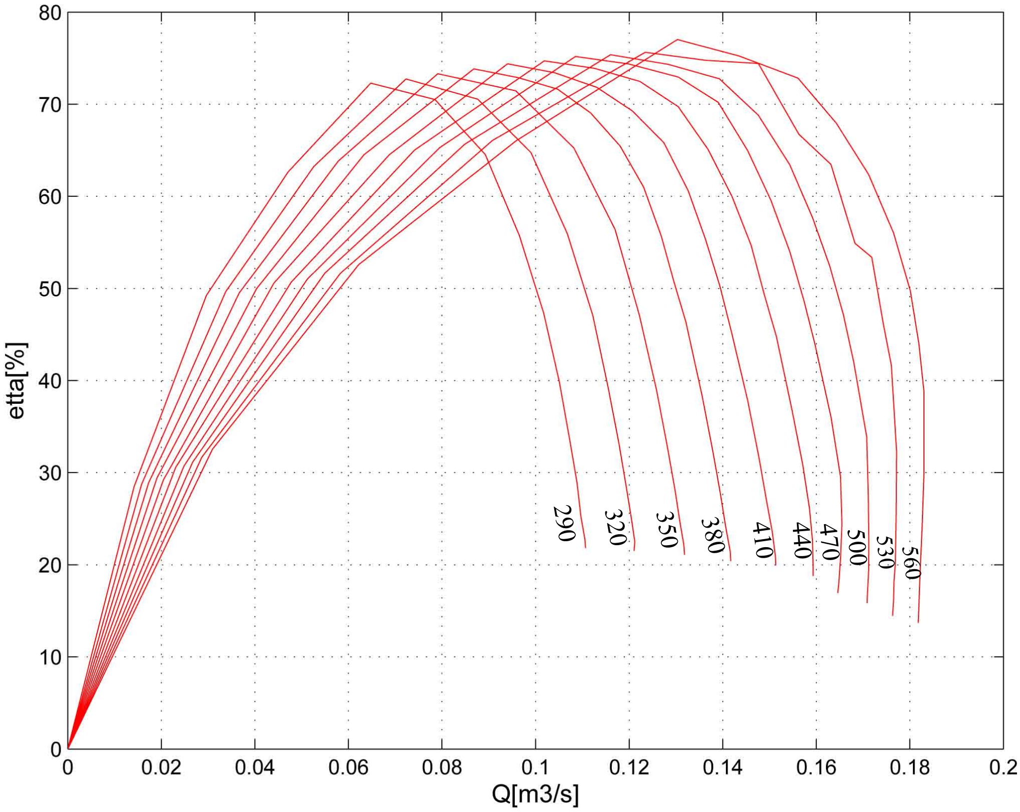


Figure 6.26: Efficiency curves for constant RPT rpm's with throttle valve as energy dissipator.

6.4 Other observations

There was observed increasing noise and vibration in both test series, coming from the spiral casing as the head and flow was increased. At the highest generator speeds, the vibrations and noise was quite powerful, and the measurements were taken as swiftly as possible in order to navigate out of the critical area.

The highest measured temperature variation in the water during testing was 0.9°C. This is well within the restriction from IEC of 5°C per day.

6.5 Procedures

After performing the tests, procedures for running the Francis rig in pump mode has been written. In the procedures it is described how to take measurements for pump characteristics, both with feed pump and throttle valve as energy dissipator. There is also a procedure for how to fill the throttle valve loop. These procedures describes the test methods the way they were carried out in this project. The procedures can be found in appendix A and B.

7 Discussion

7.1 Guide vane system

As seen in figure 6.19, there is a clear deviation in the results between the two methods of energy dissipation used in the tests. The reason for the deviation is unclear. The problem seems to lie with the behavior of the guide vanes, which seem to lurch about quite a bit, despite being set to the same fixed starting angle. Change in the guide vane angle effects the head loss over the guide vanes, and since the guide vanes are within the pressure measurement area used to calculate head, this effects the performance measurements for the runner. The guide vane angle seem to vary consistently with head and flow in the throttle valve measurements, figure 6.20, closing as the flow increases and reach around $0.15m^3/s$. However the guide vane opening varies differently in the two test methods, as in figure 6.24. In some of the feed pump measurement series the guide vane opening varies completely different from the rest, as seen in figure 6.21.

In figure 6.19 the largest deviation between the two dissipation methods seems to be for the 500 rpm series. Looking at the guide vane opening for this series (figure 6.23) compared to the 170 and 530 rpm series (figure 6.22 and 6.24), there is a much bigger difference in guide vane behavior for the 500 rpm series. This is a strong indication that it is indeed the variation in guide vane opening that causes the difference in results between the two test methods.

Why the variation is so different between the two measurement series is unclear. A theory on why the lurch in the guide vanes affect the two measurement series differently is that the starting angle was not the same. Even though the displayed angle was the same for the two starting points, play in the system means that they might have had different tolerances. One starting point might have had a greater tolerance on the plus side and the other starting point may have had a greater tolerance on the minus side.

When testing the RPT-model in turbine mode, the guide vane angle stayed constant throughout the measurement series. This is because the guide vanes are designed to lead water only in a pressure-to-suction direction, as in a Francis turbine. The trailing edges of the guide vanes are sharp, and not rounded off, as is the standard for Francis turbines. RPT turbines however usually have guide vanes with rounded trailing edges for a smoother flow around the vanes in suction-to-pressure directed flow. The sharp trailing edge of the guide vanes in the Francis rig in the Waterpower Laboratory causes massive turbulence over the vanes in pump mode, and this causes great noise and vibration. Due to the play in the guide vane system the guide vanes will move and change the flow opening.

The Olimstad RPT model does not have a respective large sized prototype. It was designed at the Waterpower laboratory at NTNU to compare CFD results with laboratory measurements. Thus there is no given demand as to how the spiral casing, stay vanes, guide vanes or draft tube of the model rig should be. However, if the rig is to be used for model testing of an RPT with a prototype, these components must be adapted to fit the prototype design. Thus it would always have been necessary to replace the current guide vanes before such a test, since the current guide vanes are Francis guide vanes and not RPT guide vanes.

7.2 Choice of dissipation method

Disregarding the variation in results between the two methods, having concluded that these variations are due to problems with the guide vane system, there are some other factors to consider when deciding what dissipation method should be preferred.

Before the tests were performed it was believed that at least one of the dissipation methods would create major noise or vibration problems when dissipating the energy from the system. However, this did not turn out to be a problem with either method.

The feed pumps are easily controlled from the control room. The rpm control is accurate and can be controlled down to ± 1 rpm. The pump room is monitored by a surveillance camera, so it is possible to adjust head and flow without leaving the control room. The extra heat added to the water from the feed pump ought not to be an issue, but it should nevertheless be estimated before a test in order to avoid exceeding the IEC recommendation on water temperature variation. Accomplishing 0 flow with the feed pumps is tricky, since it easily ends up changing direction instead, flowing through the RPT from high pressure to low pressure side.

With the throttle valve there is no problem achieving 0 flow, as this happens when the valve is completely closed. The main draw back of the throttle valve is that it has to be adjusted manually. This means one has to leave the control room every time head and flow shall be adjusted unless two people perform the test.

8 Conclusion

The main objective of this thesis was to run through a measurement series and produce a pump characteristic for the *Olimstad RPT*, and then evaluate how the Waterpower Laboratory is suited for this type of test. Testing two different dissipation methods and evaluate which should be preferred when performing a pump mode test was also important.

What has been discovered is that the guide vane system does not function well. The guide vanes ought be adapted for suction-to-pressure flow, i.e. get rounded trailing edges as is standard for RPT guide vanes. Furthermore, the play in the guide vane system causes problems. This ought to be fixed so that the guide vane angle does not change after it has been set. The method for adjusting the guide vane angle would also benefit from an upgrade. Todays system with the toggle switch is bothersome. It would be good to be able to specify the guide vane angle one desires to use, instead of having to try to hit this angle by continuous back and forth with the toggle switch.

The two dissipation methods tested were both effective. The throttle valve works best for achieving 0 flow, but the feed pumps are easier to regulate. None of the methods showed signs of high noise or vibrations, and both may be used for future tests.

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APENDICES

A Procedures for running an RPT model in pump mode in the Francis Rig

Energy dissipation through feed pumps

This part of the procedure treats running the Francis turbine test rig in pump mode with a closed loop, like the one seen in figure A.27a. The water is directed through the turbine runner then to the pressure tank on through the feed pump and then back through the draft tube tank to the turbine. When going from an open loop to a closed loop, the loop needs to be filled before you can start running. A detailed procedure for this already exists, and can be found on the Waterpower Laboratory's server.

Start up

1. **Turn on the power for the feed pump**
   This is done in the pump room in the basement. Turn the switch to *Start*, keep it there for a second and then let it go so that it stops at *1*.
2. **Make an inspection round in the lab**
   Walk through the lab and see that all drain tubes on the current pipe loop are closed.
3. **Check for water on top of the turbine**
   Water will leak up through the guide vanes and accumulate on top of the turbine when it is running. Check for water before starting. If there is water, use the water vacuum cleaner to remove it.
4. **Open shut off valve for vacuum pump**
   Open the valve between the vacuum pump and the draft tube tank, see figure A.29a.
5. **Open valve for priming water for the vacuum pump**
   The valve can be seen in figure A.29b.
6. **Turn on cooling water and hydraulics**
   Always turn on the cooling water first, then the hydraulics. See figure A.28a for hydraulics and figure A.28b for the cooling water.
7. **Open valve on labyrinth water bucket**
   Accessed by walking behind the generator, see figure A.28c and A.28d.
8. **Adjust the guide vanes**
   Set the guide vane opening to the desired angle by using the toggle switch between the computer screens.
9. **Set the rpm of the generator to 0**
   Using the +/- buttons set the generator "skallverdi" to 0 rpm.
10. **Start the generator in pump mode**

Click on "Pump" to make sure the genrator is in pump mode.[4] Since the rpm is set to 0 the turbine should not start spinning.

11. **Start the pump**
    Start the feed pump at 100 rpm. The water will now start flowing from the pressure tank through the turbine.

12. **Increase the speed of the generator**
    Start spinning the turbine by increasing the speed of the generator using the "+" buttons. Since the generator is in pump mode the rpm will be displayed as negative.

13. **Get the RPT pumping**
    Continue increasing the generator speed until the flow changes direction. The RPT is now working as a pump!

Taking measurements for a pump characteristic

1. **Set recording time and directory**
   Set the recording time to 30 seconds, and specify the name of your recording file and the directory you want to save in. There should be a description in the control room explaining which folders to use.

2. **Set generator speed**
   Run the generator up to the rpm you want to take the first measurement series at. Increase the speed gradually, letting the flow and head stabilize as you go.

3. **Find starting point**
   Run up the feed pump rpm towards the rpm of the generator and try to find the feed pump rpm that gives no flow. Increase the speed gradually, letting the flow and head stabilize as you go.

4. **Take first measurement point**
   Press the *Record* button when the head and flow looks to be stable.

5. **Decrease the speed of the feed pump**
   Decrease the speed of the feed pump in order to reduce the head and increase the flow. How much you reduce the speed between each measurement point depends on how many measurement points you wish to take.

6. **Take the next measurement point**
   Press the *Record* button when the head and flow looks to be stable.

7. **Continue decreasing the speed of the feed pump**
   Continue decreasing the rpm of the feed pump and taking measurements until you reach 0 rpm. This will be the last measurement point for the series with the highest possible volume flow.

[4] Unfortunatley the text displaying the mode of the genaratordoes not change from "Turbine" to "Pump" until the turbine starts spinning.

8. **Set new recording file**
   Set a new recording file so that you will get one document for each generator rpm series.

9. **Set generator speed**
   Set the generator speed of the next measurement series.

10. **Take measurements for the new series**
    Take the first measurement point with the feed pump still at 0 rpm and work your way back up until you reach a feed pump rpm where the flow becomes 0.

11. **Set new recording file, new generator speed and start a new series**
    Continue in this fashion until you have completed all your measurement series.

Shut down

1. **Decrease speed of feed pump and generator**
   Slowly decrease the speed of both the pump and the generator. When they are both at 100 rpm, continue decreasing the speed of the generator until you get to 0 rpm.

2. **Stop the feed pump**

3. **Stop the generator**

4. **Close valve on labyrinth water bucket**
   Accessed by walking behind the generator, see figure A.28c and A.28d.

5. **Turn off cooling water and hydraulics**
   See figure A.28a for hydraulics and figure A.28b for the cooling water.

6. **Close valve for priming water for the vacuum pump**
   The valve can be seen in figure A.29b.

7. **Close shut off valve for vacuum pump**
   Close the valve between the vacuum pump and the draft tube tank, see figure A.29a.

8. **Turn off the power for the pumps**
   In the pump room in the basement. Turn the switch to *0*.

Tips

- The magnitude of the flow and head variation due to increase/decrease in the feed pump rpm will vary with where you are in the head-flow diagram, and you will have to take more frequent measurement points in some areas than others. Play around with it a bit to see what works best.

Energy dissipation through throttle valve

This part of the procedure treats running the Francis turbine test rig in pump mode with a closed loop, like the one seen in figure A.27b. The water is directed through the turbine runner to the pressure tank, then through the throttle valve and back through the low pressure tank to the turbine. In order to use this set up the loop must first be filled, for a procedure on how to fill the loop see appendix BLA *Procedure for filling closed loop with throttle valve*.

Start up

1. **Close the throttle valve**
   Make sure the throttle valve is closed. The throttle valve is adjusted by a handwheel and is situated underneath the pressure tank, see figure A.29.

2. **Make an inspection round in the lab**
   Walk through the lab and see that all drain tubes on the current pipe loop are closed.

3. **Check for water on top of the turbine**
   Water will leak up through the guide vanes and accumulate on top of the turbine when it is running. Check for water before starting. If there is water, use the water vacuum cleaner to remove it.

4. **Open shut off valve for vacuum pump**
   Open the valve between the vacuum pump and the draft tube tank, see figure A.29a.

5. **Open valve for priming water for the vacuum pump**
   The valve can be seen in figure A.29b.

6. **Turn on cooling water and hydraulics**
   Always turn on the cooling water first, then the hydraulics. See figure A.28a for hydraulics and figure A.28b for the cooling water.

7. **Open valve on labyrinth water bucket**
   Accessed by walking behind the generator, see figure A.28c and A.28d.

8. **Adjust the guide vanes**
   Set the guide vane opening to the angle you want by using the toggle switch between the computer screens.

9. **Set the rpm of the generator to 0**
   Using the +/- buttons set the generator "skallverdi" to 0 rpm.

10. **Start the generator in pump mode**
    Click on "Pump" to make sure the genrator is in pump mode.[5] Since the rpm is set to 0 the turbine should not start spinning

[5]Unfortunatley the text displaying the mode of the genaratordoes not change from "Turbine" to "Pump" until the turbine starts spinning.

11. **Increase the speed of the generator**
    Slowly increase the speed of the generator. The RPT is now pumping, but because the throttle valve is closed this causes an increase in head but no flow.

Taking measurements for a pump characteristic

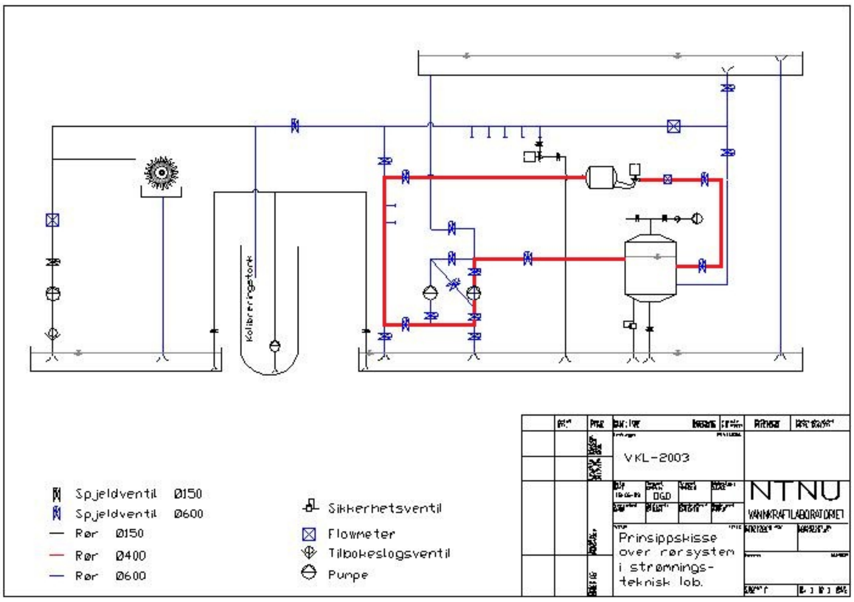
1. **Set recording time and directory**
   Set the recording time to 30 seconds, and specify the name of your recording file and the directory you want to save in. There should be a description in the control room explaining which folders to use.
2. **Set generator speed**
   Run the generator up to the rpm you want to take the first measurement series at. Increase the speed gradually, letting the flow and head stabilize as you go.
3. **Find starting point**
   Start with the throttle valve completely closed. This gives 0 flow at the first measurement point.
4. **Take first measurement point**
   Press the *Record* button when the head and flow looks to be stable.
5. **Open the throttle valve**
   Start to open the throttle valve by turning the handwheel once or twice.
6. **Take the next measurement point**
   Press the *Record* button when the head and flow looks to be stable.
7. **Continue opening the throttle valve**
   By one or two turns on the handwheel each time, and taking measurements until you reach fully open valve. This will be the last measurement point for the series with the highest possible volume flow.
8. **Set new recording file**
   Set a new recording file so that you will get one document for each generator rpm series.
9. **Set generator speed**
   Set the generator speed of the next measurement series.
10. **Take measurements for the new series**
    Take the first measurement point with the valve still fully open and work your way back up until the valve is close, taking measurements all the way.
11. **Set new recording file, new generator speed and start a new series**
    Continue in this fashion until you have completed all your measurement series.

Shut down

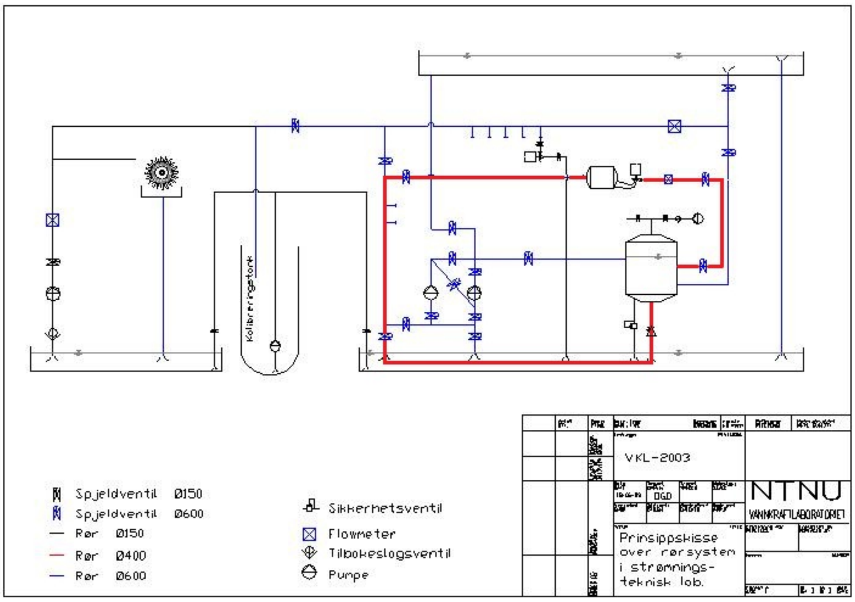
1. **Decrease speed the generator**
   Slowly decrease the speed of the generator until you reach 0 rpm.

2. **Stop the generator**

3. **Close valve on labyrinth water bucket**
   Accessed by walking behind the generator, see figure A.28c and A.28d.
4. **Turn off cooling water and hydraulics**
   See figure A.28a for hydraulics and figure A.28b for the cooling water.
5. **Close valve for priming water for the vacuum pump**
   The valve can be seen in figure A.29b.
6. **Close shut off valve for vacuum pump**
   Close the valve between the vacuum pump and the draft tube tank, see figure A.29a.

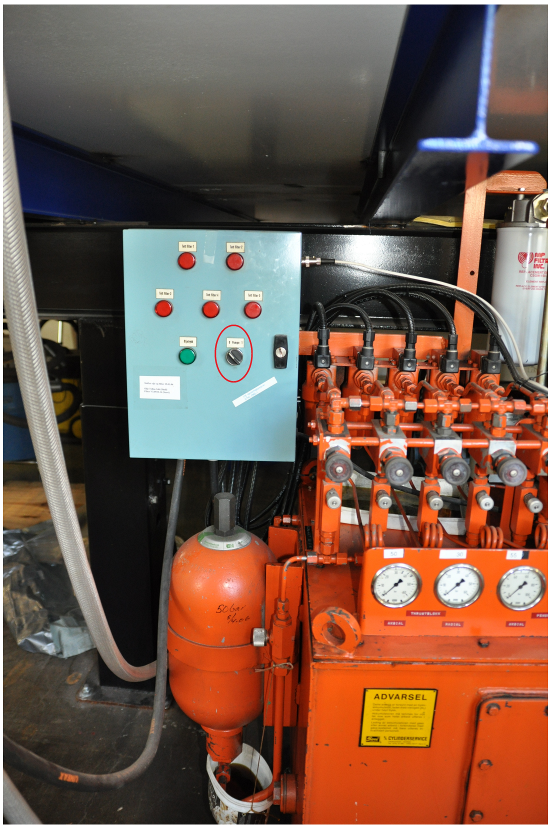


(a) Closed loop with feed pumps



(b) Throttle valve loop

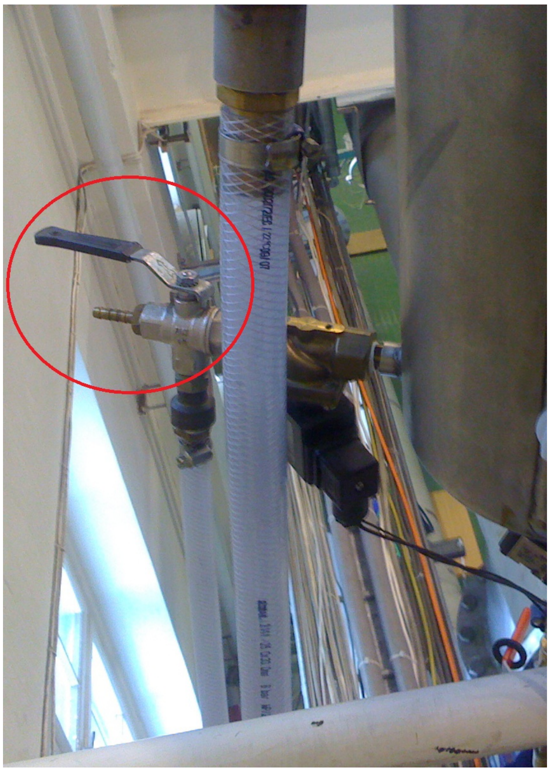
Figure A.27: Piping diagram of different loop configurations for running the Francis Test Rig in pump mode



(a) Control switch for hydraulics

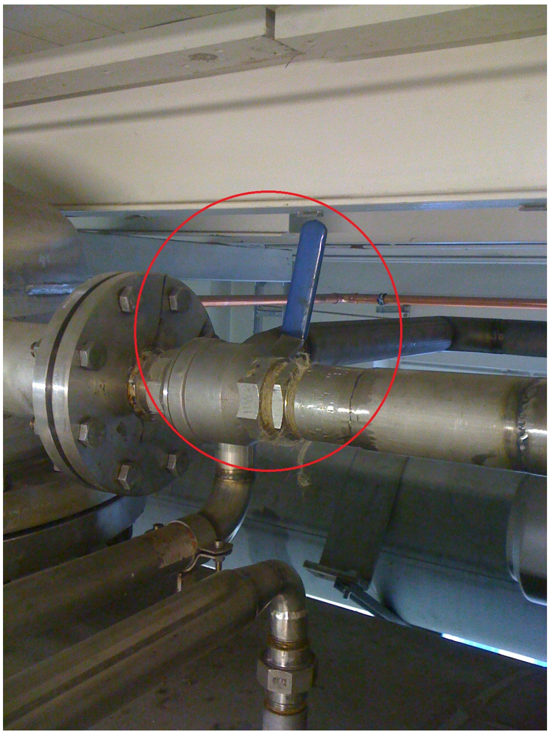
(b) Valve for cooling water for hydraulics

(c) Labyrinth water bucket



(d) Valve on labyrinth water bucket

Figure A.28: Descriptive pictures for pump mode procedure



(a) Shut off valve for vacuum pump.

(b) Valve for vacuum pump priming water.

(c) Throttle valve.

(d) Throttle valve wheel.

Figure A.29

B Procedure for filling closed loop with throttle valve

The valves in the PLS control system are numbered and can be seen in figure B.30.

1. **Turn on the power for the feed pump**
   This is done in the pump room in the basement. Turn the switch to *Start*, keep it there for a second and then let it go so that it stops at *1*.

2. **Close throttle valve**
   Using the handwheel, figure B.31d.

3. **Turn on cooling water and hydraulics**
   Always turn on the cooling water first, then the hydraulics. See figure A.28a for hydraulics and figure A.28b for the cooling water.

4. **Open airing valve on draft tube tank**
   See figure B.31a.

5. **Close shut off valve for vacuum pump**
   Close the valve between the vacuum pump and the low pressure tank, see figure B.32a.

6. **Open airing valve on pressure tank**
   Use handwheel, see figure **??**.

7. **Open valve 4 in the PLS control system**
   If there is water in the system, let the water flow down into the pipe that runs along the bottom of the lower reservoir, and wait for the levels to stabilize.

8. **Open/close valves in PLS control system**
   Close valve V2, V6, V9 and V10. Open valve V5, V15, V13, V12 and V18.

9. **Open bleed valves**
   Open both bleed valves by the stairs, see figure BILDE, and the bleed valve at the highest point after the draft tube tank, see figure BILDE.

10. **Start the feed pump**
    Start the pump at 100 rpm.

11. **Increase the speed of the feed pump**
    Until the level in the high pressure tank is slightly above the outlet of the pipe leading to the Francis turbine.

12. **Make sure guide vanes are in closed position**
    Close them using the toggle switch between the computer screens.

13. **Open valve V9**
    Using the PLS control system.

14. **Slowly open guide vanes**
    The turbine might start to spin, that is ok.

15.

16. **Fill the draft tube tank**
    Try to get as much water in the draft tube tank as possible, without filling it up completely. 95% on the monitor screen is good.
17. **Close the bleed valves when only water is exiting from the valves**
18. **Close airing valve on draft tube tank**
    Close the valve when the water level in the tank is at 95%.
19. **Close valve V9**
    Using the PLS control system.
20. **Fill up the pressure tank**
    Slowly increase the feed pump speed and fill the tank to about 80%.
21. **Close airing valve on the pressure tank**
22. **Close reservoir valves, valve V12 and V18**
23. **Run down and stop feed pump**
    Slowly run down the pump and stop it at 100rpm.
24. **Close valve V5**
25. **Open the throttle valve**
    Using the handwheel on the valve.
26. **Open valve V9**
    You should now have a closed loop filled with water.

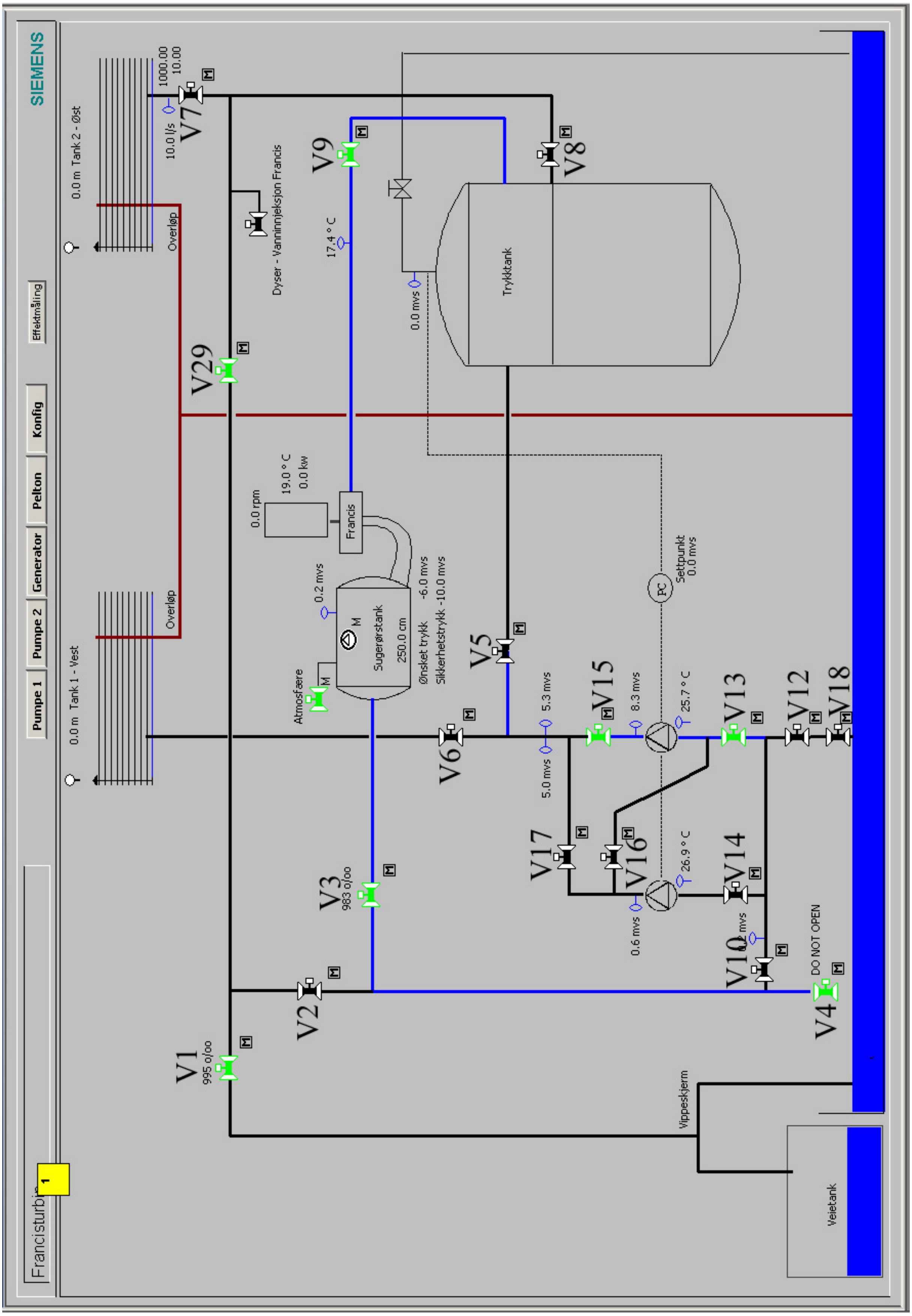
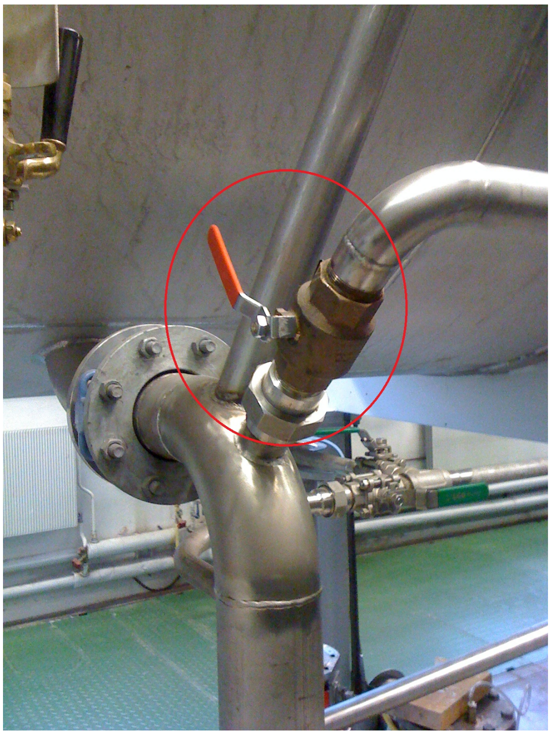


Figure B.30: PLS control window with valve numbers.



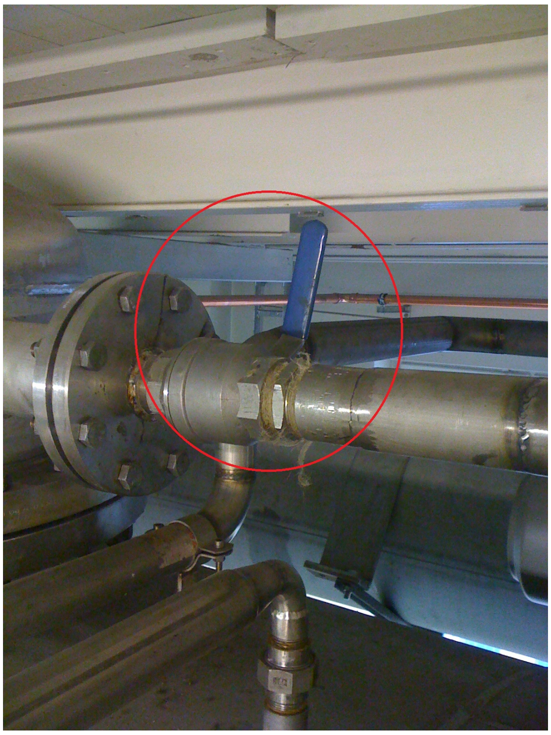
(a) Draft tube tank airing valve.

(b) Throttle valve wheel.

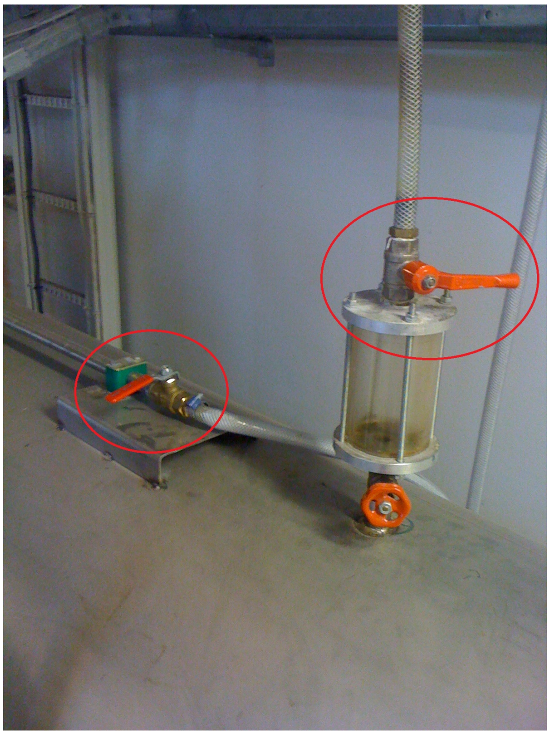
(c) Throttle valve.

(d) Throttle valve wheel.

Figure B.31



(a) Shut off valve for vacuum pump.



(b) Bleed valves by stairs.

(c) Bleed valve at highest point.

Figure B.32

C Measurement setups and calibrations

Detailed procedures for the calibrations can be found in *Hydraulic performance of a high head Francis turbine* [4].

Methods

Generator torque

The force acting on an arm with a given length is measured, and the torque is the force multiplied by the arm length. Multiplying this value with the rotatianal speed of the shaft gives the power output the measured torque represents.

The torque measured on the generator shaft is measured on an arm connected to the generator. The generator itself rests on a pressurized oil film, allowing it to rotate freely with virtually no friction.The low friction is important in order to be able to measure the correct torque, since any friction between the generator and the rig would make the measured values incorrect from the true torque delivered by the generator shaft. The torque on the shaft is balanced only by the force on the load cell measuring the force on the arm, keeping the generator stationary.

The calibration of the generator torque load cell is done by weighing down the load cell with calibrated dead wights, and measuring the generator arm from from center of the shaft to the load cell. The applied torque is then correlated with the signal output from the load cell in order to obtain the calibration curve.

Pressure transducers

The inlet pressure is measured as an absolute pressure. Thus the static pressure in the feed tube, from the height difference in the measuring point on the pipe and the location of the transducer, is subtracted from the measured pressure. For the differential pressure cell the static pressure from the feed tubes cancel each other out, leaving only the height difference between the measurement points. This hight difference is measured as a pressure difference in the differential pressure transducer.

Both pressure transducers are calibrated by the use of a dead weight manometer. By adding dead weights to the manometer exerting a known pressure on the high pressure side of the transducer a calibration curve for the signal output from the transducer can be created.

Weighing tank

The weighing tank is calibrated by substitution calibration. A five ton dead weight is used, and water is filled into the tank between each measurement point to move up in the tanks weight range.

Flow meter

The method used by the flow meter is based on Faraday's law of induction. A set of magnetic coils form a magnetic field perpendicular to the flow direction. The fluid acts as a conductor moving in a magnetic field, and a voltage is induced. This voltage is the measured signal. Two electrodes mounted in the pipe on the sensor sense the voltage signal. The measured voltage signal is proportional with the flow velocity. Thus, in a pipe with a known cross section and velocity, one can find the volume flow.

The flow meter is calibrated by utilizing the weighing tank in the laboratory. By directing the flow to the weighing tank for a given time the average flow rate for the time interval can be found. Because the weighing thank sensors also needs to be calibrated the flow meter calibration is regarded as a secondary calibration method.

Friction torque

The friction torque measured on the axial bearings works in the same way as the generator torque. The force on the load cell from the arm balances out the friction torque from the axial bearing, keeping the bearing from rotating.

The friction torque is calibrated by weighing down the load cell with calibrated dead wights, and measuring the generator arm from from center of the shaft to the load cell. The applied torque is then correlated with the signal output from the load cell in order to obtain the calibration curve. This is done twice, once with the generator and shaft rotating in each direction, pump and turbine mode, in order to cancel out friction effects. The calibration curves are then averaged to find the final calibration values.

Rotational speed

The measuring device consists of a disc with a slit that is fastened to the shaft. When the disc rotates with the shaft, the disc passes through an optical fork that registers a pulse every time the slit passes. The time between two pulses is measured and converted into the rotational speed of the disc and shaft.

This set up does not need calibration since the only value that is measured is time, and the time can not be calibrated.

Water temperature

The temperature sensor is calibrated by an external party.

O_2 level

The sensor measures the quantity of dissolved oxygen in the water based on diffusion of oxygen through a PolyTetraFluoroEthylene membrane (PTFE). The oxygen sensor is calibrated by an external party.

Calibration values

Apparatus	Calibration equation	Date calibrated
Flow meter	y = 0.117691x - 0.587622	18.10.2012
Inlet pressure	Y= -124.70632650 + 62.74312533x	16.10.2012
Diff pressure	Y= -124.34578396 + 62.69302404x	16.10.2012
Generator torque	Y= -205.41335133 + 511.88539772x	17.10.2012
Friction torque	y= -1.9307 + 3.1386x	26.10.2012

Generator torque load cell

CALIBRATION REPORT

CALIBRATION PROPERTIES
Calibrated by: Johanne Seierstad, Andrea Stranna, Tage Augustson
Type/Producer: Hottinger Z6FC3
SN:
Range: 0 - 500 kg
Unit: Nm

CALIBRATION SOURCE PROPERTIES
Type/Producer: Kalibreringsbevis dødvekter
SN: CAL 016-06/730-3
Uncertainty [%]:

POLY FIT EQUATION:
Y= -205.41335133E+0X^0 + 511.88539772E+0X^1

CALIBRATION SUMARY:
Max Uncertainty : Inf [%]
Max Uncertainty : 2.571345 [Nm]
RSQ : 0.999935
Calibration points : 60

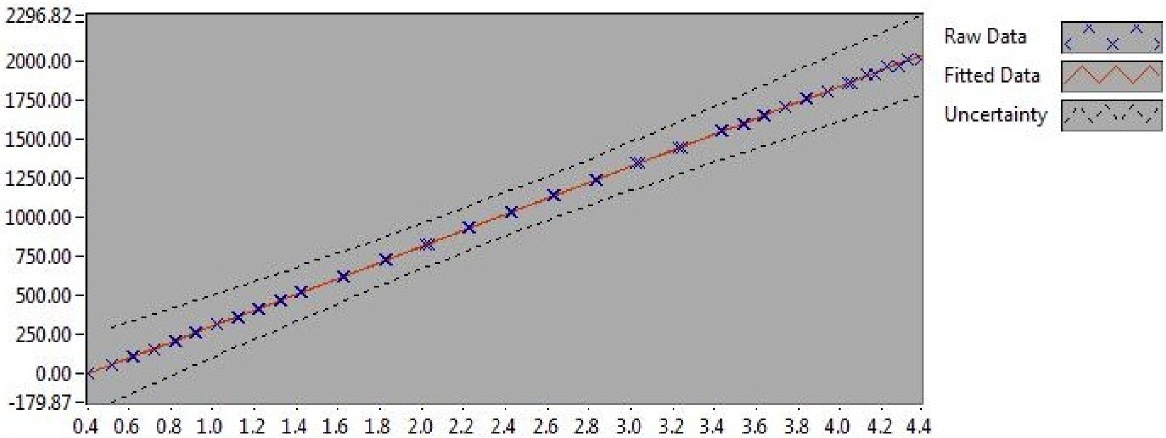


Figure 1 : Calibration chart (The uncertainty band is multiplied by 100)

Inlet pressure transducer

CALIBRATION REPORT

CALIBRATION PROPERTIES
Calibrated by: Andrea Stranna, Johanne Seierstad, Tage Augustson
Type/Producer: Druck PTX 1830
SN: 2867610
Range: 0-10 bar a
Unit: kPa

CALIBRATION SOURCE PROPERTIES
Type/Producer: Pressurements deadweight tester P3223-1
SN: 66256
Uncertainty [%]: 0,01

POLY FIT EQUATION:
Y= -124.70632650E+0X^0 + 62.74312533E+0X^1

CALIBRATION SUMARY:
Max Uncertainty : Inf [%]
Max Uncertainty : 0.142407 [kPa]
RSQ : 0.999998
Calibration points : 60

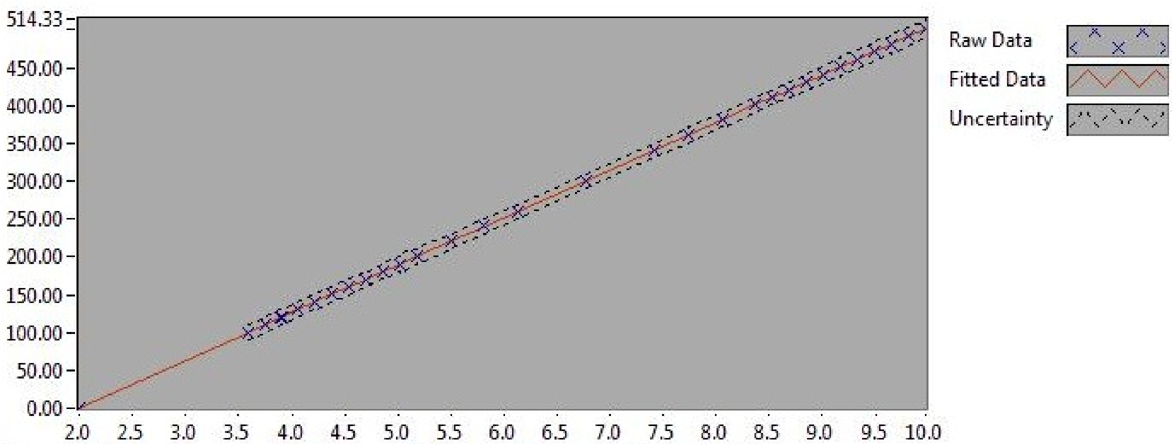


Figure 1 : Calibration chart (The uncertainty band is multiplied by 100)

Differential pressure transducer

CALIBRATION REPORT

CALIBRATION PROPERTIES
Calibrated by: Andrea Stranna, Johanne Seierstad
Type/Producer: Druck PTX 1830
SN: 2867610
Range: 0-10 bar a
Unit: kPa

CALIBRATION SOURCE PROPERTIES
Type/Producer: Pressurements deadweight tester P3223-1
SN: 66256
Uncertainty [%]: 0,01

POLY FIT EQUATION:
Y= -124.34578396E+0X^0 + 62.69302404E+0X^1

CALIBRATION SUMARY:
Max Uncertainty : Inf [%]
Max Uncertainty : 0.100681 [kPa]
RSQ : 1.000000
Calibration points : 60

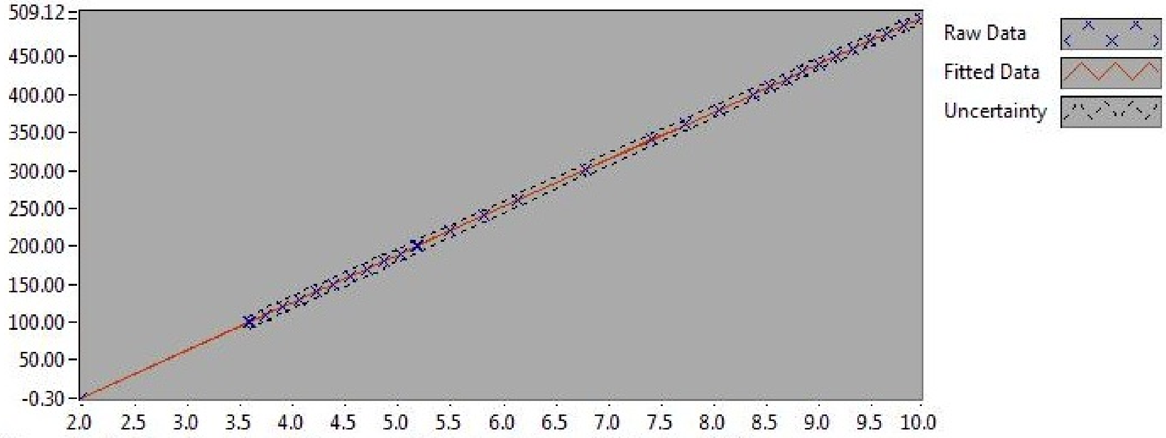
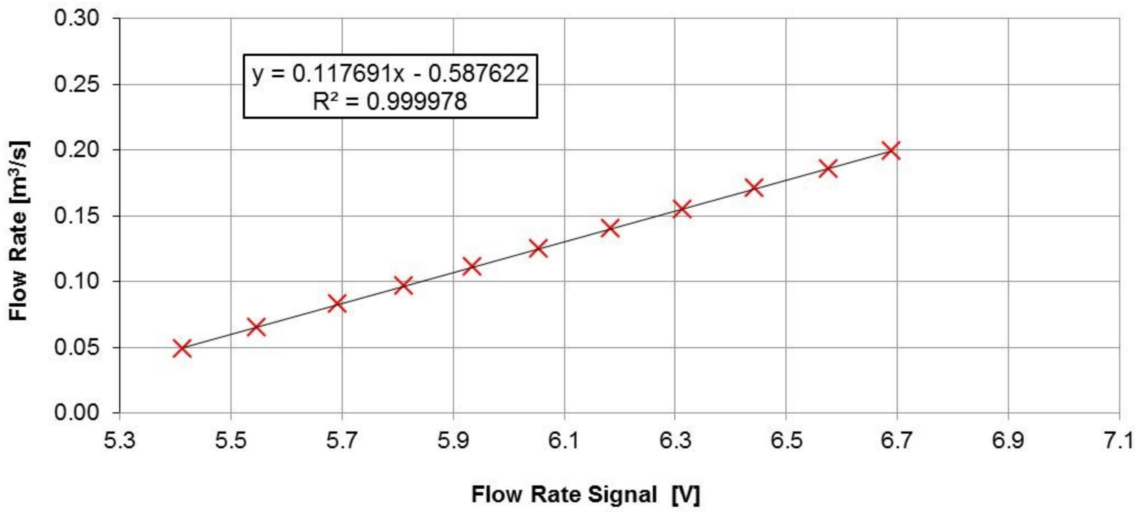
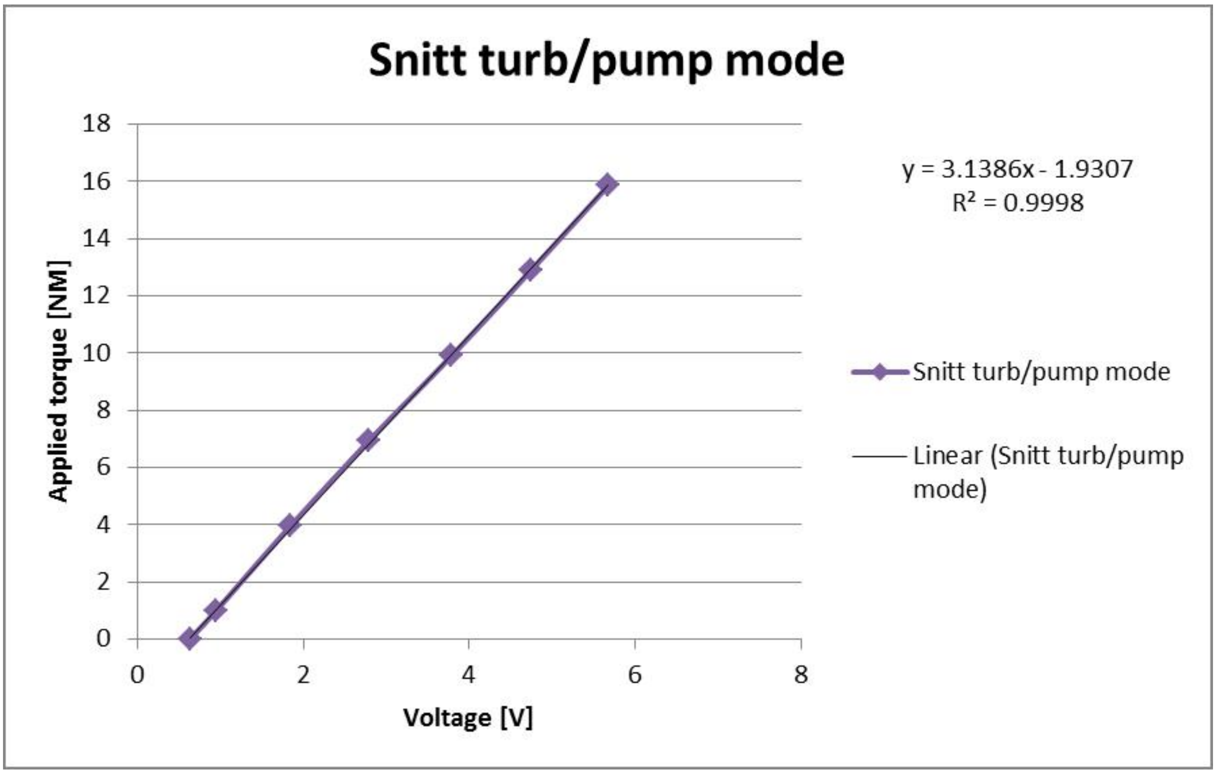


Figure 1 : Calibration chart (The uncertainty band is multiplied by 100)

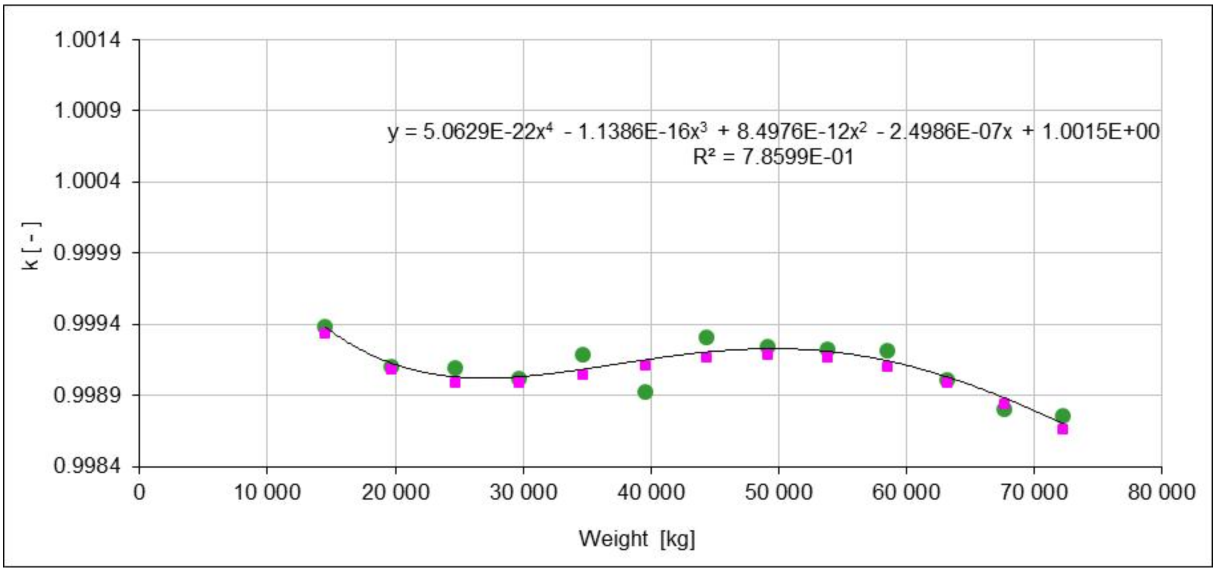
Flow meter



Friction torque load cell



Weighing tank



D Matlab codes for processing data

Examples of the matlab scripts used for processing data from the measurement series.

```
function[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(m,
ndata)

Q_snitt = zeros(m,1);
wTemp_snitt = zeros(m,1);
nGen_snitt = zeros(m,1);
H_snitt = zeros(m,1);
alpha_snitt = zeros(m,1);
etta_snitt = zeros(m,1);



for n= 1
    Q = ndata(n:n+42,1);
    wTemp = ndata(n:n+42,4);
    nGen = ndata(n:n+42,9);
    H = ndata(n:n+42,18);
    alpha = ndata(n:n+42,41);
    etta = ndata(n:n+42,21);

    Q_snitt(n,1)= mean(Q*(-1));
    wTemp_snitt(n,1)= mean(wTemp);
    nGen_snitt(n,1)= mean(nGen);
    H_snitt(n,1)= mean(H);
    alpha_snitt(n,1)= mean(alpha);
    etta_snitt(n,1)= -10000/mean(etta);
end
for n= 2:m
    a = (n-1)*45 +1;

    Q = ndata(a:a+42,1);
    wTemp = ndata(a:a+42,4);
    nGen = ndata(a:a+42,9);
    H = ndata(a:a+42,18);
    alpha = ndata(a:a+42,41);
    etta = ndata(a:a+42,21);

    Q_snitt(n,1)= mean(Q*(-1));
    wTemp_snitt(n,1)= mean(wTemp);
    nGen_snitt(n,1)= mean(nGen);
    H_snitt(n,1)= mean(H);
    alpha_snitt(n,1)= mean(alpha);
    etta_snitt(n,1)= -10000/mean(etta);
end
```

```
%ettaFP endring i virkningsgrad gjennom FP-serien

clear all;
clc;

[ndata] = xlsread('fp290rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(17,ndata);
plot(Q_snitt, etta_snitt)
axis([0 0.2 0 80])
xlabel('Q[m3/s]','fontsize',12)
ylabel('etta[%]','fontsize',12)
hold on
grid on

[ndata] = xlsread('fp320rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(19,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp350rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(21,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp380rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(22,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp410rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(25,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp440rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(27,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp470rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(29,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp500rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(31,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp530rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(34,ndata);
plot(Q_snitt, etta_snitt)

[ndata] = xlsread('fp560rpm_xlsx.xlsx'); %laster inn excel-filen
[Q_snitt wTemp_snitt nGen_snitt H_snitt alpha_snitt etta_snitt] = data_test2(36,ndata);
plot(Q_snitt, etta_snitt)
print -depsc ettaFP
```

E Experiment and unitcard

NTNU SINTEF

- **VEDLEGG K FORSØK PÅGÅR KORT**

Forsøk pågår!
Experiment in progress!

Dette kort skal settes opp før forsøk kan påbegynnes This card has to be posted before an experiment can start

Ansvarlig / Responsible Andrea Stranna	**Telefon jobb/mobil/hjemme** -/92462817/-
Operatører/Operators Andrea Stranna Tage Augustson Johanne Seierstad	**Forsøksperiode/Experiment time**(start – slutt) **24 September – 15 December 2012**
Prosjektleder Torbjørn Nielsen	**Prosjekt** **Model testing of a reversible pump turbine**

Model test of pump turbine. Taking measurements for a full Hill-diagram of the turbine in turbine mode. Taking measurements for a pump characteristic of the turbine in pump mode using the new energy dissipater or the feed pumps as energy dissipater.

NTNU
Institutt for energi og prosessteknikk

Dato 27/9- 2012

Signert Olav Bolland

SINTEF Energi
Avdeling energiprosesser

Dato

Signert

NTNU SINTEF

Annet						

- VEDLEGG J **APPARATURKORT UNITCARD**

Francis Rigg

Dette kortet SKAL henges godt synlig på apparaturen! *This card MUST be posted on a visible place on the unit!*

Faglig Ansvarlig Torbjørn Nielsen	**Telefon mobil/privat** 735 93572/91897572
Apparaturansvarlig Andrea Stranna	**Telefon mobil/privat** 92462817

Sikkerhetsrisikoer
High pressure oil and water
Rotating equipment

Sikkerhetsregler
Use safety glases.
Do not climb in the turbine!

Nødstopp prosedyre
Emergency shutdown of the feed pumps are located in the main laboratory control room, and on the laboratory first floor.

Her finner du (Here you will find):

Prosedyrer (Procedures) Andrea Stranna
Bruksanvisning (Users manual) Andrea Stranna

Nærmeste (nearest)

Brannslukningsapparat (fire extinguisher)	**I 1. og 2. etasje i Lab.**
Førstehjelpsskap (first aid cabinet)	**I 1. etasje ved trapp.**

NTNU
Institutt for energi og prosessteknikk

Dato 27/9- 2012

Signert Olav Bolland

SINTEF Energi
Avdeling energiprosesser

Dato

Signert