UNIVERSITETET I AGDER

Measurement & Analysis of Labyrinth Leakage in Francis Turbines

Marius Nesland Evensen & Gjøran Reinhardtsen

SUPERVISORS

Prof. Joao Leal

Johan Olav Brakestad

Ketil Homme

University of Agder, [2019]

Faculty of Engineering and Science

Abstract

This master's thesis is discussing the potential of measured leakage water from Francis turbines in Brokke and Holen power plants. There is a leakage that represent a loss, coming from the labyrinth seals in the turbines' runners (crown and band side), and this leakage will increase over time. For this report the leakage from the upper labyrinth side (crown) has been measured. The leakage is different between the four Francis turbines at Brokke and between the three Francis turbines at Holen power station. Portaflow 220B has been used, which is a flow instrument using ultrasonic sound. The measuring instrument was tested and verified before doing the measurements in the power plants. The test has been done on a swimming pool purification system, that has the same sized pipe as Brokke and Holen. This test was done in the Energy research project. The logging program, together with the Fuji Electrics Portaflow has been tested in this master's and also on the purification system at Spicheren. Comparing the measured results with the results from the purification system own measuring instrument, gives us an idea of how good the results from Portaflow 220B are. Different setups- and measuring points have also been tested, and the results showed that "reflex mode" makes the most reliable results together with measuring point nr. 2.

After the amount of leakage water was measured, the potential of this water was investigated. This potential is bigger than the compared values from other turbines that are presented in the literature. To see the total leakage loss for the turbines (both upper and lower leakage combined), the lower band side leakage had to be analyzed. This with the help of leakage relationships found in the literature.

The results of the measurement at Brokke and Holen show that turbine 4 at Brokke has the biggest amount of leakage, also when the results are compared with different power. The turbines at both Brokke and Holen show a pattern that follows the active power, due to the change in production water. The leakage is linear with the power change. Turbine 4 at Brokke can be seen as the worst graded turbine. This can be explained by multiple operational hours, and the eldest revision accomplished in 1998. Turbines 1 and 2 at both Brokke and Holen are stable in terms of leakage water compared with others found in the literature. Holen 3 did have a notable leakage, but in terms of the conditions for the high head turbine this potential is rated as a "healthier" turbine, than turbine 4.

Further investigation on solutions that could reduce the amount of leakage, specially from turbine 4 at Brokke would be interesting to look at in the further work on this topic. It will be a costly repair to change the turbine runner, and it is impossible to change operational pattern to pay attention to the leakage.

Preface

As master students we have been at the University of Agder for half a decade. At first, we took the bachelor's degree in renewable energy and electrical power engineering. We then continued with a master in renewable energy. This is our second year at the master and our final University year at University of Agder. This is the final report and the master thesis. The course is named ENE500 and contains of 30 ECT.

A big motivation for this task was to see how a power plant and high head Francis turbine worked in reality. The technology and machinery in a power plant are really impressive. To see how thing works and to do something practical, and not just theoretical work were also a big part of why we chose the project. Hopefully some of the results will be useful for Otrakraft DA.

We would like to send a big thank you to Otrakraft DA represented with Ketil Homme, Torstein Bjørgum and Åsulv Haugetveit, for giving us this opportunity to implement and answer such an exciting project task. Also, a big thanks for giving us the possibility to use and test the Portaflow 220B, and for several nice meetings.

We also have to thank our supervisors, Senior Engineer Johan Olav Brakestad and Professor Joao Leal for wonderful help to complete the master's thesis. They have helped us with both academic and practical work.

Reidar Trydal also needs a big thank you for giving us the operational parameters for all turbines at Brokke and Holen. This was crucial information for our analysis of the results.

Rainpower, Andritz, Agder Energi and IKM have given us useful information on the topic in our project, so they also need to be thanked.

University of Agder must also be thanked for lending us necessary equipment and thus helping us to complete the project and the master's degree within renewable energy.

Thanks for all your encouragement!

Marius Nesland Evensen & Gjøran Reinhardtsen

Grimstad, May 24th, 2019

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Notation

Table 1: Notation.

Symbol	Description	Unit
Q	Flow rate	m^3/s
Q_{LW}	Flow leakage water	l/s
$P_{Turbine}$	Power from turbine	W
P	Active effect	W
v	Speed	m/s
R	Resistance	Ω
U	Voltage	V
I	Current	A
n	Specific speed	rpm
f	Frequency	Hz
η	Efficiency	-
ω	Angular velocity	rad/s
p	Pressure	Pa
g	Gravitation constant	m/s^2
ρ	Density of water	kg/m^3
H	Head	m
A	Flow area/Area of the pipe cross-section	m^2
D	Diameter	M
M	Torque	Nm

1. Introduction

Hydropower as a renewable energy source has been important for many decades. Both in Norway and all over the world. Around 99 % of all power production in Norway comes from hydropower. On global basis 1/6 of the power produced comes from hydropower [1]. The majority of the power stations in Norway, were build and set in production for many decades ago. Some of the machinery have been rehabilitated or replaced, but there are still turbines with old parts in the machinery that has operated for years.

The Norwegian government has decided that it will be less development of hydropower stations in the future, but a greater focus on rehabilitation and to make the efficiency greater. It will require a lot of planning to maintain or rehabilitate a big Francis turbine or the generator in a hydropower plant. These are a highly costly operations and will stop the energy production from several months up to a whole year. It all comes down to selecting the perfect moment to implement the replacements. When should the turbine be replaced? How much money will be lost when stopping the machinery for a given time? For how long should a new turbine produce energy to earn in the lost money in the operation of replacement? These are all questions that must be answered before making any decision for replacements or rehabilitations in a hydropower plant.

The Francis turbine is an inward-flow reaction turbine that combines radial and axial flow concepts. Francis turbine are the most common water turbine in use today. They operate with net head of 40-600 meters and are primarily used for electrical power production. The generators that often are used together with Francis turbines can be from a few kilowatts to 800 MW. The speed range of the turbine is all from 75 to 1000 rpm [2].

The Francis turbine is a reaction turbine. The working fluid comes to the turbine under immense pressure and the energy is extracted by the turbine blades from the working fluid. A part of the energy is given up by the fluid because of pressure changes occurring in the blades of the turbine. The remaining part of the energy is extracted by the volute casing of the turbine. At the exit, water acts on the spinning cup-shaped runner features, leaving at low velocity and low swirl with very little kinetic or pressure energy left [2] and [3].

Francis turbines have a leakage loss from the corresponding labyrinth seals[1]. Both an upper and a lower leakage loss. This report investigates this loss (potential), through measuring and comparison with values found in scientific literature. See Fig. 2 in Chapter 1.2 for a better understanding of the report. The measuring took place at Brokke and Holen power plants in cooperation with Otrakraft and the University of Agder. In Chapter 1.3 the problem statements are presented. The scope of the report can be seen in Chapter 1.2, while a brief overview of the report structure can be seen in Chapter 1.4. This report is built up on the previous work done in the pre-master thesis project, named Energy research project. It can be found in [3].

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[1] See chapter 2 - "Theory" for underlaying theory, and understanding of the labyrinth leakage

1.1 Otrakraft DA

Otrakraft DA was established in 1960 and the headquarters are located in Rysstad in Valle municipality. The company is owned by Agder Energi (68,6 %) and Skagerak kraft (31,4 %). Otrakraft has three different power stations. The stations are Brokke, Holen and Skarg, and they have got 8 generators in total, which produces 2,7 TWh a year. This corresponds to 2 % of the total production in Norway [1].

In Fig. 1, an overview over the water reservoirs and the power plants is presented. The picture show that Urevatn and Vatnedalsdammen in the north are feeding Holen powerplant with water. Urevatn feeds one of the three turbines at Holen (Holen III), and Vatnedalsdammen two of those three (Holen I and II). The water that goes through Holen powerplant, drops into the Botsvatn. From Botsvatn the water goes through a tunnel down to Brokke powerplant. A further explanation on the different turbines, water reservoirs and tunnels from Brokke and Holen is presented in Chapter 1.1.1 and Chapter 1.1.2.

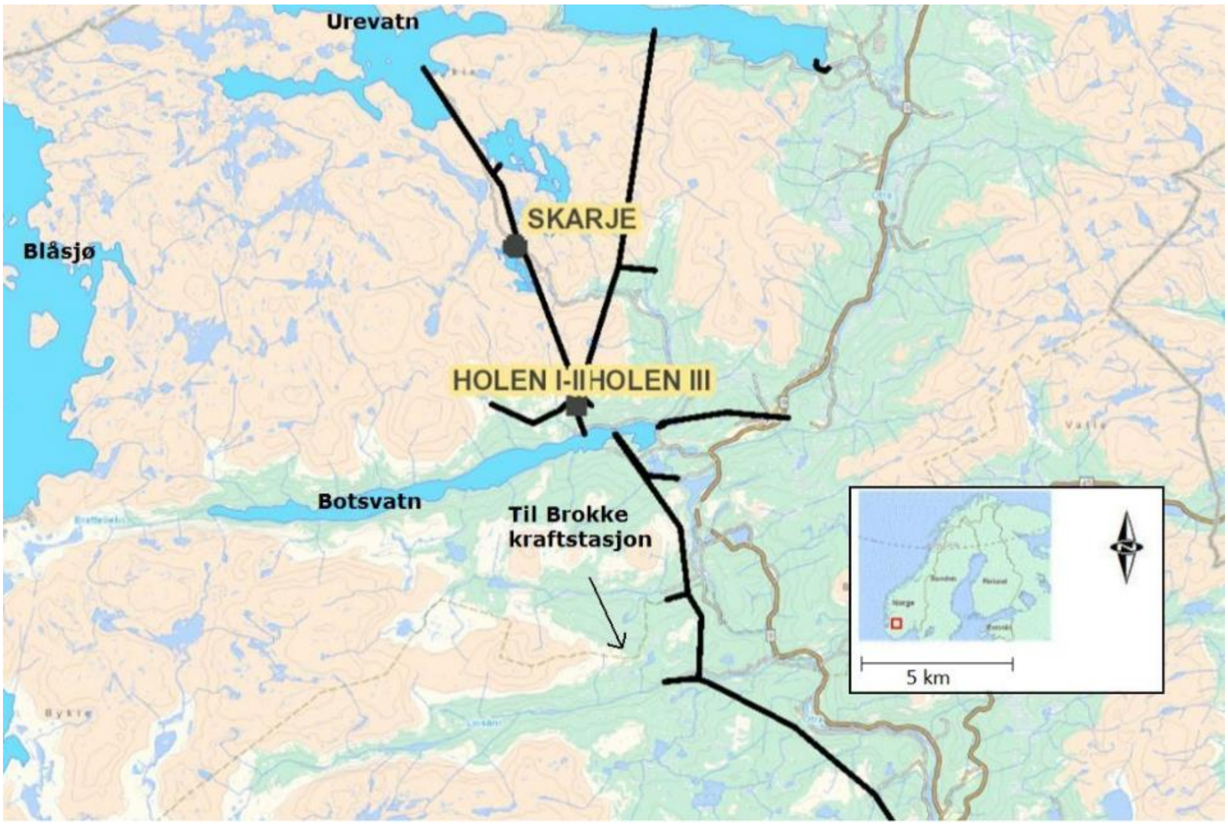


Figure 1: Overview from Holen and Brokke powerplant with associated water tunnels [4].

1.1.1 Brokke Power plant

Brokke power station contains four Francis turbines and four generators. The size of three of the generators are 100 MVA and the last generator is 140 MVA. The maximum fall height of the water is 303 meters and the minimum fall height is 244 meters. The water comes from Botsvatn and eleven streams along a 31 km tunnel. The production from this power station stands for half of the total energy production per year by Otrakraft. Three of the four turbines were put into operation in 1964/1965. The fourth and the last turbine was put into operation in 1976 [5].

It is also useful to know the number of hours per year with operation from the different turbines. This number is predicted to be the same on all turbines and approximately equal to 7000 hours operation per year for each and single turbine.

There has been some revision on the turbines. Table 2 is showing when the turbine runners in turbine 1, 2 and 3 were replaced. There have also been some repairs in the same turbines in 2015. The expected efficiency is 95 % for these three turbines. When it comes to turbine 4, there has been no rehabilitation or replacements, just small fixes. The last revision for this turbine were in 1998 and the expected efficiency is also 95% on this turbine [5].

Table 2: Aggregate information Brokke power plant.

Aggregate nr.	Size [MVA]	Last significant revision	Replacements
1	100	2004	Turbine runner
2	100	2006	Turbine runner
3	100	2007	Turbine runner
4	140	1998	Small fixes

1.1.2 Holen Power plant

Holen power station contains three Francis turbines and three generators. The size of two of the generators is 140 MVA and the third generator is 180 MVA. Turbine 1 and 2 takes water from Vatnedalsdammen and together with six other mountain streams. Vatnedalsdammen can be controlled between 840 to 700 meters above sea level. The magazine capacity is 1150 m^3 of water. The maximum fall height of the water is 316 meters and the minimum fall height is 149 meters. These two turbines were put into operation in 1981. Turbine 3 uses the water from Store Urevatn. There is also a pumping station, located at Skarjesvatn. The pumping stations pump water from Reinevatn and Skarjesvatn to Store Urevatn and then feeding turbine 3 with water. The maximum fall height of the water is 651 meters and the minimum fall height is 590 meters. This turbine was put into operation in 1986 [5].

When it comes to the number of hours with operation at Holen, there is a slightly difference between the three turbines (See Table 3), and all the values are well below the 7000 hours of Brokke turbines. From Table 3, turbine 3 operates with the lowest number of hours per year with 3000 hours. Turbines 1 and 2 operates with almost the same numbers of operation per year. These number may also be something to think about, when talking about maintenance and wear and tear over time.

Table 3: Overview of the number of hours with production per year.

Aggregate nr.	Amount of operation per year [h]
1	4500
2	4600
3	3000

There has been some revision on the turbines at Holen as well as Brokke. There have not been any big replacements at Holen. Back in 1998 there has been maintenance on turbine 1. The turbine has been checked visuality and some small fixes have been done. The same has been done with turbine 2 in 2003 and turbine 3 in 2008. This can also be seen in Table 4.

Table 4: Aggregate information Holen power plant.

Aggregate nr.	Size [MVA]	Last significant revision	Replacements
1	140	1998	Small fixes
2	140	2003	Small fixes
3	180	2008	Small fixes

1.2 Scope of the report

At first, the main purpose with this project, is to measure the labyrinth leakage water at Brokke and Holen power plants. Then further look at the potential of this water and check if the amount of leakage can tell something about the condition of the turbines. Further on, the percentage of the leakage versus production water is compared with written literature.

The flowmeter Portaflow 220B (PF220B) were picked to do the measurements in this project. To get to know the device and check its reliability, different reference measurements were done. A letter of calibration came together with the measuring device, but to make sure that it worked as it should, a test was performed at Spicheren swimming in Kristiansand [3]. At Spicheren, the pipes of the purification system had the same size as the pipes at Brokke and Holen. In this study additional testing was made at Spicheren, and results are presented in Chapter 4.4. In [3] the PF220B was tested without a logging program, and this because the device came without this function. In the present study, the logger has also been tested and results has been compared.

Energy research project [3], preceding the present study, was done during the autumn of 2018. In that project, measurements have been made from all four turbines at Brokke, but without a logger. The measurements took place for only 15 minutes per turbine and were done in one day. It was then difficult to make a comparison between the measured leakage water and different operational conditions, because the operational conditions such as active power, production water and vibration did not change significantly during that day. A simple economical potential from the leakage water was also estimated.

For this report a logging program has been developed, and further programmed for its purpose. The purpose of this program is to make measurements over a longer time and monitor the behavior of the leakage versus the operational conditions. The measurements have been done for a week on each turbine. This to check the behavior of the leakage with different operational conditions. In addition to the four turbines at Brokke powerplant, the leakage has also been measured on the three turbines at Holen power plant. Turbines 1 and 2 from Holen powerplant are on the same size as turbine 4 at Brokke. In the discussion (Chapter 7), it is interesting to compare those three turbines. The turbines at Holen also have more regular start/stop sequences during normal operation, than Brokke. Hence, it was possible to see how the labyrinth leakage behaves under a start/stop sequence.

In the results, the leakage behavior has been checked up against active power and production water. By comparing this between the different turbines, an analysis has been made. In the analysis the leakage in percentage has been investigated together with the leakage loss potential in lost economical potential. The results from both Brokke and Holen are discussed in the discussion chapter (Chapter 7). Maintenance and vibration are also discussed in this chapter, to come up with an answer on the amount of leakage from the different turbines. The results from the Energy research project has also been compared with the results from the present study. In the end, some conclusions are summarized along with further future work points.

The travelling distance between Brokke Powerplant and the University is approximately 170 km and a drive of 2,5 hours each road. The travelling distance to Holen is even longer with 3 hours each road and 200 km. Many hours of travelling were invested in this project. In total 7 turbines were surveyed, and measurements last for approximately 7 weeks. The measurements took place for one week per turbine. Lots of time was invested in this report for measurements, instrumental preparations, and traveling. The report writers also lived in Valle (next to Brokke and Holen power plants) for 1 whole week in a row, to join at the power plant for several days. The number of trips to the power plants is somewhere in between 10-12 times. Approximately around 60 hours of driving. There have also been some trips to the power plants, where there have been no results to collect, due to small technical errors.

In Fig. 2 an overview of the method used for the measuring and analysis of the labyrinth leakage water is presented.

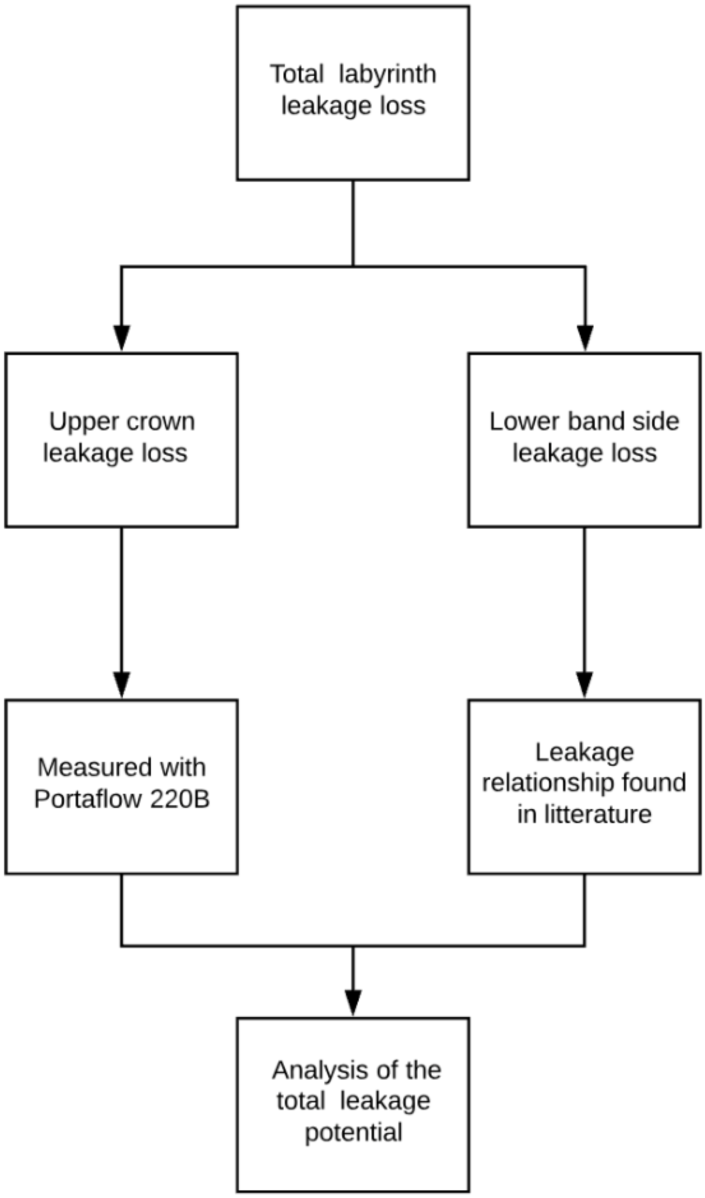


Figure 2: Overview of the report method.

1.3 Problem statements

In a Francis turbine, some of the water will go outside the turbine and through the labyrinths. This will always happen, but with time the leakage volume will increase. This extra leakage volume represents a loss. The leakage water comes from losses both under and over the turbine runner. It is not possible to measure the leakage that comes from the lower labyrinth in the turbines at Brokke and Holen power plants. This amount of leakage water follows directly to the drain. For this report, measurements of the upper leakage water from the crown side labyrinth will be presented. With help of the literature, different amounts of leakage water from the lower labyrinth will be analyzed. This to analyze the total amount of leakage water and further the potential of this water.

In Brokke power station located in Valle, there are different amounts of leakage water from the upper labyrinth seals, from the different turbines. In Table 5 Otrakraft have assumed the size of the leakage water for each turbine.

Table 5: Assumed amount of leakage Brokke Powerplant.

Turbine nr.	Leakage [l/s]
1	50
2	50
3	50
4	200

It is assumed that turbine 4 has the biggest amount of leakage with 200 l/s. This is also the oldest turbine. The overview of maintenance history was presented in the last chapter.

Turbines 1 and 2 at Holen powerplant have the same size as turbine 4 at Brokke powerplant. Therefore, it is assumed that turbine 1 and 2 has the same amount of leakage as turbine 4 at Brokke, with 200 l/s. Turbine 3 has the biggest head and use much less amount water than turbines 1 and 2 to produce the same amount of power or even more. The pressure is higher and there is a smaller amount of production water, so the assumed amount of leakage water is set to minimum or more than 200 l/s. The overview of maintenance history was presented in the chapter. This may have an impact on the amount of leakage that occurred and on the statements that are made for this task [5].

Table 6: Assumed amount of leakage Holen Powerplant.

Turbine nr.	Leakage [l/s]
1	200
2	200
3	≥ 200

Several statements have been made. There are plenty of steps that must be fulfilled to get the wanted results in this project. The main statements that have been carried out in this project, are presented underneath.

- Present a literature review for the given problem.
- Test and verify the measuring instrument PF220B for different flows and pipes.

- Development of a logging program to the measuring instrument PF220B and test and verify the program.
- Measure the amount of leakage water over time and investigate the potential of this loss.
- Compare the leakage loss from the different turbines at Brokke and Holen with different operational conditions and perform an analysis.
- Find the labyrinth leakage percentage of the production water and compare the results against percentages from literature.
- Make a plan on the further work regarding this topic.

1.4 Report structure

In this section, a summary for each section in the master thesis is presented. Each section is presented using the following bullet points.

- **Section 1 – Introduction**

This section presents the motivation together with the information about Otrakraft DA and their power plants. It also contains information about the turbines in the power plants. The scope for this project where the key points and the reason behind this project are presented. Further on the section the problem statements for this project are described.

- **Section 2 – Theory**

The underlaying theory for the report is presented in this section. This is important to make a foundation for the understanding of both Francis turbines, and the associated labyrinth leakage loss. Parts of this section were also presented in [3].

- **Section 3 – Previous work on the field**

In this section previous work on the field is presented. A literature review is presented to gain a scientific perspective of the problem, and presentation of relevant research on the field. For this report the literature review is crucial, since it is based on measurements only for the upper crown labyrinth leakage. When analyzing the total leakage, see eq. (1) the total (upper + lower), the lower labyrinth leakage is estimated with respect to the relations found in literature. This to get an understanding of the potential of the labyrinthic leakage loss.

The section also presents information and results from the Energy research project [3]. In the research project the measurements took place over a short period. In the master thesis the measurements are taken over longer time, so the results from both will be compared. This was important to present for the purpose of further analysis, and comparison with the latest results presented in this report.

- **Section 4 – Method: Instrumentation & Measurement**

This section presents the methods used for the report. Operation and reference measurements for the ultrasonic device, PF220B is central for deciding the certainty of the results and measuring. For long time monitoring of the Francis turbines a logging program had to be developed. This LabVIEW made program is presented, together with the associated instrumentation part of the report.

- **Section 5 – Results**

Section 5 of the report presents the results. The results are focused on long time measuring on both Brokke and Holen power plants. Long time measuring results from four separate Francis turbines at Brokke, and three Francis turbines at Holen are presented. Stability tests are also included. This was done to check the instant labyrinth leakage and its behavior over a short amount of time. Section 5 also includes results from both start and stop sequences for all three Francis turbines at Holen.

- **Section 6 – Analysis**

Section 6 of the report presents an analysis with the possibility to see the potential of the total labyrinth leakage on each turbine. The amount of leakage in percentage of production water is found in this section and compared with percentages from literature review. The results are also set into perspective and compared with operational data.

- **Section 7 – Discussion**

This section presents the discussion of the report. The results from the different turbines are compared and discussed in this section. The results of the analysis will be discussed and also some of the main statements will be answered in this section.

- **Section 8 – Conclusion/ Recommendations**

This section presents the concluding remarks for the report, and further recommendations. The concluding remarks are taken from the discussion and presents the answer of the different problem statements for this project.

- **Section 9 – Further work**

This section gives a tentative future plan on further work that can be carried out to analyze the problem statements. The further work part also presents the opportunities to get better or more accurate results in this project. It also presents possible solutions that could take this project further on and find more research material on the field.

2. Theory

2.1 Francis turbine

The Francis turbine is a type of reaction turbine. This is a category of turbine in which the working fluid comes to the turbine under immense pressure, and the energy is further extracted by the turbine blades from the working fluid.

A part of the energy is given up by the fluid. This is because of pressure changes that occur in the blades of the turbine, quantified by the expression of degree of reaction. The remaining part of the energy is lost due to friction in the volute casing of the turbine. At the exit, the water acts on the spinning cup-shaped runner features. The water leaves at a low velocity and low swirl with very little kinetic or pressure energy left. The turbine's exit tube (draft tube) is shaped to help decelerate the water flow and recover the pressure [6].

A perspective of an axial section through a Francis turbine can be seen in Fig. 3. A Francis turbine has the following main parts: spiral casing, guide and stay vanes, runner blades, draft tube.

The spiral casing around the runner of the turbine is known as the volute casing or scroll case. Throughout its length, it has numerous openings at regular intervals. This to allow the working fluid to impinge on the blades of the runner.

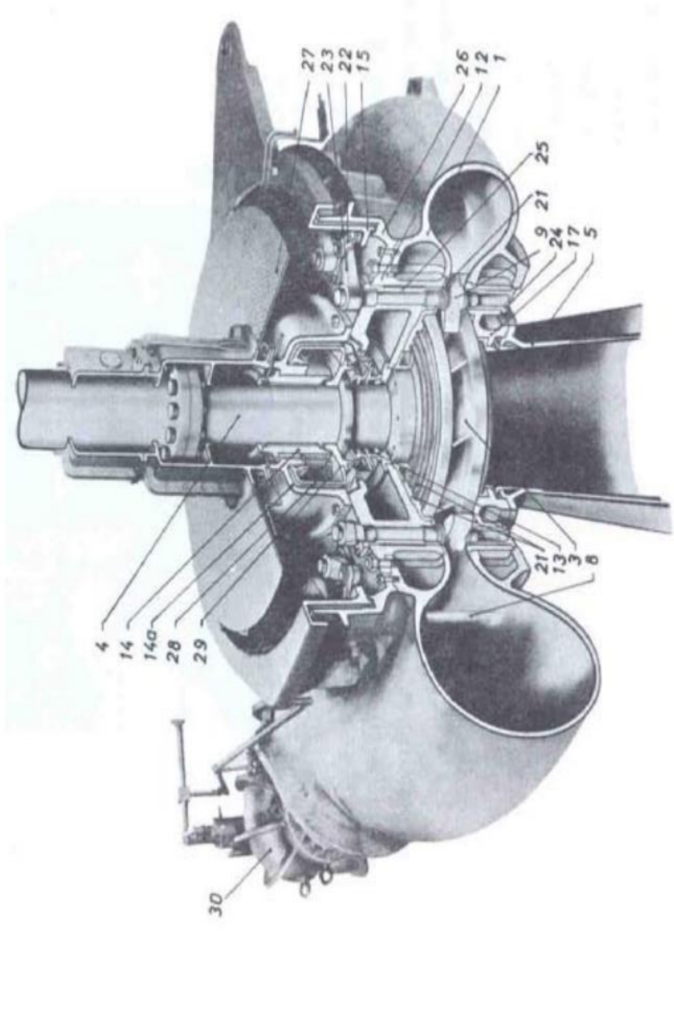
These openings convert the pressure energy of the fluid into kinetic energy, just before the fluid impinges on the blades. Thus, maintains a constant velocity despite the fact that numerous openings have been provided for the fluid to enter the blades, as the cross-sectional area of this casing decreases uniformly along the circumference.

The primary function of the guide and stay vanes is to convert the pressure energy of the fluid into the kinetic energy. It also serves to direct the flow at design angles to the runner blades.

Runner blades are the heart of any turbine. These are the centers where the fluid strikes, and the tangential force of the impact causes the shaft of the turbine to rotate, thus producing torque. A close attention in design of blade angles at inlet and outlet is necessary, as these are major parameters affecting power production.

The draft tube is a conduit that connects the runner exit to the tail race where the water is discharged from the power station. Its primary function is to reduce the velocity of discharged water to minimize the kinetic energy at the outlet. This permits the turbine to be set above the tail water without appreciable drop of available head [6] and [7].

Further descriptions about the Francis turbine and its components can be found in [6] , [7] and [8].



1. The scroll casing
3. Runner
4. Shaft
5. Draft tube cone
8. Stay vanes
9. Guide vanes
12. Upper cover
13. Sealing box
14. Guide bearing
14a. Bracket for the bearing(14)
15. Regulating ring
17. Lower cover
21. Replaceable wear and labyrinth rings
22. Link
23. Lever
24. Lower bearing for guide vane
25. Upper bearing for guide vane
26. Bearing for the regulating ring
27. Floor
28. Rotating oil cylinder
29. Oil scoop fastened to (14a) and (14) with the opening against the rotating oil in rotating oil cylinder (28)

Figure 3: Perspective of an axial section through a Francis turbine [8].

2.2 Labyrinth leakage in the runner seals

The main objective of the labyrinth seals is to reduce the leakage between the runner and the turbine covers. The runner seals also, due to its placement, balances the runner's axial forces for the upper turbine cover. In Norway it is common for high head Francis turbines over 80 meters to use the labyrinth leakage water for cooling water to the aggregate. In that case the labyrinth also acts like a filter to prevent sediments [7] and [8].

The runner seals are usually labyrinth type and consist of a rotating part and a static part. Fig. 4 shows the runner seals and its placement. The labyrinth (A) is the upper crown side labyrinth, while labyrinth (B) is the lower labyrinth on the band side.

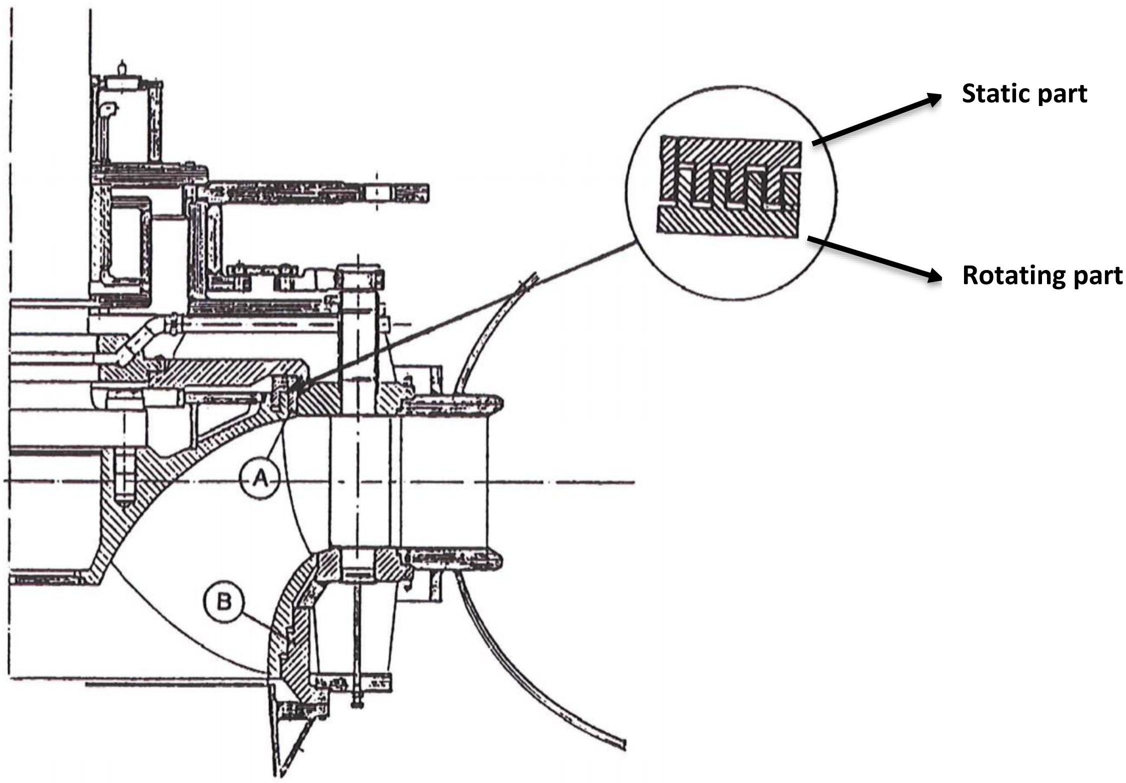


Figure 4: Illustration of the labyrinth seals for the runner [7].

Total volumetric leakage loss is given with the following relationship in eq. (1):

$$Leakage_{Total} = Leakage_{Crown/upper} + Leakage_{Band/lower} \quad (1)$$

The losses in the runner seals are mainly volumetric loss. These losses will decrease with an increased speed. Lower head also decreases the volumetric leakage, because the pressure get lower with lower head. The total flow through the runner will increase with a higher speed. This causes a lower volumetric flow loss relationship with the water in the runner. Through wear of the Francis turbine, the leakage will increase [7]. In Fig. 5 the labyrinth seals for both static and rotating parts are presented.

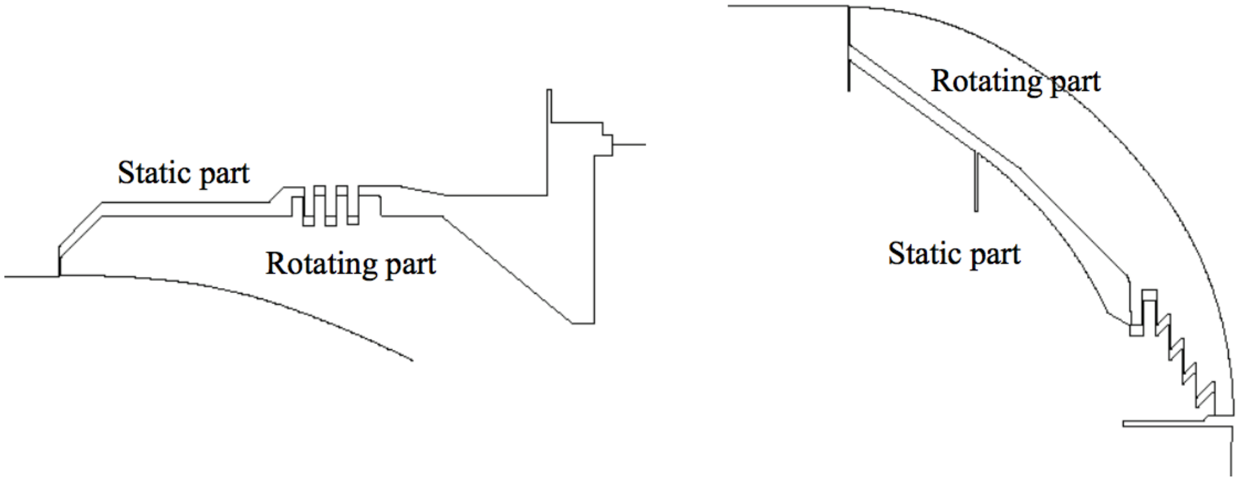


Figure 5: Runner seal on crown side and runner seal on band side [9].

Table 7 shows the causes, consequences, methods of testing and detection of wear/leakage in the labyrinth of the runner.

Table 7: Testing and detection of wear/leakage in labyrinth [10].

Causes	Possible consequences	Methods for testing and detection	Detection
- Erosion of sand - Corrosion - Cavity erosion - Mechanical wear and tear	- Reduction of efficiency - Increased mechanical strain on bearings - Increased amount of sand in the cooling water of the aggregate	- Measurement of leakage water from the labyrinth - Measurement of the gap in the labyrinth seals - Pressure measurement on the upper turbine cover - Visual inspection/sounds	- Increasing leakage water over time - Increasing gap in the labyrinth seals - Increasing pressure in the upper turbine cover - Increased temperature on the bearing strain - Visible signs of wear and tear. Such as scratches/pits/holes - Measurement of vibration

2.3 Pump plate

The pump plate consists of radial ribs welded to the upper rim of the turbine wheel. This can be seen in Fig. 6. The pump plate acts as a pump which helps to increase the pressure at the labyrinth's outlet and low pressure against the turbine shaft. Thus, the pump plate leads to less leakage through the labyrinths. The leakage water also gets filtered through the labyrinths, before it is pumped up into the cooling water pool. The pump plate is a Kværner design and is used at most the turbines and used at all the turbines at Brokke and Holen power plants.

The pump plate contributes to the following advantages [7]:

- Less leakage through the labyrinths
- Pump the leakage water up into the cooling water pool
- Prevents labyrinth wear
- Prevents wear on the shaft seal
- Axial force control
- Dry shaft coupling

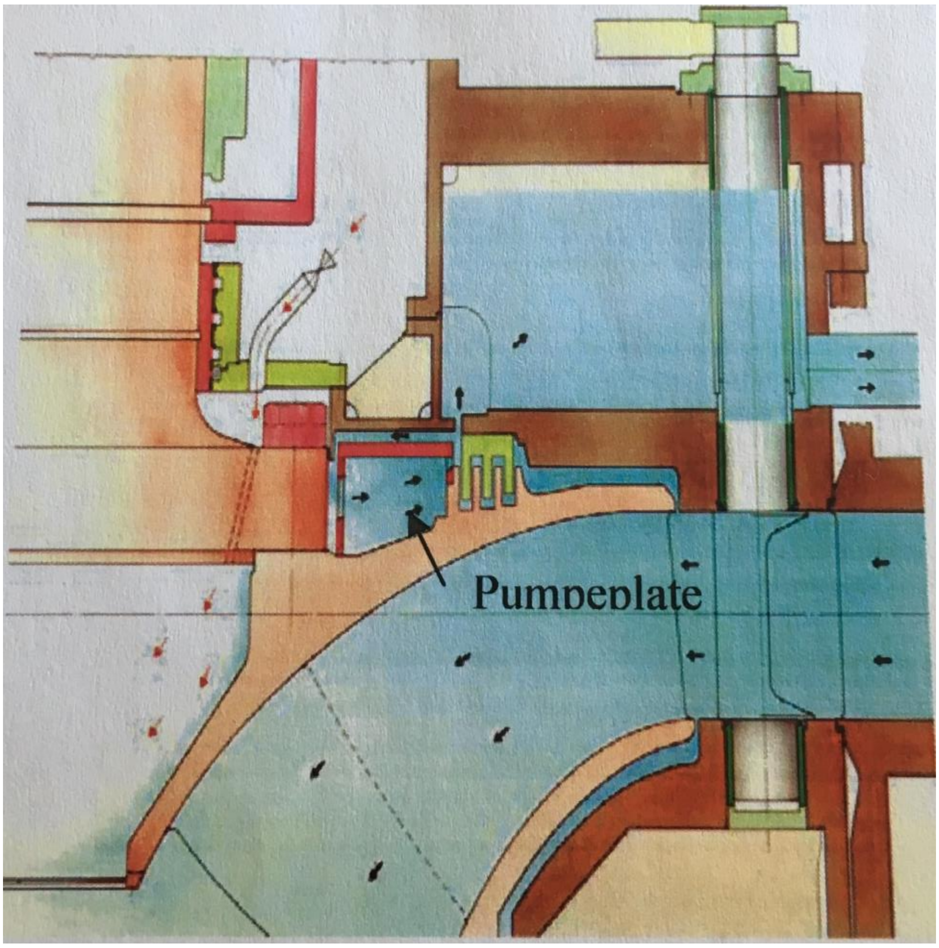


Figure 6: Pump plate principle [7].

2.4 Measurement of the labyrinth leakage in the runner seals

The two most used methods for measurement of the leakage are pitot measurement and ultrasound measurement. This report uses ultrasound measurement as preferred method. A further description of pitot measurement can be found in [7].

The water flow is calculated with the eq. (2):

$$Q = v * A \ \left[\frac{m^3}{s}\right] \tag{2}$$

Where:

v : Water flow speed in the leakage pipe [m/s].

A: Flow area in the leakage pipe [m^2].

The flow area is given with the following eq. (3):

$$A = \pi R^2 \ [m^2] \tag{3}$$

Where:

R: Inner radius of the pipe [m].

The operation of the ultrasound device is further described in Chapter 4.1.1. An ultrasound device calculates the velocity of the flow with the following eq. (4):

$$v = \frac{\Delta t}{t^{-2}} * \frac{L}{\cos\theta} \tag{4}$$

Where:

Δt: Difference in running time of the acoustic signals.

t: Time.

L: The distance along the transplant path from the transduce to rear pipe wall.

θ: Angle in relation to the flow path [7].

The relationship for the transducers, and context associated with eq. (4) that the device is based on can be seen in Fig. 7.

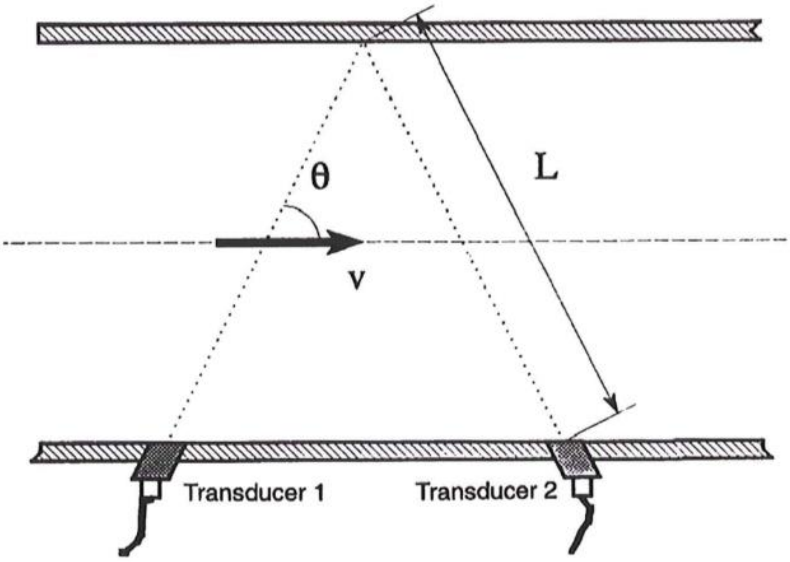


Figure 7: Relationship for the transducers [7].

3. Previous work on the field

3.1 Literature review

Labyrinth seals are the most common type of non-contact seal between the runner and the turbine covers. This is widely used in turbo-machinery, to suppress the leakage flow. Water leaking through a labyrinth will cause reduced efficiency since it will not be utilized by the runner. The leakage flow through the seals depends upon the size of the gap. For a new turbine the labyrinth gap will be small, and the leakage will be low. As the seals wear, the gap increases and so does the leakage. The labyrinth consists of two parts: a static seal connected to the covers and a rotating part connected to the runner [9]. Labyrinth seals are at present day, still the main seals for Francis turbines. There are some different types of labyrinth seals for runners, more information can be found in [11].

Cavitation[2] is considered as a phenomenon that wears the turbine over time. Thus, creates larger labyrinth losses. In [11] the effects on cavity number and cavity length for the leakage flow are presented. Where cavity number is the number of cracks that have occurred from the cavitation. It was presented that the leakage loss increases when the cavity depth increases, the leakage losses decrease when the length increases. Their results also show that the leakage losses decrease as the cavity number increases, when keeping the length of each cavity constant. When the cavity length increases, the leakage losses decrease when the total length is kept constant [11]. Other causes that may provoke leakage losses for the turbine is sand in the water, erosion of turbine parts [12], and tough operating conditions for the turbine over time, with continuous operation throughout the years [13]. Both vibration and pressure measurements have been proved to be important for both maintenance and rehabilitation of hydropower plants [10].

Much effort has been put into determination of volumetric and mechanical efficiencies due to losses and leakage behavior of Francis turbine. Some of the reports are found in [11], [12] and [14].

According to international standard for rehabilitation and performance improvement of hydraulic turbines found in [9], the internal mechanical losses may significantly lower down the efficiency of Francis turbines operating at low specific speed. This is shown graphically in Fig. 8, where the specific speed (N_q) is on the x-axis and the turbine efficiency (η) on the y-axis. It is possible to see how the losses are distributed. The specific speed can be calculated with eq. (21). This has been calculated for each turbine at Brokke and Holen in Chapter 6.1.

[2] Cavitation is the formation of vapour cavities in a liquid, small liquid-free zones ("bubbles" or "voids"), that are the consequence of forces acting upon the liquid. It usually occurs when a liquid is subjected to rapid changes of pressure that cause the formation of cavities in the liquid where the pressure is relatively low [28].

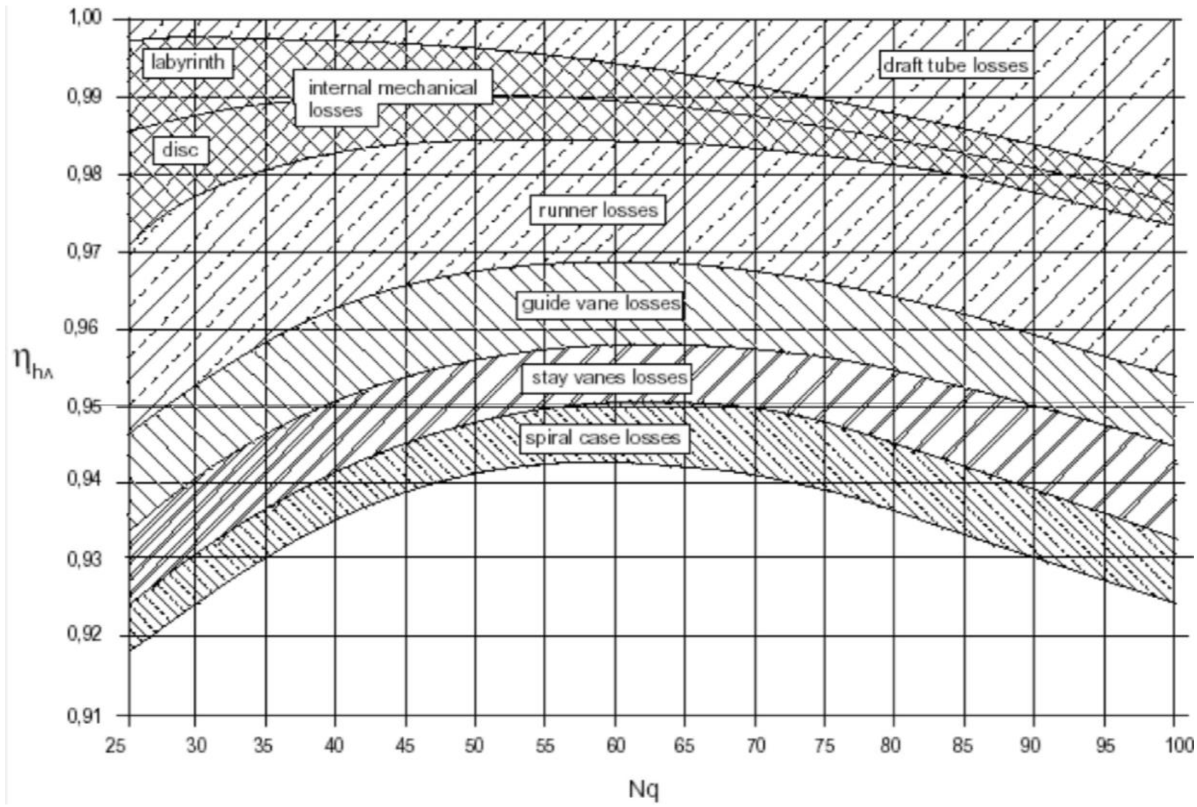


Figure 8: Plot of loss distribution at peak efficiency depending on the specific speed Nq for a wide range of model Francis turbines in [9].

It is possible to see how a new high head Francis turbine (i.e. with a low specific speed) with present time´s technology and standards will perform.

The labyrinth losses and disc friction losses contribute significantly to the turbine hydraulic losses in case when the specific speed N_q of a turbine is low. The turbine output is decreased due to labyrinth losses (friction losses and volumetric losses – water leakage) by the nearly constant value (*kW*) for the whole operating range of the turbine. Their relative importance in percentage decreases with the flow. If labyrinth losses represent e.g. 3 % at full load, they can be higher than 6 % at part load [9]. This is verified in [9] with numerical simulations compared with the measured values.

In [15] an analysis of the leakages associated with a low head Francis turbine is presented. The analysis was carried out with numerical simulations and compared with analytical calculated values. Numerical simulations of Francis turbines have been proved to be really accurate, this can also be seen in [14]. In [15] it is stated that the total leakage flow that passes the sealing region on the band side, and goes down the drain, is three times bigger than the loss from the labyrinth crown region. This relationship is shown to be the same with both simulation and analytical calculated values. In [7] the same losses are assumed to be the same for the band side sealing and the upper labyrinth loss on the crown. The estimation of the total leakage loss, both upper and lower, varies a lot in the literature. This must be considered in a loss analysis.

There are some analytical equations that are given to estimate the losses associated with the Francis turbine. The equations are given underneath and found in [15] and [16]:

$$\eta_{IEC} = \frac{P_{out}}{P_{in}} = \frac{M_{runner}*\omega}{\rho*g*Q*H_{net}} = \frac{M_{runner}*\omega}{\rho*g*Q*\left[\left(\frac{P_{stat-in}}{\rho*g} - \frac{1}{2*g}*\left(\frac{Q}{A_{in}}\right)^2\right) - \left(\frac{P_{stat-out}}{\rho*g} - \frac{1}{2*g}*\left(\frac{Q}{A_{out}}\right)^2\right)\right]} \quad (5)$$

$$\eta_{IEC} = 1 - \frac{\sum P_{Loss}}{P_{in}} = 1 - \frac{P_{Loss-SpiralCase}+P_{Loss-GuideVanes}+P_{Loss-Runner}+P_{Loss-DraftTube}+P_{Loss-Leakage}+P_{Loss-DiscFriction}}{P_{in}} \quad (6)$$

$$P_{Loss-SpiralCase} = \rho * g * Q_{Total} * H_{Loss-SpiralCase} = \rho * g * Q_{Total} * \left(\frac{p_{Total-SpiraInlet} - p_{Total-SpiralOutlet}}{\rho*g}\right) \quad (7)$$

$$P_{Loss-GuideVanes} = \rho * g * Q_{Total} * H_{Loss-GuideVanes} = \rho * g * Q_{Total} * \left(\frac{p_{Total-GuideVaneInlet} - p_{Total-GuideVaneOutlet}}{\rho*g}\right) \quad (8)$$

$$P_{Loss-Runner} = \rho * g * Q_{Total} * H_{Loss-Runner} = \rho * g * Q_{Total} * \left(\frac{p_{Total-RunnerInlet} - p_{Total-RunnerOutlet}}{\rho*g} - \frac{M_{Runner}*\omega}{\rho*g*Q_{runner}}\right) \quad (9)$$

$$P_{Loss-DraftTube} = \rho * g * Q_{Total} * H_{Loss-DraftTube} = \rho * g * Q_{Total} * \left(\frac{p_{Total-DraftTubeInlet} - p_{Total-DraftTubeOutlet}}{\rho*g}\right) \quad (10)$$

$$P_{Loss-Leakage} = \rho*g*(Q_{LeakageBand}+Q_{LeakageCrown})*H_{Runner} = \rho*g*(Q_{LeakageBand}+Q_{LeakageCrown})*\frac{M_{Runner}*\omega}{\rho*g*Q_{runner}} \quad (11)$$

$$P_{Loss-DiscFriction} = (M_{Friction-Band} + M_{Friction-Crown}) * \omega \quad (12)$$

Where:

ρ: Density of water $[kg/m^3]$.

g: Gravitation constant $[m/s^2]$.

Q: Flow rate $[m^3/s]$.

H: Head $[m]$.

p: Pressure $[Pa]$.

M: Torque $[Nm]$.

ω: Angular velocity $[rad/s]$.

P: Power [W].

For estimation and measuring of the leakage water for the Francis turbine, several options have been studied and further explained in [17] and [18]. These methods are: Velocity-area method, pressure-time (Gibson) method, tracer method, ultrasonic method (ultrasonic flow meters), and electromagnetic method (electromagnetic flow meters). From [17] it can be seen that measuring the leakage water with ultrasound can be seen as reliable. For this report the reliability of this measuring device will be further investigated [3].

In [19] a thermodynamic method used to test the efficiency on a high head plant can be seen. With the help of such an efficiency test with inlet and outlet temperatures close to the labyrinth, a certain estimation of the lower labyrinthic leakage could be done.

3.2 Energy Research Project

This chapter specifies the main essence and results that this master thesis is built upon from the pre-master thesis, called "Energy Research Project" from 2018. The report can be found in [3]. In the Energy research project, the following topics were studied:

- Underlaying theory associated to the labyrinth leakage problem.
- Testing and verification of the PF220B.
- Measurements of the upper (crown) labyrinth leakage loss at turbine 1, 2, 3 and 4 at Brokke power plant
- Planning and learning how to build a logger in LabVIEW. This for the purpose of analyzing the labyrinth leakage over time.
- Analysis with comparison between the amount of leakage water in percentage of the total production water, compared with literature. Cost analysis including the total loss in cost.

During the Energy research project, it was important to check the reliability of the PF220B. Thus, it has also been an important matter throughout this report. In Chapter 4.4 a further verification of the PF220B has been done together with the testing and verification from the Energy research project.

At the 26th October 2018, the authors of this report did a measuring sequence to estimate the upper leakage (crown) from the labyrinths at all four turbines at Brokke power plant. The input parameters for the PF220B can be seen in Table 8.

Table 8: Input parameters PF220B.

Parameters	Values
Pipe outside diameter	205 mm
Pipe wall thickness	2.00 mm
Pipe wall material	Stainless steel 316
Fluid type	Water
Fluid temperature	6.00 °C
Sensor mode	Reflex
Sensor separation distance	106.09 mm

When measuring the leakage on the different turbines it was important to have approximately the same conditions and the same measuring point. Different measuring points have been tested on the turbines and this is shown, together with the preferred measuring point in appendix C.2.

3.2.1 Results

In Table 9, the results of the average value of the measurements from turbine 1-4 are presented. It can be seen that the leakage water that has been measured is very stable at the selected measuring point. This is also confirmed in Fig. 9, where plots from the leakage water per turbine is presented.

Table 9: Results of measurements from the turbines at Brokke.

Measurement	Turbine 1 $\overline{(l/s)}$	Turbine 2 $\overline{(l/s)}$	Turbine 3 $\overline{(l/s)}$	Turbine 4 $\overline{(l/s)}$
1	40.7	43.8	66.8	136.0
2	40.8	43.5	65.6	135.6
3	40.7	43.8	65.9	136.0
4	41.0	44.1	66.4	136.1
5	41.3	43.7	66.2	135.7
6	40.9	43.6	65.9	135.8
7	41.0	43.6	66.0	135.9
8	40.9	43.4	66.0	135.5
9	40.9	43.2	66.4	135.4
10	41.2	43.8	66.1	135.0
11	41.1	44.0	66.0	135.3
12	40.7	43.8	66.5	135.1
13	40.7	43.8	66.4	135.7
14	41.1	43.7	66.0	135.2
15	40.6	43.9	66.0	135.2

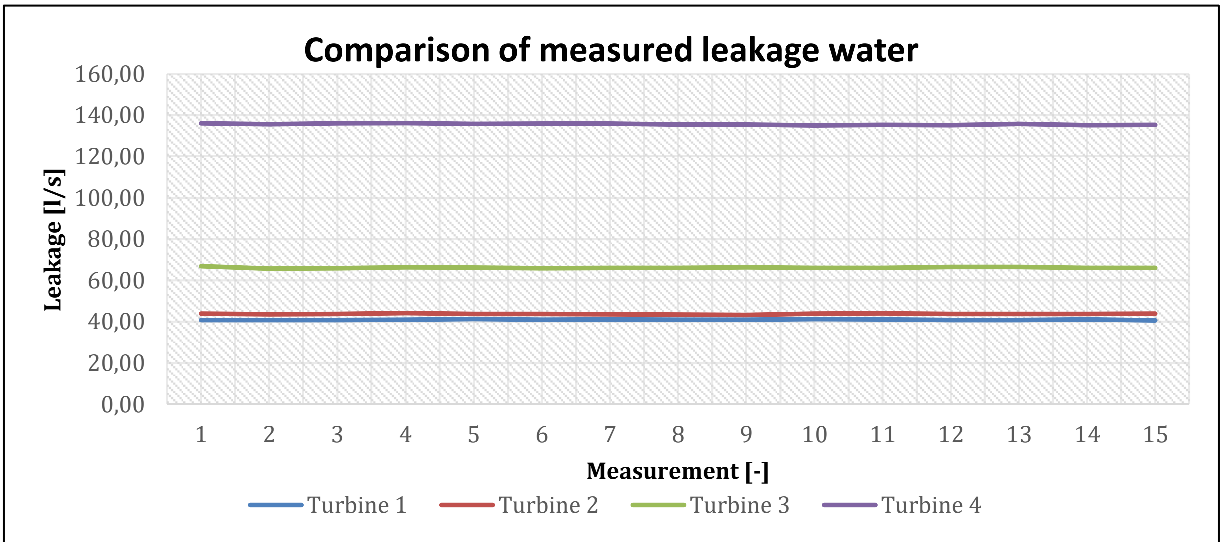


Figure 9: Comparison of measured leakage water.

The plots above confirm that the choice of measuring point has been good. The plots look very stable over the fifteen tests and are also an indication on how the operational conditions was when the measurements took place. Because the almost constant amount of leakage, corresponds to operational conditions on every one of the four turbines which were the same in the measurement intervals.

In Table 10, the average values of the measured leakage water from all tests are presented. The biggest loss came from the biggest turbine, and that loss was an average value of 135.6 [l/s]. There was also a significant loss from turbine 3 and the losses from turbines 1 and 2 were lower and about the same value.

Table 10: Average values of measurements from turbines.

Turbine nr.	Average $\overline{(l/s)}$
1	40.9
2	43.7
3	66.1
4	135.6

Some of the operational parameters that where measured on the different turbines are presented in Table 11 together with active power produced by the turbine and generator. The power is similar for turbines 1, 2 and 3. The biggest turbine was producing nearly 80 MW. Some of the calculations and measurements from the Energy research project can also be seen in appendix D.2.

Table 11: Different operational parameters from the different turbines.

	Turbine 1	Turbine 2	Turbine 3	Turbine 4
Power [~MW]	60.7	60.2	59.2	78.4
Load [~%]	63.9	61	67.4	64
Speed [~RPM]	375	375	375	375
Average Leakage [l/s]	40.9	43.7	66.1	135.6

3.2.2 Analysis

An estimation of the total leakage for both upper and lower labyrinth leakage is found to be varying in the literature, see last column in Table 12. Therefore, an economic analysis has been carried out, to see how the potential varies with the different possibilities. For the analysis the following cases were considered and shown in Table 12.

Table 12: Analysis of the different cases.

Case	Leakage relation for lower labyrinth loss	Literature
1	Only the upper leakage (crown) is considered. Measured water at Brokke.	-
2	The lower leakage (band) is in the same size as the crown.	[7] and [8]
3	The lower leakage is twice the size as the upper leakage.	-
4	The lower leakage is three times the size as the upper leakage	[15]

In Table 13 a comparison of the total leakage (both upper and lower leakage) from all turbines combined versus the annual production can be seen.

For the calculations done in Table 13, an annual power production from Brokke is assumed to be 1462 million kWh [5]. As seen, it varies with the different cases. There is a big difference from case 1 to 4 with almost 1 % in difference from case 1 compared to case 4.

Table 13: Comparison of total leakage vs. Annual power production at Brokke.

Case	Total leakage loss vs. Annual power production [%]
1	0.35
2	0.70
3	1.05
4	1.40

4. Method: Instrumentation & Measurement

4.1 Portaflow 220B

The flowmeter PF220B is designed to work with clamp-on transducers to enable the flow of a liquid within a closed pipe to be measured accurately without needing to insert any mechanical parts through the pipe wall or protrude into the flow system. Using ultrasonic transit time teqniques, the PF220B is controlled by a micro-processor or system which contains a wide range of data that enables it to be used with pipes with an outside diameter ranging from 13 mm up to 1000 mm and constructed of almost any material. The instrument will also operate over a wide range of fluid temperatures.

The flowmeter can be used to measure clean liquids or oils that have less than 3 % by volume of particulate content. Cloudy liquids such as river water and effluent can be measured along with cleaner liquids such as demineralized water [20].

4.1.1 Operation and Functionality

When ultrasound is transmitted through a liquid the speed at which the sound travels through the liquid is accelerated slightly if it is transmitted in the same direction as the liquid flow and decelerated slightly if transmitted against it. The difference in time taken by the sound waves to travel the same distance but in opposite directions is therefore directly proportional to the flow velocity of the liquid.

The PF220B system employs two ultrasonic transducers attached to the pipe carrying the liquid and compares the time taken to transmit an ultrasound signal in each direction. If the sound characteristics of the fluid are known, the microprocessor can use the results of the transit time calculations to compute the fluid flow velocity. Once the flow velocity is known the volumetric flow can be easily calculated for a given pipe diameter, assuming uniform velocity distribution.

The PF220B system can be set up to operate in one of four modes determined mainly by the pipe diameter and the transducer set in use. It is reflex mode, reflex mode double bounce, reflex mode triple bounce and diagonal mode. Detailed description of the different modes is presented in Fig. 48 in appendix A.1.

The PF220B does also have a totalizer function. This allows to sum up measurements over time. It is difficult to just read of the measurements taken at 2 Hz sampling frequency looking on the screen. When the measurements are totalized for a minute for instance, it is easier to get a more precise average value of the flow measurements.

The PF220B also comes with a letter of calibration. This letter is presented in Fig. 53 in appendix A.3. [20].

4.2 Development of logging program for the PF220B in LabVIEW

Through the testing of the PF220B, it was found that the logging function associated with the instrument did not fit this report's needs. For a better logging and data processing an own logging program had to be developed using a computer program named LabVIEW. More information and the manual for LabVIEW can be found in [21].

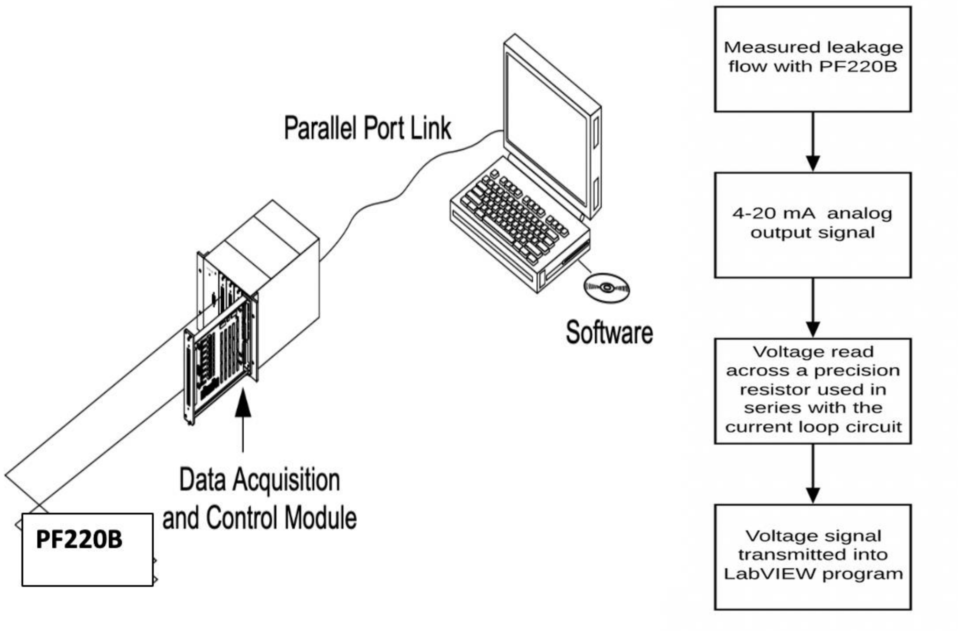


Figure 10: Connection between PF220B, control module and software from computer together with a simple flow chart [22].

The PF220B supports the possibility of creating an output 4-20 mA pulse signal. The 4-20 mA loop has been an industry standard for many years. The 4-20 mA loop has a variety of uses including digital communications, control applications, and reading remote sensors [22]. The setup for the logging can be seen in Fig. 10 and with further description in [22]. For the connection setup the information found in appendix B.

For the programming in LabVIEW the following block scheme gives a simplified description of the signal processing:

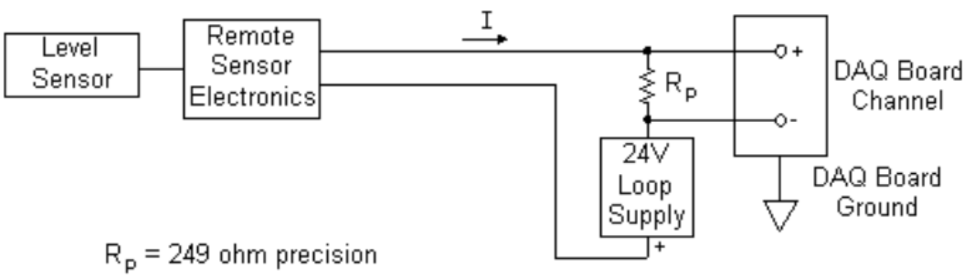


Figure 11: LabVIEW circuit chart [22].

For the conversion from the current [mA] signal to [l/min] the following relationship (also described in Fig. 46 in appendix A.1.) has been used [20]:

$$Flow\ rate\ \left[\frac{Liters}{minut}\right] = \frac{I*(Flow\ rate_{max} - Flow\ rate_{min})}{16} + Flow\ rate_{min} \tag{13}$$

With the formula above it is possible to calculate the flow rate [l/min] for the measured output current pulse signal from the PF220B.

For the purpose of the report it has been used a DAQ device that only supported voltage signals. Since the DAQ device cannot directly measure current, the voltage is read across a precision resistor used in series with the current loop circuit (Fig. 11). The resistance had a value at 240 Ω. To get the most accurate voltage signal up within the limit of 5 V, a resistance of 249/250 Ω would be more preferable. This has been proved to be very accurate in [22]. See appendix B.3 for both setup and equipment used.

To convert the voltage signal into LabVIEW Ohm's formula was used to convert the voltage signal to current:

$$I_{(mA)} = \frac{V_{(Volts)}}{R_{(k\Omega)}} \tag{14}$$

With eq. (14) the following voltage limitations can be seen in Table 14.

Table 14: Voltage limits.

Max Voltage	Min Voltage
4.8 V	0.96 V

Eq. (14) was used so it was possible to use the linear relationship from [mA] –> [l/min]. An overview of the programming scheme in LabVIEW can be seen in Fig. 12.

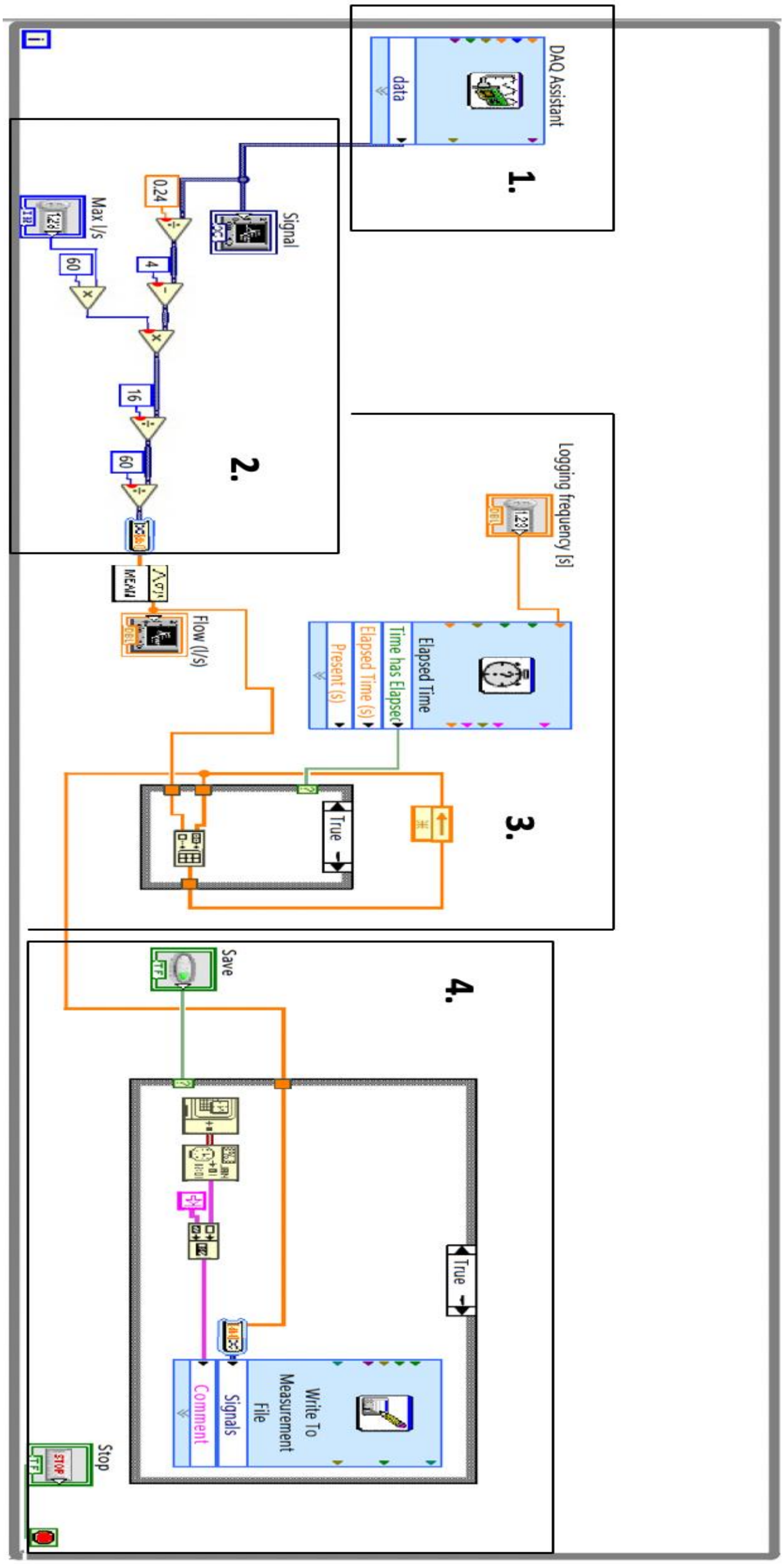


Figure 12: Programming scheme in LabVIEW with numbered functions.

The program is fitted in a "While loop", this is for the purpose of continuous measurement. The DAQ assistant (programming block Nr.1 in Fig. 12) is a function that handles the input voltage signal from the DAQ device connected to the computer. In the DAQ assistant function, a maximum voltage of 4.8 V is set, and the minimum voltage is set to 0.96 V. These values have been calculated with the help of Ohm's law.

The signal is further handled with the eqs. (13) and (14) (programming block Nr.2 in Fig. 12) to get the actual signal to [l/min]. This signal is further calculated to [l/s]. When running the program, it is desirable to input the supposed maximum leakage, this to get an even more accurate conversion of the current [mA] to flow [l/min]. As seen in eq. (13) the conversion formula depends on the maximum flow. This can easily be adjusted after needs in the control screen.

The programming scheme "Mean function" calculates the mean of the signal, and this can be further seen on the control screen. This function is used to prevent a noisy signal. After the current signal is transformed to the physical size [l/s], the actual flow can be read from the control screen (see Fig. 13). The "Logging frequency" part, (programming block Nr.3 in Fig. 12) is programmed to decide when the logging should be done. This can be a handy function, when logging data series over days and weeks. For instance, it is then possible to log values every minute, hour, day and so on. This can save memory space for the computer, and not get to large data series. This part is connected to the last part of the programing scheme (programming block Nr.4 in Fig. 12). Hence makes it possible to save the data to a text file with an associated time and date stamp. This is an important part of the logger. Since it is a desire to compare the measuring results with different operational data. The time and date stamp make it possible to get an accurate comparison.

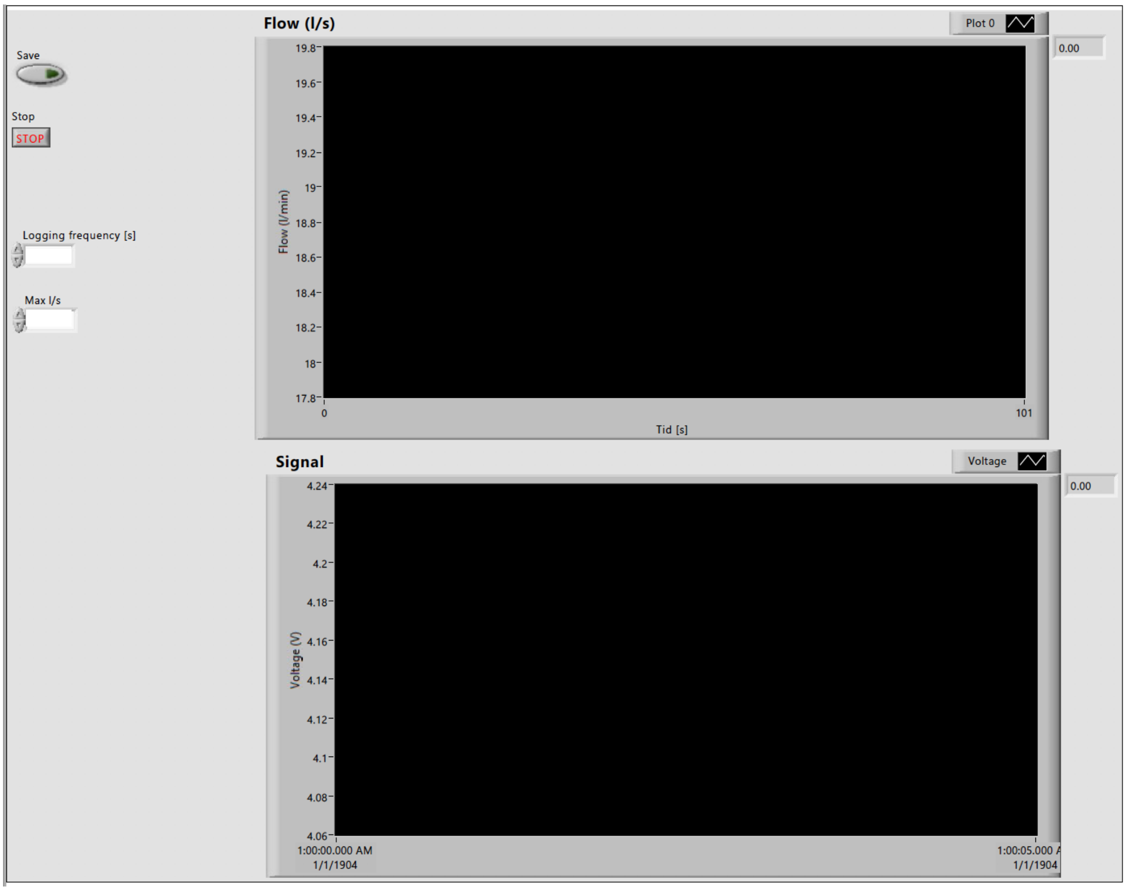


Figure 13: Control screen of the LabVIEW program.

As seen from the control screen, the actual flow can be observed in a graph presenting the flow [l/s] and the actual measuring time. The "Save" button is programmed to save the desired flow measurements from the PF220 to a data file. The date and time can be set to an accuracy of a tent of a second. The voltage signal from the DAQ can also be studied on the control screen. A validation of the logging program can be seen in Chapter 4.4.3. When processing the data file from the program, both Matlab and Excel were used. Matlab was preferred for larger files than Excel. Both programs were capable to process the numbers in a suited way for this report.

4.3 Measurement uncertainty

Measurement is the assignment of a number to a characteristic of an object or event, which can be compared with other objects or events. The scope and application of measurement are dependent on the context and discipline [23]. This report is very dependent on measuring of a volumetric leakage. A big part of this report and the Energy research project have been validation of the PF220B. This to make reliability of the measured results. As seen in Chapter 4.4 – Reference measurements, the PF220B has been compared with different instruments, pipes, fluid flows and measuring points. All to validate and give high reliability of the results (In appendix A.3 the letter of calibration for the PF220B is also given). Through all the measuring done in this report, it has always been an aim to have as similar conditions as possible. In terms of instrumentation, measuring point and logging program set up. Hence make it possible to compare and see the correlation.

For this report meter readings are very important to be reflected on. When comparing results and measurements from different instruments, different meter readings may occur. To prevent mistakes, measurements have been done multiple times. As seen in appendix C.3 stability testing of the leakage was carried out. Thus, it was possible to get a sounder understanding of the behavior of the leakage. With help of the logger it was possible to study the leakage over time, which was important to see the leakage behavior. The LabVIEW logger also included some average filtering. Averaging has been important for this report.

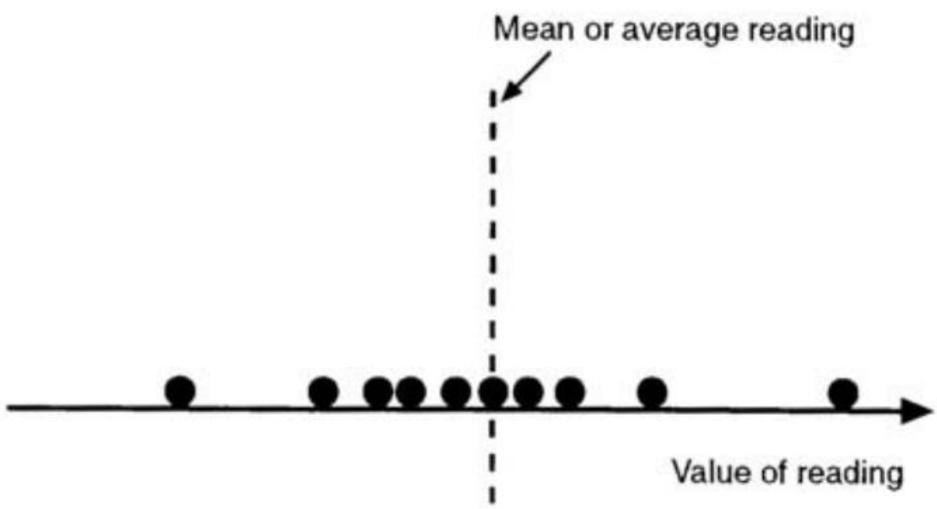


Figure 14: Average of data.

4.4 Reference measurements Spicheren swimming

It is beneficial to perform both assembly and testing of the PF220B. It is hard to find a monitored pipe with the flow close to 200 [l/s]. Spicheren swimming do have a purification system for both the swimming pool and the whirlpool. In this system there are instruments that measure the flow. Therefore, there is the possibility to compare the flow from the instruments there, with the measurements from the PF220B. This is to get a scale or a reference on the measurements. The results of the measurements are presented in Tables 17 and 18 and in Chapter 4.4.1.

To validate and make sure that the measurements from PF220B are reliable, the Fuji Electrics Portaflow has also been tested at Spicheren. This type of Fuji Electrics Portaflow only support small pipes. This device has been tested on the purification system for that whirlpool. The dimension of the pipes is smaller on this system. The results from this measurement are presented in Table 19 and in chapter 4.4.2. In the same chapter, a comparison between the PF220B and the Fuji Electrics Portaflow are presented.

To get measurements that last for a longer period, a logging program have been developed in this study. It is also important to know that this logging program, produces the correct values in the measurements. Therefore, a test with PF220B and the logging program from LabVIEW has been done. This is presented in chapter 4.4.3 together with a comparison between the PF220B and the PF220B with logging program. This is to check the reliability of the device and logger that are used for the measurements in this project.

4.4.1 Portaflow 220B test swimming pool and whirlpool

The first test that has been done, is with the purification system for the swimming pool. The size of the pipe is almost the same as in Brokke and Holen, but at the swimming pool the setup has a plastic pipe a bit thicker. The parameters that were put into the PF220B are listed up in Table 15.

Table 15: Input parameters PF220B swimming pool.

Parameters	Values
Pipe outside diameter	200 mm
Pipe wall thickness	8.00 mm
Pipe wall material	Plastic
Fluid type	Water
Fluid temperature	27.5°C
Sensor mode	Reflex
Sensor separation distance	109.56 mm

After the test on the purification system for the swimming pool, the test on the system for the whirlpool was done. The size of the pipe is almost half as big as the pipe used for the swimming pool. The input parameters are listed up in Table 16.

Table 16: Input parameters PF220B whirlpool.

Parameters	Values
Pipe outside diameter	90 mm
Pipe wall thickness	4.30 mm
Pipe wall material	Plastic
Fluid type	Water
Fluid temperature	37.5°C
Sensor mode	Reflex
Sensor separation distance	94.67 mm

Fig. 63 in appendix C.1.6 shows where the transducers were attached on the pipe and also the instruments existing at Spicheren to measure the flow in the pipe. The totalizer function in the PF220B was used and tested over several different time intervals. The flow then gets summed up over the time that has been selected, and then divided on that amount of time to get the average value of that singular measurement. The test has been done with time intervals 1, 5, 15, 30 and 60 seconds. The reason for this, is to find the best or the better intervals to use in our measurement. In Tables 17 and 18, the results for the swimming pool and whirlpool are presented. The results for time intervals 30 sec and 60 sec give the least deviations. The deviation was found using eq. (15). Therefore, those time intervals give the most reliable results and were adopted herein.

Through the test it was also cleared out that with a pipe of approximately 200 mm in diameter, it is reasonable to set the transducers in reflex mode. For a pipe at that size, diagonal mode was also considered. The results for the test showed that the reflex mode gave a better signal, better setup and more reasonable numbers.

$$Deviation[\%] = \frac{Q_{Spicheren} - Q_{PF220B}}{Q_{Spicheren}} * 100 \quad (15)$$

Table 17: Average values from test with different time intervals, including the deviation swimming pool.

Test interval	1 sec	5 sec	15 sec	30 sec	60 sec
Average value PF220B [l/s]	22.6	22.6	23.0	22.7	22.6
Average value Spicheren instrument [l/s]	25.3	24.6	24.3	24.0	23.8
Deviation [%]	10.7	8.1	5.3	5.4	5.0

Table 18: Average values from test with different time intervals, including the deviation whirlpool.

Test interval	30 sec	60 sec
Average value PF220B [l/s]	5.4	5.5
Average value Spicheren instrument [l/s]	6.4	6.1
Deviation [%]	15.6	9.8

4.4.2 Fuji Electrics Portaflow test whirlpool

After the decision to use time intervals 30 sec and 60 sec in chapter 4.4.1, these intervals have been used in the test of the Fuji Electrics Portaflow and in the test between PF220B and PF220B with logger. The test has the same input parameters as in Table 16. The method used here is the same as explained in the last chapter. The results are presented in Table 19 and show that they are almost similar for the two devices. The deviation between the instrument at Spicheren and the Fuji Electrics Portaflow with interval of 30 sec is 1.6 % bigger than the same with the PF220B. At 60 sec intervals, the deviation is also bigger for the Fuji Electrics Portaflow with 1.7 %.

Table 19: Average values from test with deviation between PF220B and Fuji Electrics Portaflow.

Test interval	30 sec	60 sec
Average value Fuji Electrics Portaflow [l/s]	5.3	5.4
Average value PF220B [l/s]	5.4	5.5
Average value Spicheren instrument [l/s]	6.4	6.1
Deviation Fuji Electrics Portaflow [%]	17.2	11.5
Deviation PF220B [%]	15.6	9.8
Deviation between them [%]	-1.6	-1.7

4.4.3 Portaflow 220B logger test

This test has the same input parameters as in Table 15. The results are presented in Table 20 and show that they are almost the same for the two devices. The results show that the deviation between the instrument at Spicheren and both PF220B and PF220B with logger is the same for interval 60 sec. With time interval 30 sec, the deviation between PF220B with logger and the instrument at Spicheren, is bigger than the PF220B, with deviation at 6.3%, versus 5.4%. All the three tests show that PF220B is reliable, and the same for the logging program that was developed in LabVIEW.

Table 20: Average values from test with deviation between PF220B and PF220B with logger.

Test interval	30 sec	60 sec
Average value PF220B [l/s]	22.7	22.6
Average value PF220B with logger [l/s]	22.5	22.6
Average value Spicheren instrument [l/s]	24.0	23.8
Deviation PF220B [%]	5.4	5.0
Deviation PF220B with logger [%]	6.3	5.0
Deviation between them [%]	-0.9	0

4.5 Brokke and Holen setup for operational parameters

A purpose of this report is to compare the leakage water from each turbine with the associated operational parameters at the different power plants. This to see how the leakage behaves. The operational parameters presented in this report are collected from Otrakraft. They have a monitoring system which includes data logging and computing of some operational parameters. Both at Brokke and Holen power plants, although at Holen it is only possible to collect active power and production water.

In Table 21 an overview of the parameters used in this report can be seen. Formulas for calculations can be seen in the analysis Chapter 6.

Table 21: Operational parameters.

Operational parameter	Calculated/measured
Active Power [MW]	Measured
Production water [m^3/s]	Calculated
Vibration low. guide bearing [mm/s]	Measured

The Francis turbines are equipped with vibration sensors for monitoring. The sensors are named "b & k vibro vs-068", and can be seen in Fig. 15, and the associated data scheme can be seen in [24]. The data are collected from the sensors to a computer (see Fig. 16).

Figure 15: Vibration sensors for Francis turbines, together with its placement [24].

When the operational data were collected from the operational center from Otrakraft/ Agder Energi, it was possible to get hours, minutes or seconds for data resolution. Due to the different resolutions and limitations, the data processing and analysis were a time demanding part of this report.

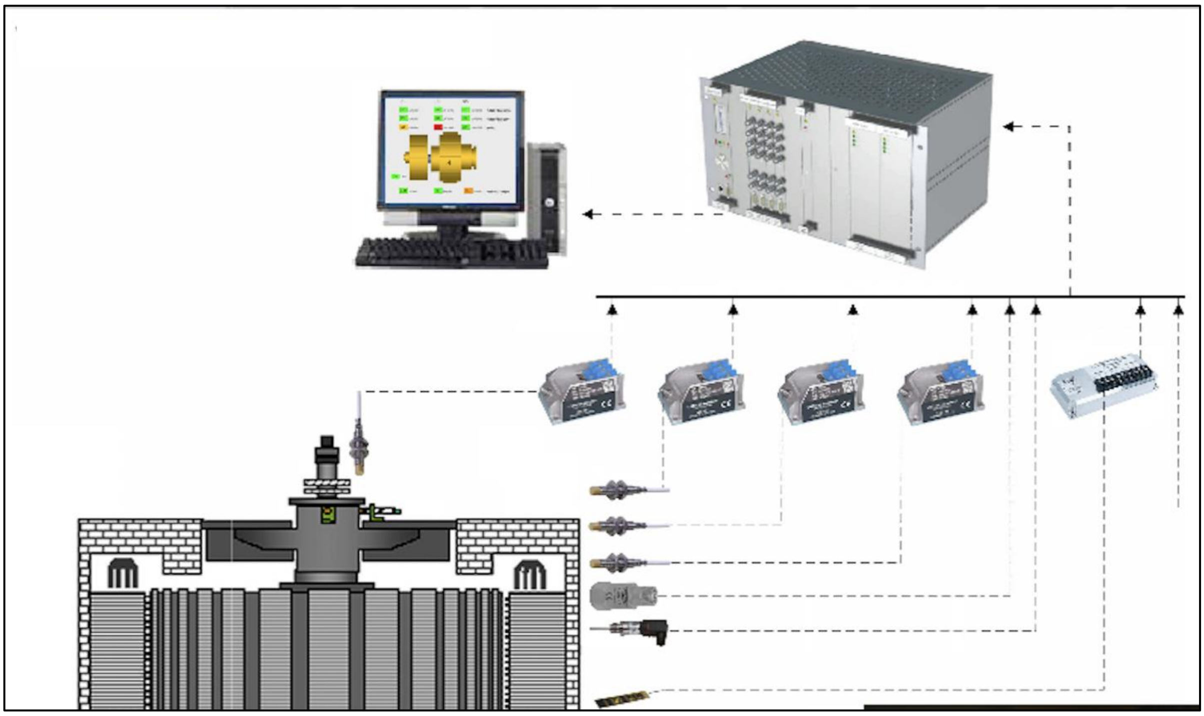


Figure 16: Placement of sensors and how the data get collected.

In Fig. 17 the placement of the sensor is illustrated. The different measuring points are marked with numbers. Sensor 1 is the measuring point that this report has focused on due to its placement. This point is closest to the leakage pipe, and therefore with interest to the correlation.

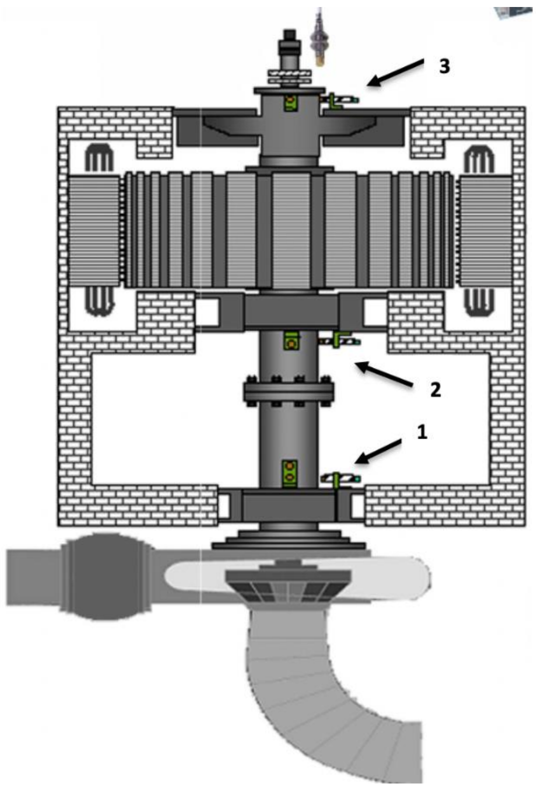


Figure 17: Placement of vibration sensors.

5. Results

5.1 Preparations for measurement at Brokke and Holen power plants

After several tests at Spicheren, some real testing on the leakage water from the upper labyrinth seals at Brokke and Holen power stations was carried out. In Table 22, an overview of the trips to the power stations is presented. The measurements have been done for a week per turbine at both Brokke and Holen. The logging frequency in the logging program was set to collect a value every second for a whole week. The reason for this is to be assured that any start/stop sequence would be collected if they occur.

Table 22: Overview over visits and measurements done at Brokke and Holen.

Machinery/Location	Date	Type of measurement	Logging frequency
Turbine 1 Brokke	8-15. March	Long time	1 sec
Turbine 2 Brokke	30. January – 6. February	Long time	1 sec
Turbine 3 Brokke	23-30. January	Long time	1 sec
Turbine 4 Brokke	16-23. January	Long time	1 sec
Turbine 1 Holen	20-27. February	Long time + start/stop	1 sec
Turbine 2 Holen	8-15. February	Long time + start/stop	1 sec
Turbine 3 Holen	19-26. March	Long time + start/stop	1 sec

The input parameters in the PF220B are shown in Table 23 and the same input parameters are used for all the turbines. The differences between the tests at Spicheren and the tests at Brokke and Holen, are among other things the pipe material, which is in stainless steel for the later. Also, the material thickness and fluid temperature have changed substantial from the tests at Spicheren.

Table 23: Input parameters PF220B.

Parameters	Values
Pipe outside diameter	205 mm
Pipe wall thickness	2.00 mm
Pipe wall material	Stainless steel 316
Fluid type	Water
Fluid temperature	4.00 °C
Sensor mode	Reflex
Sensor separation distance	106.09 mm

There were two alternative different places to attach the transducers on the turbines. To find the best spot, a test was performed and tested on turbine 4 at Brokke before starting on the real measurements. Otrakraft wanted to mount the transducers close to the output of this pipe. In this area there was a lot of vibrations in the pipe. The other area to mount the transducers was about to meters from the first point. At that location there were no noticeable vibrations. In Figs. 65-67 in appendix C.2.2, pictures of the installation measuring points are shown.

The results of these measurements on selecting the measuring point location are shown in appendix C.2.1. It can be seen that the flow is much more unstable and changing between the measurements at measuring point nr. 1. Comparing with measuring point nr. 2, the flow is higher and much more stable.

With the results from the measurements done in the different locations on the pipe, a conclusion is made. The values from measuring point nr. 2 are more stable and also the closest to the assumptions made by Otrakraft. The selected measuring point is then selected for all the turbines, both at Brokke and Holen. The whole test can be seen in appendix C.2.

After the test to select the best measuring point location was done, it was a need for a stability test. This test was done on all four turbines at Brokke before starting up the longtime measurements. This test was done to select the average interval that would be used in analyzing the measurements. The results of this test can be found in appendix C.3.

After all the tests, the measurements started up on the turbines. Over several week the measurements were done. After the measurements on each turbine, the operational data for that time of measurement was collected. The data came in resolution on 60 sec per value at Brokke and per second at Holen. The reason for getting the operational data in 60 sec is described in the stability test. At Holen it was interesting to get the operation data in second to check out the start/stop sequence. As mentioned in Chapter 4.5, the different data is active power, production water and vibration. This type of data is just possible to get out at Brokke. At Holen there is only logged data for active power and production water.

Further on, the measured labyrinth leakage will be compared against different active powers. This will be presented in tables and plots for each group of active power. This is done to check out if there is a connection between leakage and increased active power. The same thing is also looked at trough the vibration, to see if higher vibrations will produce more leakage water. There will also be presented a plot showing how the leakage water and active power behaves in the measurements on all turbines. This also to draw parallels between the labyrinth leakage and active power. It will be very interesting to see if the leakage curve increases when the curve for active power does the same.

5.2 Results and measurements Brokke power plant

5.2.1 Turbine 1

Fig. 18 clearly shows that there is a connection between the active power and leakage water on turbine 1 at Brokke. Those two curves follow each other, and when the active power reaches above 60 MW, the amount of leakage goes up to 44 l/s.

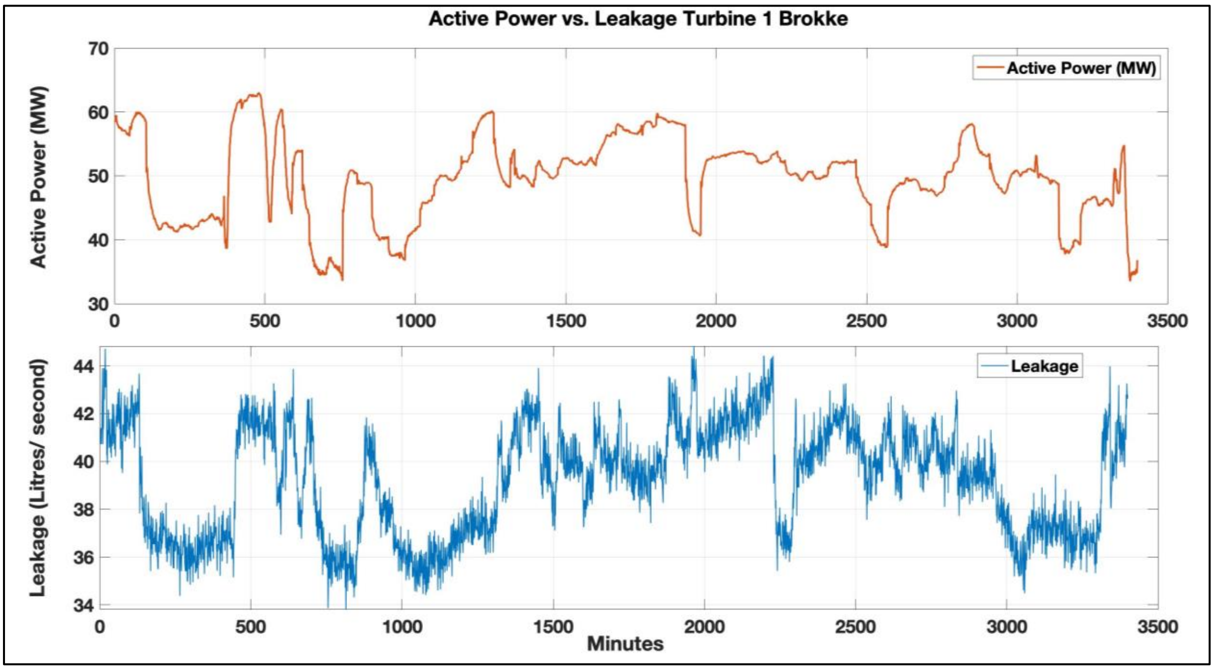


Figure 18: Active power vs. leakage turbine 1 Brokke.

In Table 24, average values of leakage, production water and vibration for different active power intervals are presented. For this turbine is it easy to see that all these parameters increase with increasing power. The leakage variation is approximately around 6 liters between minimum and maximum power. There is also an increase in the vibration with the increase in active power. In Table 69 in appendix E.1, a complete table is presented.

Table 24: Average values with different groups of active power from turbine 1 Brokke.

Active Power [MW]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
35-40	35.8	15.9	0.103
41-45	36.7	19.0	0.107
46-50	38.1	21.9	0.112
51-55	39.9	23.7	0.117
56-60	41.4	25.8	0.127

Fig. 19 shows the same results as Table 24. Generally, the higher active power, the higher is the leakage.

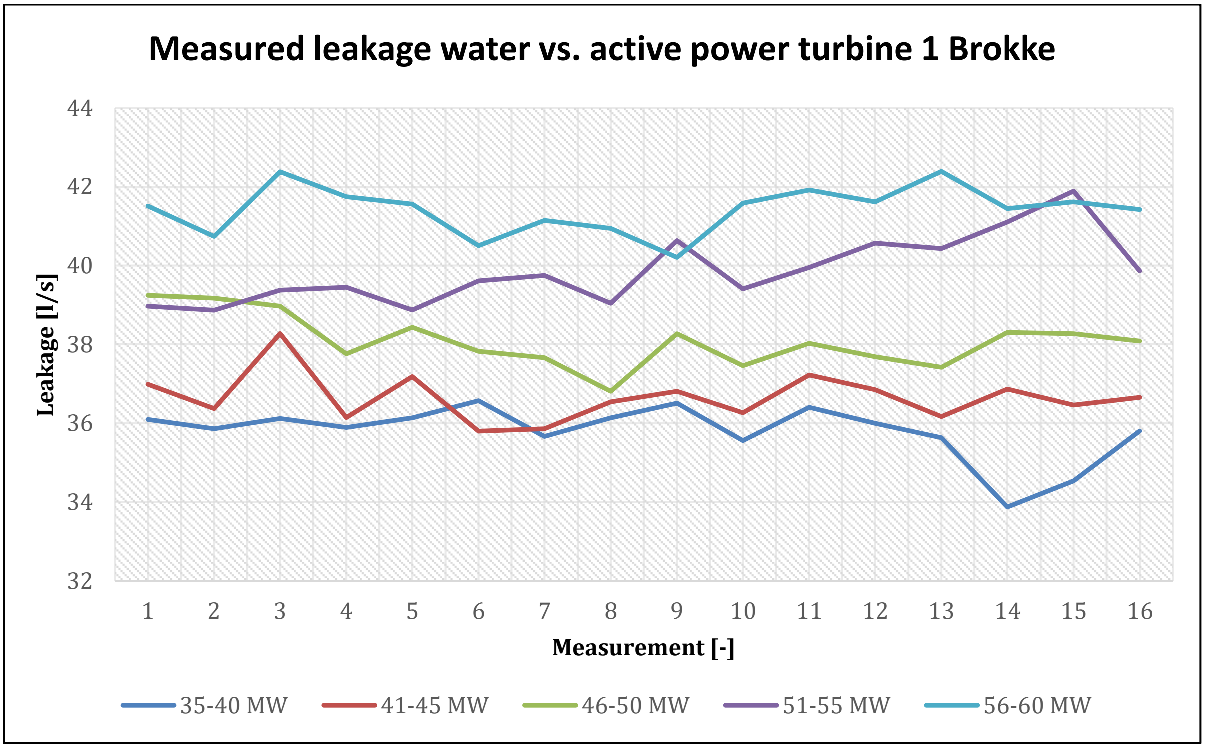


Figure 19: Measured leakage water vs. active power turbine 1 Brokke.

5.2.2 Turbine 2

In Fig. 20, the curve for both active power and leakage are plotted for turbine 2 at Brokke. The maximum leakage reaches almost 48 l/s when the active power is nearly 70 MW. There is a connection between them, but from 500 to 1500 minutes, the leakage does not follow the pattern when active power increases. One of the reasons, may be wrong timing between the curves. When comparing the active power with the leakage, there was a resolution problem. It was not possible to get the active power for the same time period as the measured leakage. It is recommended to make a new comparison in the further work for turbine 2 at Brokke.

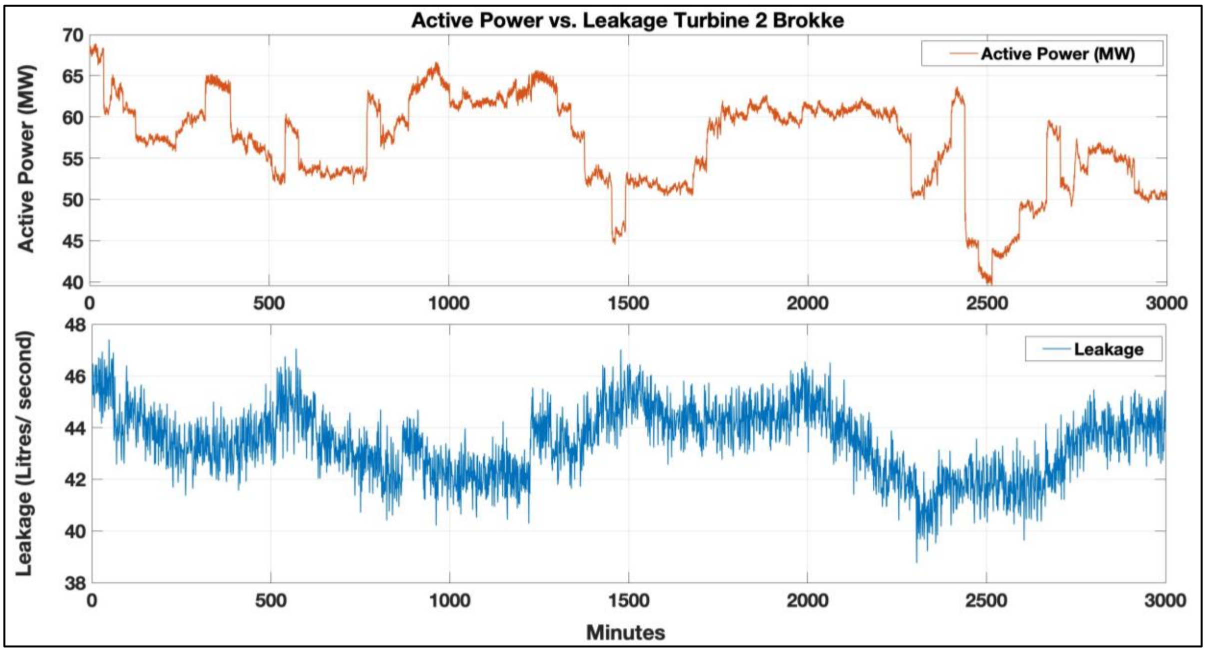


Figure 20: Active power vs. leakage turbine 2 Brokke.

In Table 25, average values of leakage, production water and vibration for different active power intervals are presented. For this turbine both the production water and leakage increase with increasing power. When it comes to the vibration, it varies a lot, and both decrease and increase with higher power. The leakage variation is approximately around 5 liters between min and max power. The amount of production water increases with approximately 10 m^3 from the lowest active power to the highest active power. The same trend as for turbine 1 (see Table 24). In appendix E.1 in Table 70, a complete table is presented.

Table 25: Average values with different groups of active power from turbine 2 Brokke.

Active Power [MW]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
45-50	40.5	19.0	0.189
51-55	42.1	22.5	0.182
56-60	43.2	24.3	0.161
61-65	43.7	26.9	0.179
66-70	45.9	28.9	0.193

Fig. 21 shows the same results as Table 25. The higher active power, the higher is the leakage. The labyrinth leakage is almost the same for both interval 56-60 MW and 61-65 MW. There is a bigger jump from the lower interval with 45-50 MW to 51-55 MW, and the same is it for interval 61-65 MW to 66-70 MW.

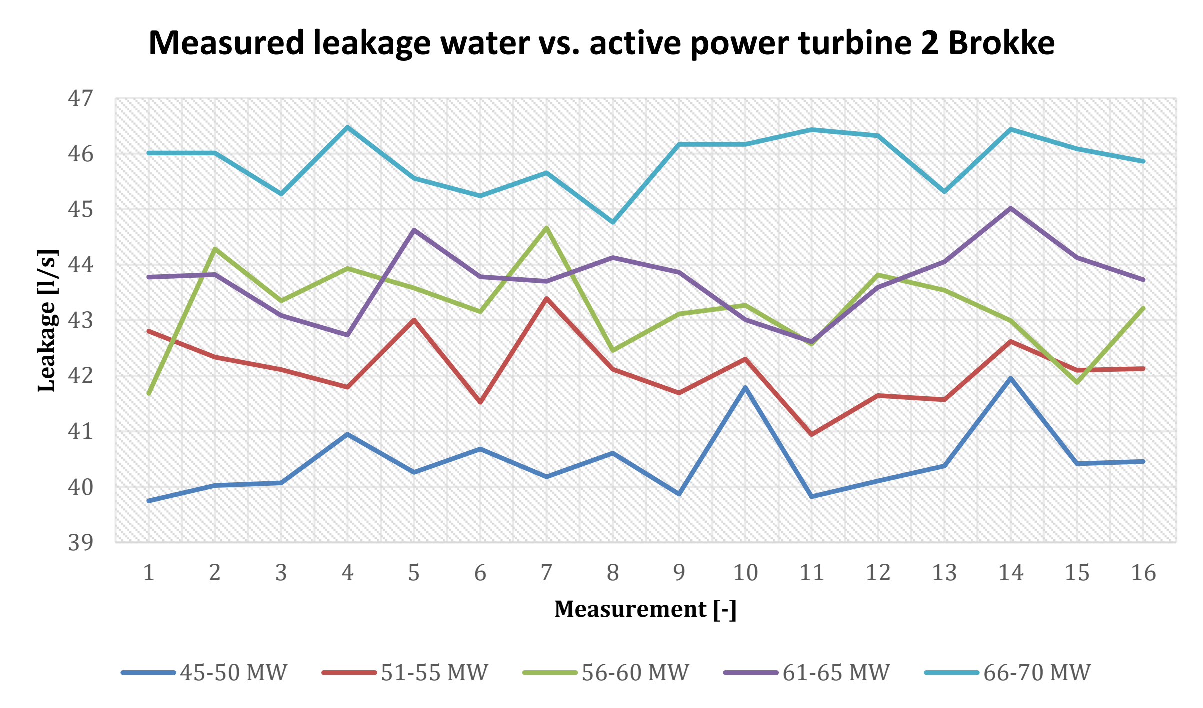


Figure 21: Measured leakage water vs. active power turbine 2 Brokke.

5.2.3 Turbine 3

Fig. 22 shows that the leakage reaches approximately 73-74 l/s when the power is nearly 66 MW. Like the same type of figure, Fig. 20 on turbine 2, it is a bit difficult to see that the leakage increases with increased active power. That can relate back to the timing problem but can also show that the leakage is very stable on this turbine, independent of the power.

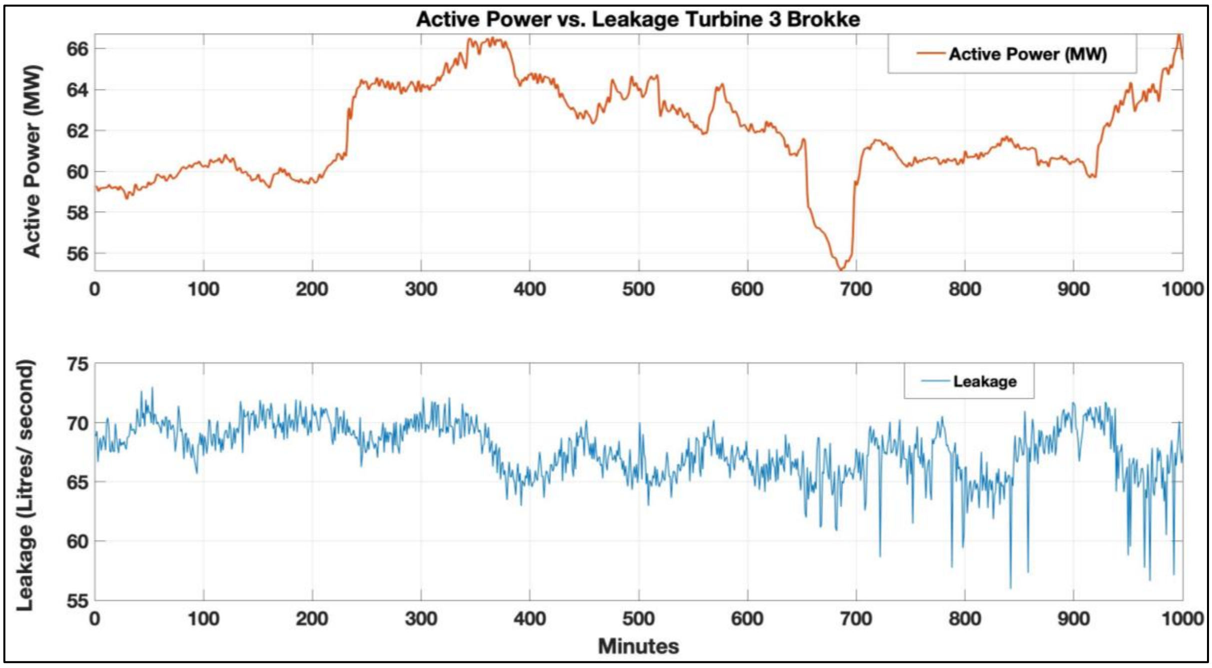


Figure 22: Active power vs. leakage turbine 3 Brokke.

In Table 26, average values of leakage, production water and vibration for different active power intervals are presented. Like for turbine 1, is it easy to see that all these parameters increase with increasing power. The leakage variation is approximately around 6 liters between minimum and maximum power, and this is the same variation as for turbine 1. There is also a big increase in the vibration with the increase in active power. It goes from 0.187 mm/s for the lowest power interval and increases to 0.251 mm/s for the highest power interval. There is also possible to see a complete table in Table 71 in appendix E.1.

Table 26: Average values with different groups of active power from turbine 3 Brokke.

Active Power [MW]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
50-55	65.2	22.8	0.187
56-60	68.6	25.2	0.176
61-65	70.1	27.1	0.200
66-70	71.2	28.4	0.251

Fig. 23 shows the same results as Table 26. The higher active power, the higher is the leakage. The leakage does not differ much between the two biggest power intervals.

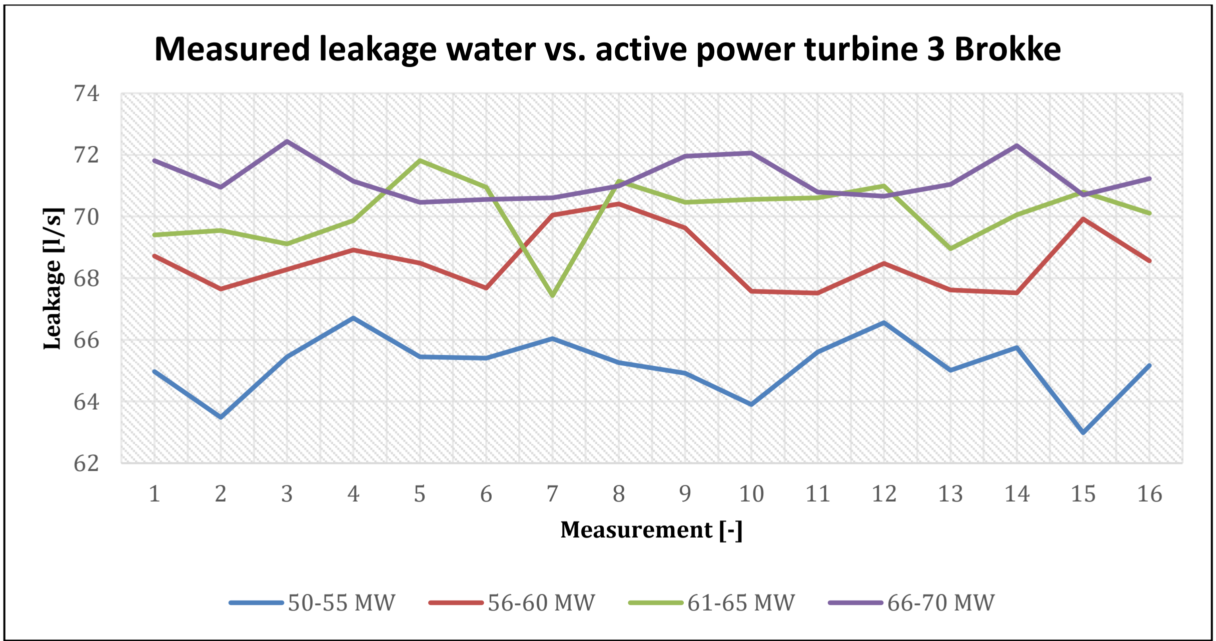


Figure 23: Measured leakage water vs. active power turbine 3 Brokke.

5.2.4 Turbine 4

Fig. 24 clearly shows that leakage on turbine 4 is big and uniform. The leakage on this turbine is also independent of the active power, just like turbine 3. The curve drops down sometimes and that can correlate to lower active power, such as 60-70 MW.

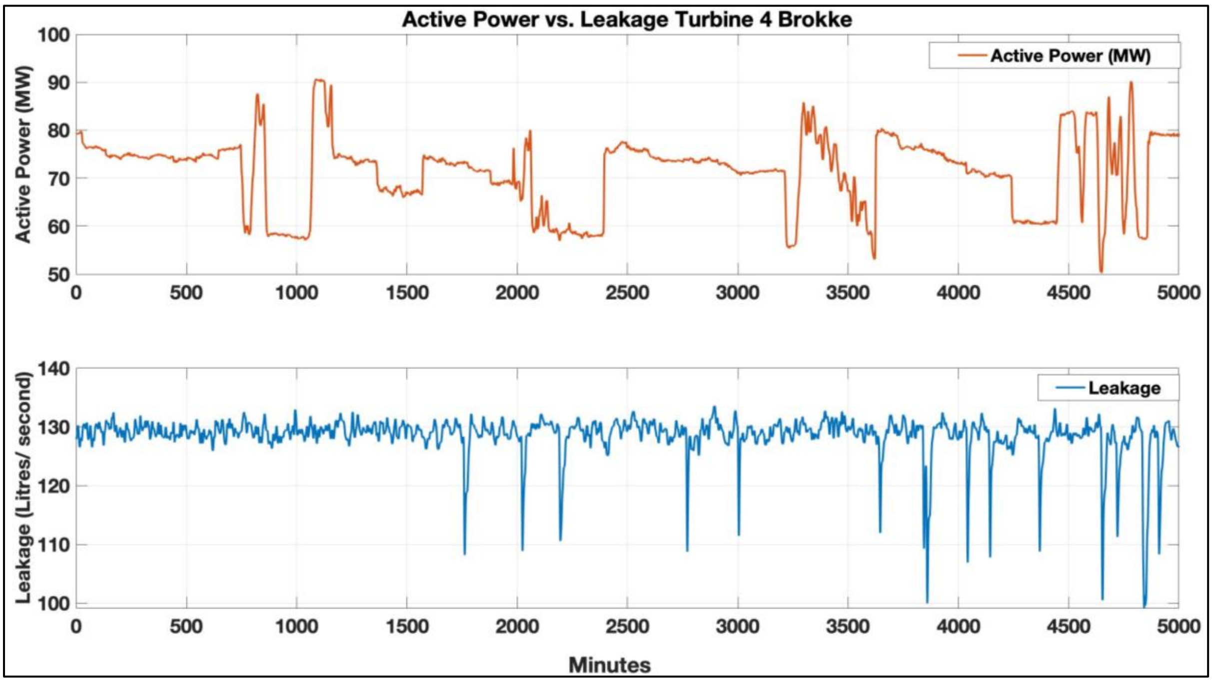


Figure 24: Active power vs. leakage turbine 4 Brokke.

In Table 27, average values of leakage, production water and vibration for different active power intervals are presented. For this turbine is it easy to see that all these parameters increase with increasing power. The leakage variation is approximately around 28 liters between minimum and maximum power. The vibration is very big on this machine, compared with the three other turbines. The biggest reason is of course that this is a much bigger turbine. The maintenance history can also play a part in the high vibration and leakage. In appendix E.1 and Table 72, a complete table is presented.

Table 27: Average values with different groups of active power from turbine 4 Brokke.

Active Power [MW]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
50-60	104.6	23.8	0.618
61-70	115.6	26.8	0.708
71-80	128.8	31.7	1.225
81-90	133.2	38.3	2.085

Fig. 25 shows the same results as Table 27. The higher active power, the higher is the leakage. The difference between the leakage curves for turbine 4 and for the other turbines is that a big increase in the leakage between the power intervals is observed.

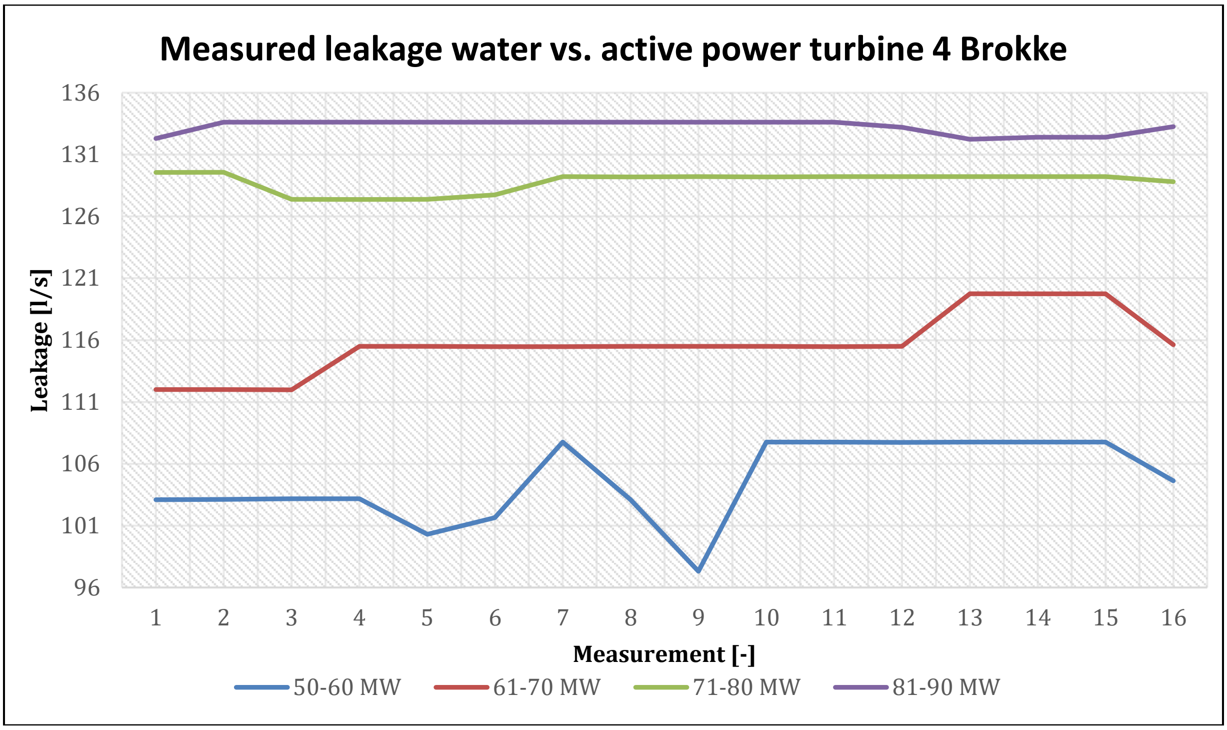


Figure 25: Measured leakage water vs. active power turbine 4 Brokke.

5.3 Results and Measurements Holen power plant

5.3.1 Turbine 1

In Fig. 26 the active power for the measurement on turbine 1 at Holen is presented. The maximum value for the active power reaches approximately just above 115 MW. From the curves, it is also easy to see that there have been three stops in the measuring period.

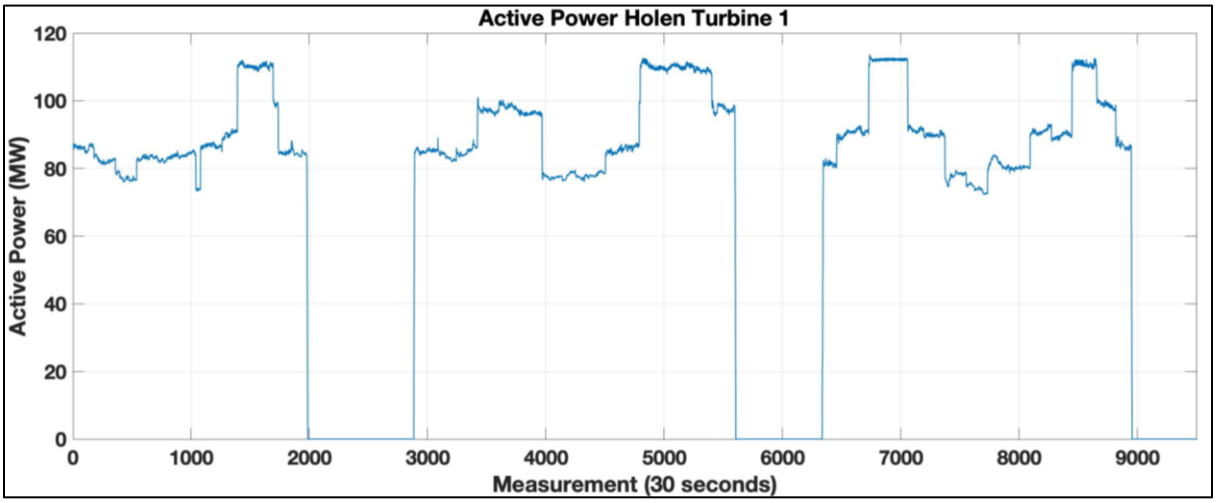


Figure 26: Active power for measuring period at turbine 1 Holen.

It is also easy to see the three stops in Fig. 27. The leakage behavior is stable somewhere around 80-82 l/s. The maximum leakage reaches up to 96-97 l/s. In Chapter 5.4 more results about the start/stop sequence and the behavior of the leakage in that sequence are presented.

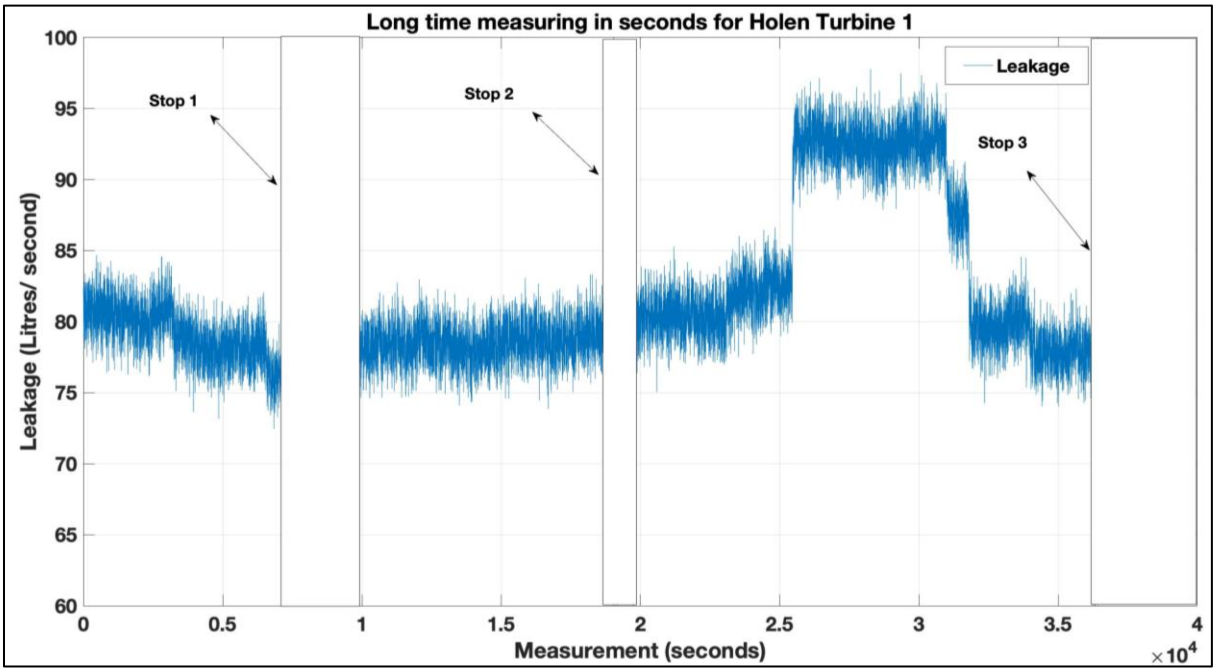


Figure 27: Leakage water for measuring period at turbine 1 Holen.

In Table 28, average values of leakage, production water and for different active power intervals are presented. The leakage increases when both the active power and amount of production water increases. The leakage variation is approximately around 18 liters between minimum and maximum power. There is also possible to see a complete table in appendix E.1 and Table 66.

Table 28: Average values with different groups of active power from turbine 1 Holen.

Active power [MW]	Leakage [l/s]	Prod.water [m^3/s]
70-80	75.4	32.8
81-90	81.3	37.0
91-100	85.7	41.2
101-110	93.0	47.8

Fig. 28 shows the same results as Table 28. The higher active power, the higher is the leakage.

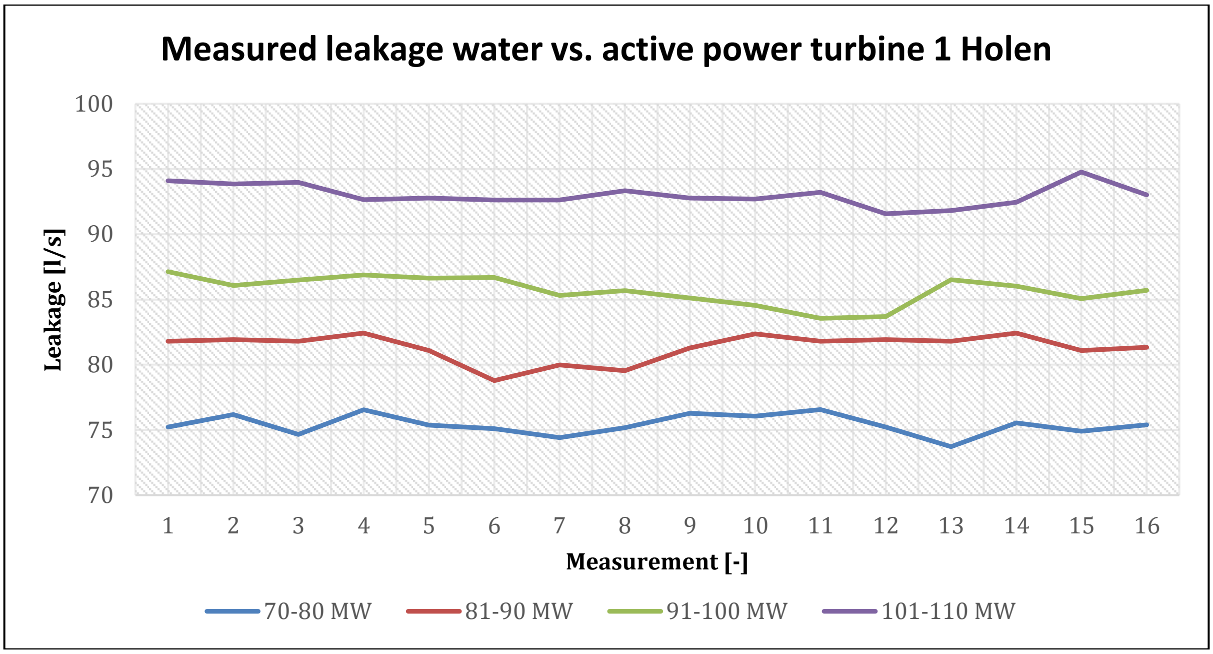


Figure 28: Measured leakage water vs. active power turbine 1 Holen.

5.3.2 Turbine 2

In Fig. 29 the active power for the measurement on turbine 2 at Holen is presented. The maximum value for the active power rises to approximately 102-103 MW. From the curves, it is also easy to see that there have been three stops in the measuring period. Two smaller stops and the last one much longer.

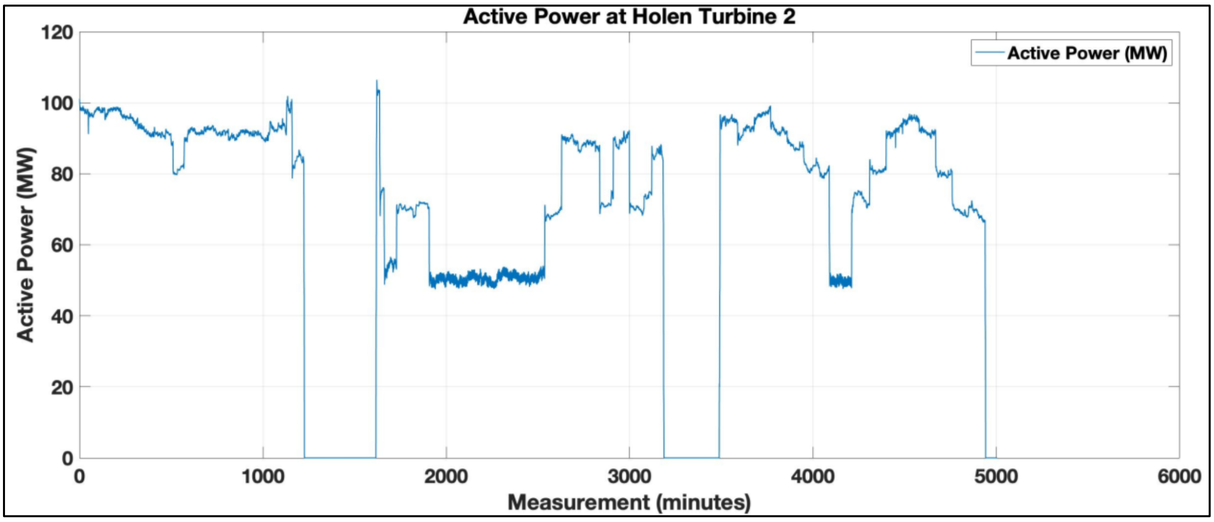


Figure 29: Active power for measuring period at turbine 2 Holen.

Fig. 30 shows three stops in the measuring period of this turbine. The maximum leakage is approximately around 95 l/s and the minimum are around 62-63 l/s. In Chapter 5.4 more about the start/stop sequence and the behavior of the leakage in that sequence are presented.

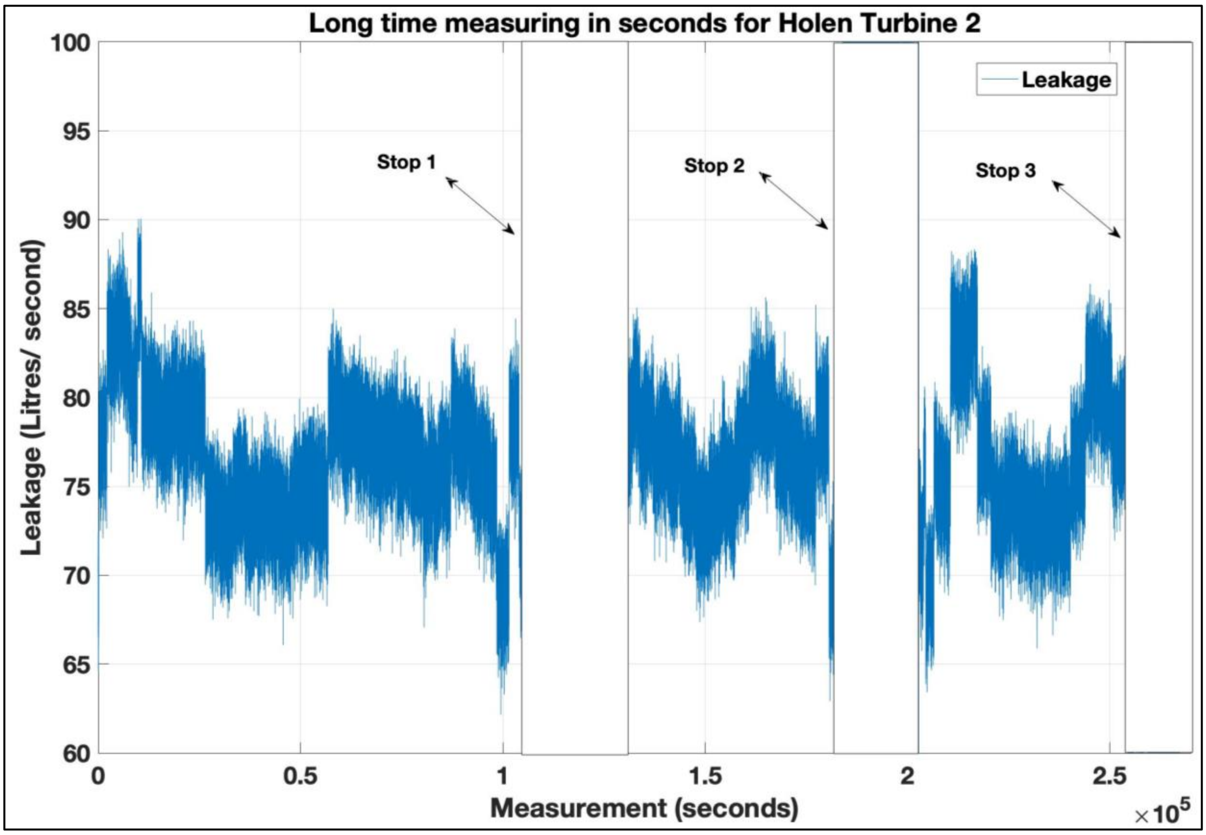


Figure 30: Leakage water for measuring period at turbine 2 Holen.

In Table 29, average values of leakage, production water and for different active power intervals are presented. The leakage increases when both the active power and amount of production water increases. The leakage variation is approximately around 15 liters between minimum and maximum power. There is also possible to see a complete table in appendix E.1 and Table 67.

Table 29: Average values with different groups of active power from turbine 2 Holen.

Active power [MW]	Leakage [l/s]	Prod.water [m^3/s]
70-80	70.3	31.9
81-90	74.7	35.8
91-100	84.4	40.6
101-110	85.1	43.9

Fig. 31 shows the same results as Table 29. The higher active power, the higher is the leakage. The difference between the two biggest power intervals 91-100 MW and 101-110 MW is very small. It is approximately 1.3 liters, this can also be seen in Fig. 31.

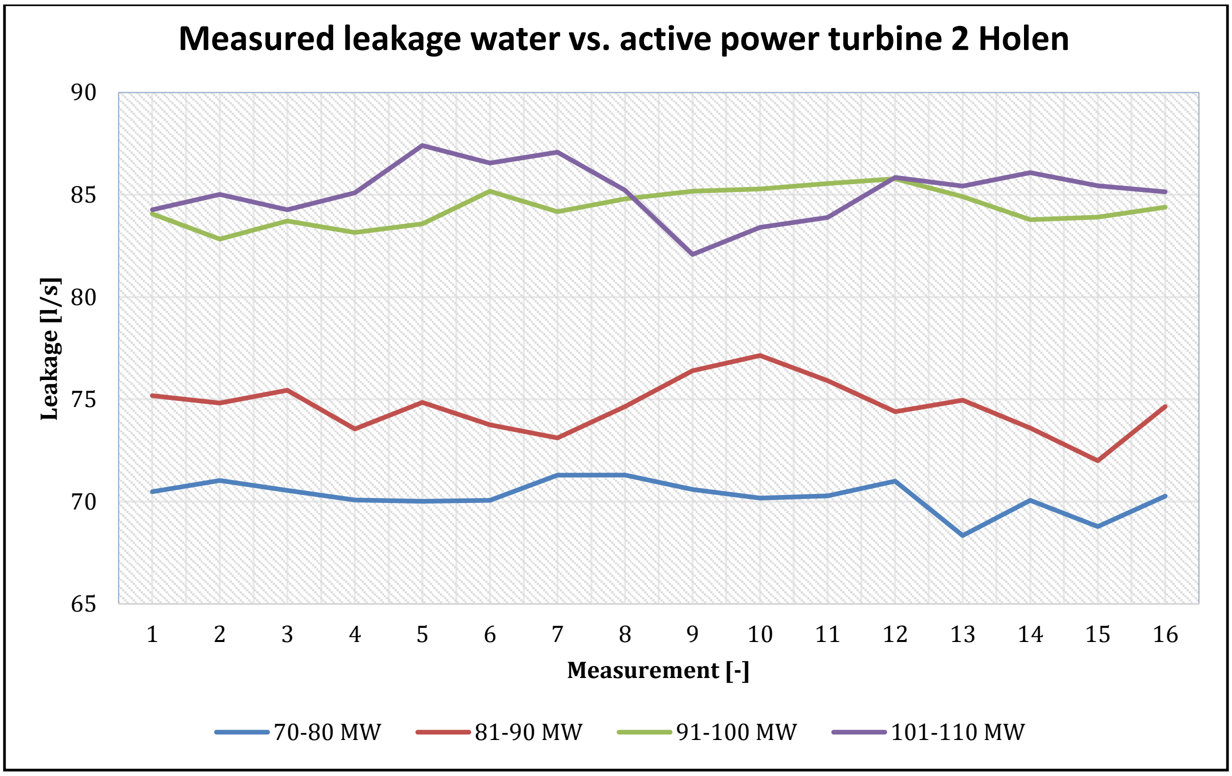


Figure 31: Measured leakage water vs. active power turbine 2 Holen.

5.3.3 Turbine 3

In Fig. 32 the active power for the measurement on turbine 3 at Holen is presented. This turbine has a big head with high pressure, and the maximum value for the active power is high. The maximum value for the active power reaches approximately just above 165 MW. From the curves, it is also easy to see that there have been three stops in the measuring period.

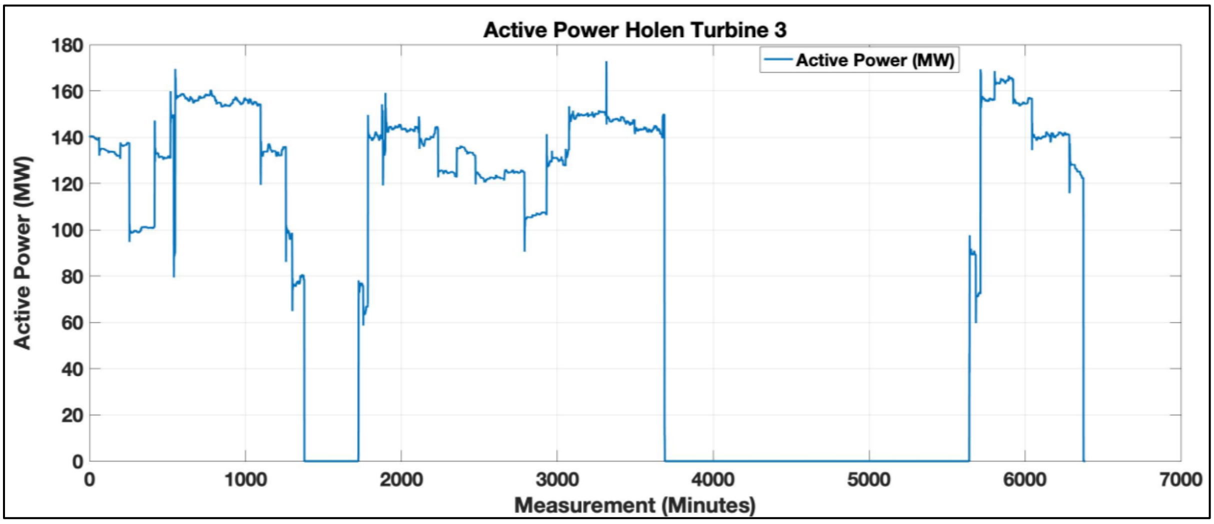


Figure 32: Active power for measuring period at turbine 3 Holen.

It is also easy to see the three stops in Fig. 33. The leakage behavior is stable somewhere around 72-74 l/s. The maximum leakage reaches up to 77-78 l/s. An overview shows that the amount of leakage is very stable on this turbine, also with different active power. In Chapter 5.4 more about the start/stop sequence and the behavior of the leakage in that sequence are presented.

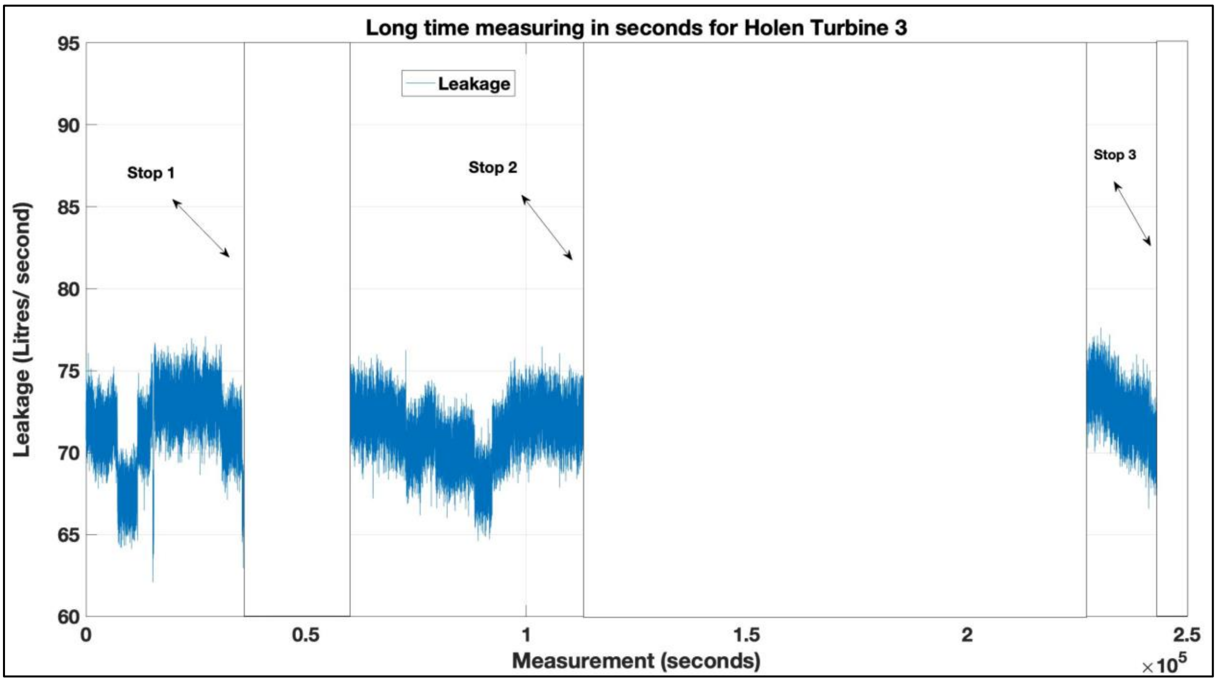


Figure 33: Leakage water for measuring period at turbine 3 Holen.

In Table 30, average values of leakage and production water for different active power intervals are presented. Like for turbine 1 and 2, is it easy to see that all these parameters increase with increasing power. The increase between the power intervals are very small. The leakage variation is approximately around 8 liters between minimum and maximum power. This is a much smaller value then it was for turbine 1 and 2 at Holen, and also turbine 4 at Brokke. All these mentioned turbines are big turbines. Because of the high pressure, there is much lesser need for water to produce the same amount of power. This can also be seen in Table 30. It is also possible to see a complete table in appendix E.1 and Table 68.

Table 30: Average values with different groups of active power from turbine 3 Holen.

Active Power [MW]	Leakage [l/s]	Prod.water [m^3/s]
70-80	64.4	14.0
81-90	65.5	16.6
91-100	66.5	18.2
101-110	68.6	19.5
111-130	69.7	23.0
131-150	72.9	25.9

Fig. 34 shows the same results as Table 30. The higher active power, the higher is the leakage.

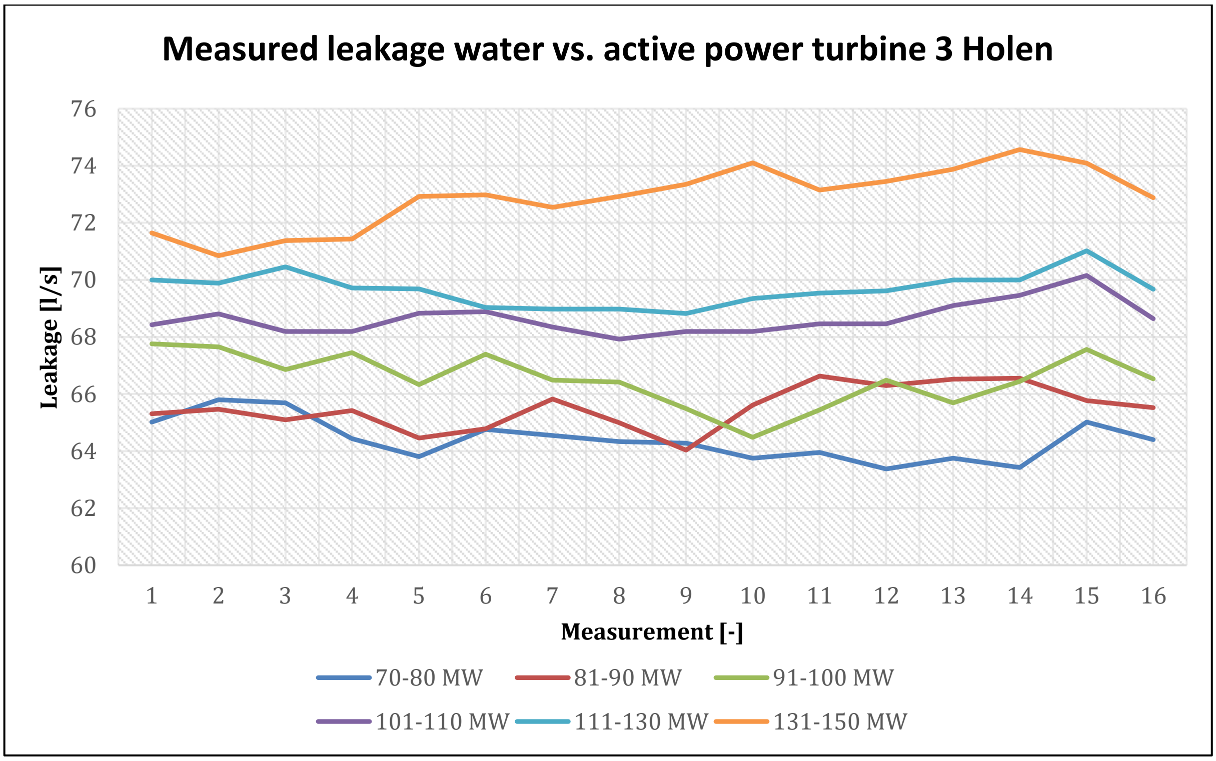


Figure 34: Measured leakage water vs. active power turbine 3 Holen.

5.4 Start/stop sequence Holen power plant

5.4.1 Start sequence

It is very interesting to look at the behavior of the leakage water in both the start and stop sequence. Lucky enough, there were several stops and starts in the measuring period at all the turbines at Holen. In Figs. 35 and 36, the start sequence for turbines 1 and 2 at Holen are presented. The plots show two start sequences in the measuring period, and the periods are very similar to each other.

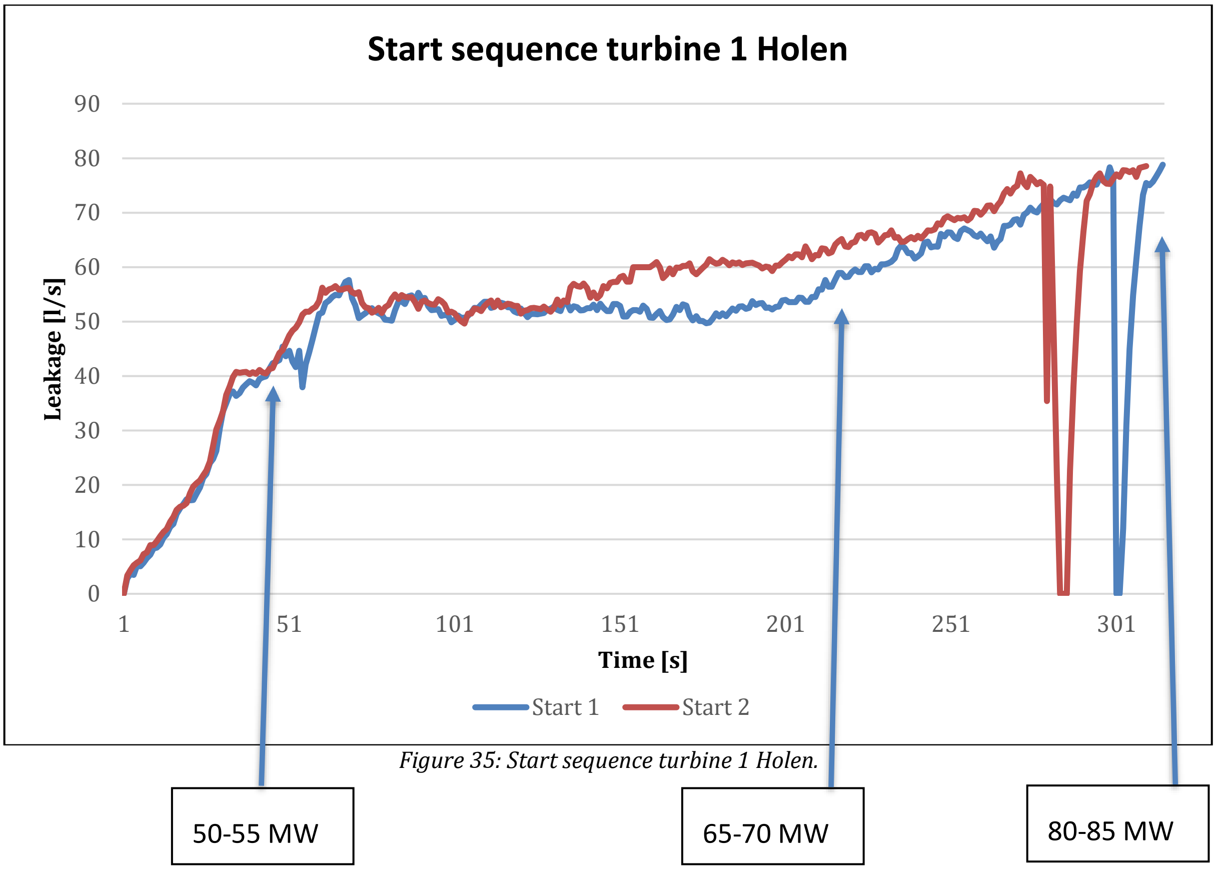


Figure 35: Start sequence turbine 1 Holen.

The leakage increases from the start, and up to around 50-55 l/s after 50-70 seconds in the sequence. The active power in this area is approximately 50-60 MW. This is also marked with the blue arrows. Then the leakage increases slowly up to 60-65, and here the active power is somewhere near 65-70 MW. Turning against the end of the start sequence, the leakage drops to zero for some seconds, before it increases to 75-80 l/s. The explanation for these phenomena, is that the turbines reaches the maximum speed. To slow down the turbines, to the normal operation speed, the guide vanes closes for some seconds. When the turbine reaches the right speed, the guide vanes opens, and the turbines run in operational speed. The same procedure is done in Fig. 36 on turbine 2.

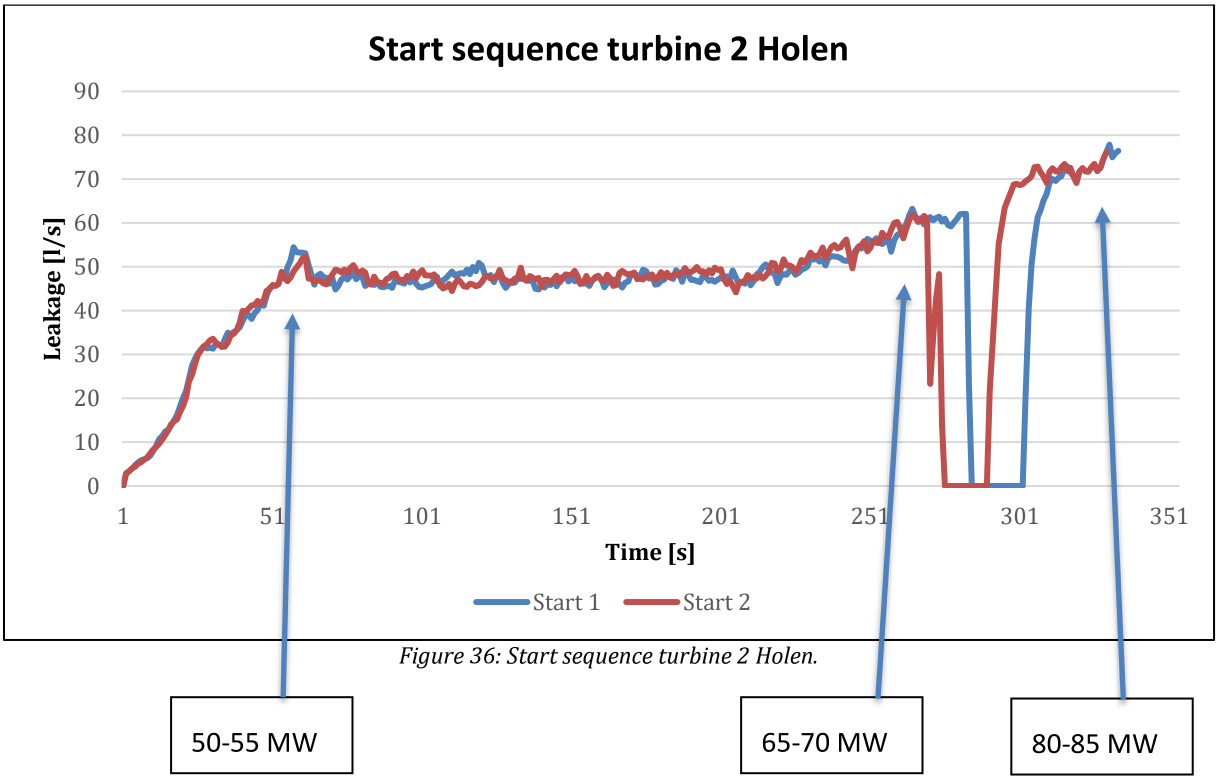


Figure 36: Start sequence turbine 2 Holen.

The starting procedure at turbine 3 (see Fig. 37) is more or less the same as on turbines 1 and 2. After approximately 25 seconds, the turbine reaches 35-40 MW and associated leakage of around 40 l/s. The turbine then speeds up to maximum speed, before the guide vanes closes, to slow down the turbine. When the guide vanes open again, the turbine has the correct operational speed and the leakage is stable on 60 l/s, with associated power of 65-70 MW. Overall behavior of the leakage is very dependent of the active power.

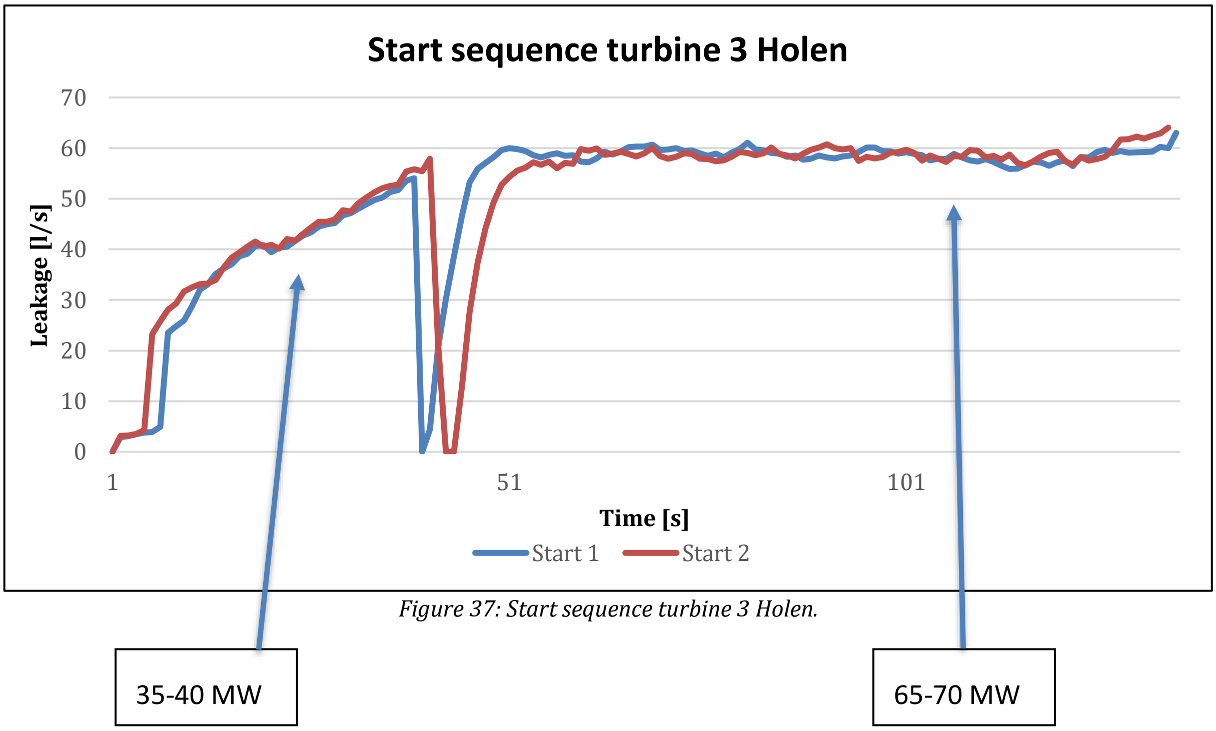


Figure 37: Start sequence turbine 3 Holen.

5.4.2 Stop sequence

It is very interesting to look at the behavior of the leakage water during the stop sequence. In Figs. 38 and 39, the stop sequence for turbines 1 and 2 at Holen are presented. The plots show three stop sequences in the measuring period, and the periods are very similar to each other.

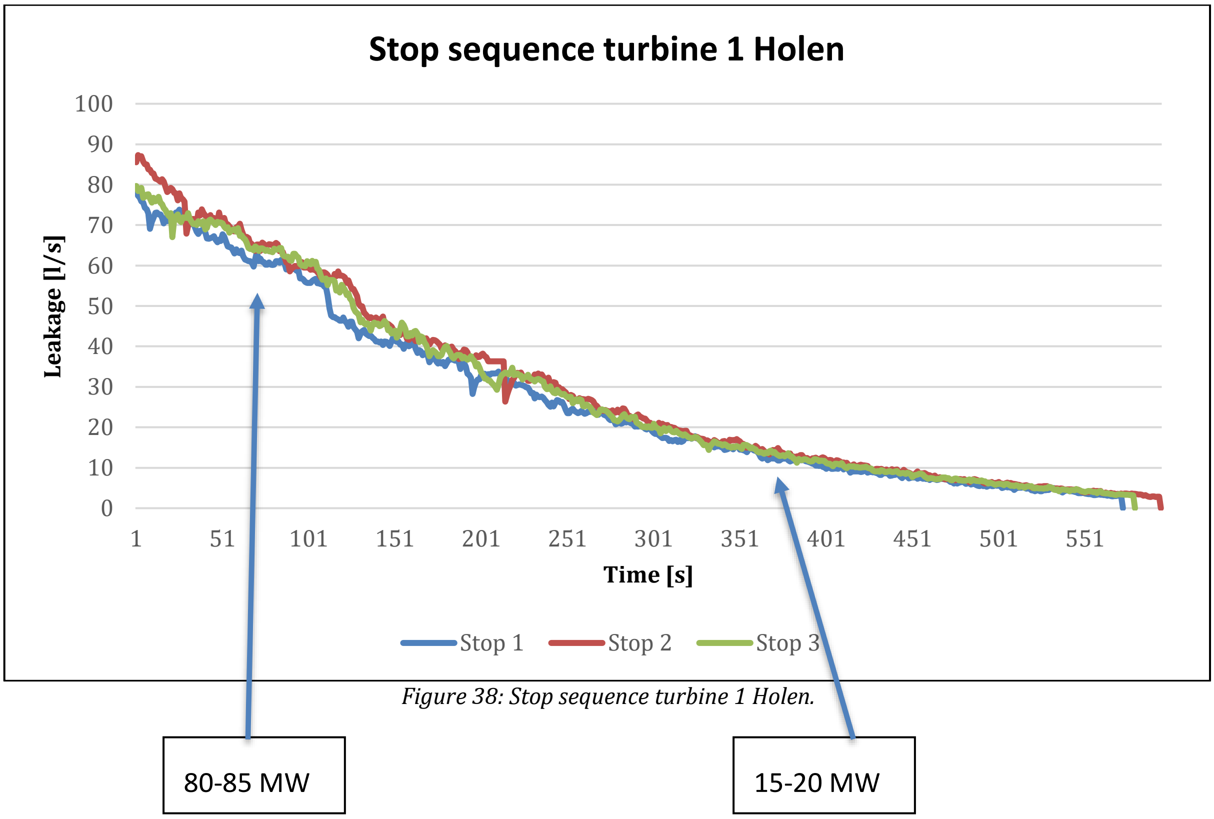


Figure 38: Stop sequence turbine 1 Holen.

When the "stop-button" is activated, the leakage is around 80 l/s. The leakage then decreases slow and stable down against zero. At approximately 50 seconds, the active power is 80-85 MW as the blue arrow shows. The stop sequence continues, and further on the leakage decrease together with the active power till the both reaches zero. The same procedure is done in Fig. 39 on turbine 2. The two turbines 1 and 2 react very similar in the stop procedure.

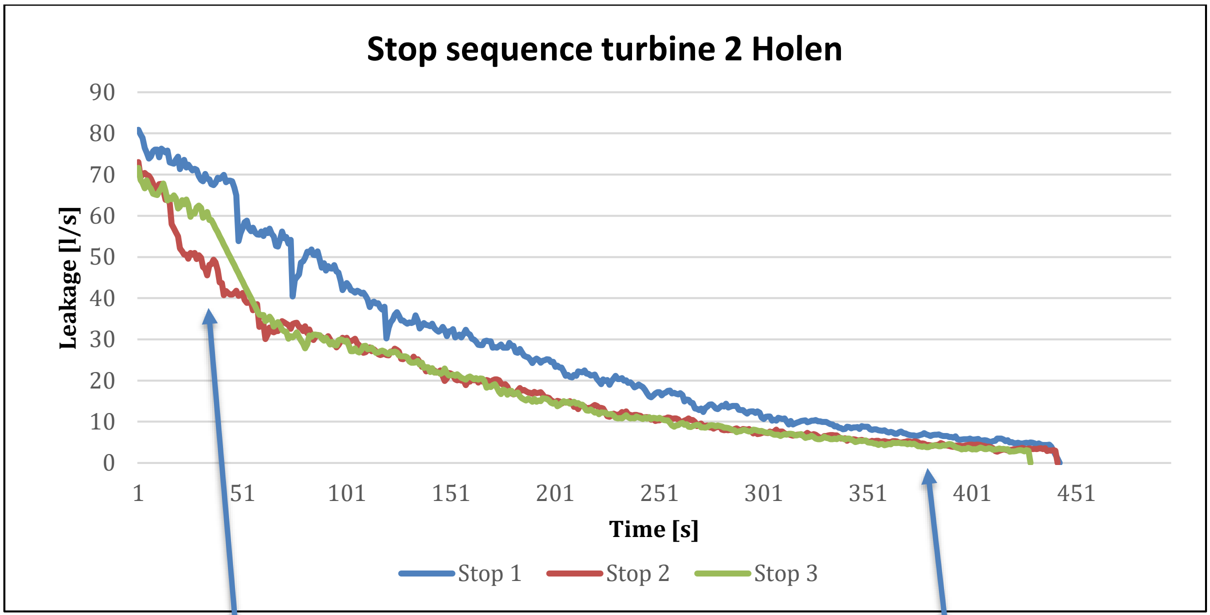


Figure 39: Stop sequence turbine 2 Holen.

The stopping procedure at turbine 3 is more or less the same as on turbines 1 and 2. After approximately 25 seconds, the turbine reaches 60-65 MW and associated leakage of around 60 l/s. Further on the turbine continues the stopping sequence and reaches 10-15 MW and associated leakage of 10 l/s, before it stops. The overall leakage behavior in the stop procedure is very stable and it is also very dependent of the active power.

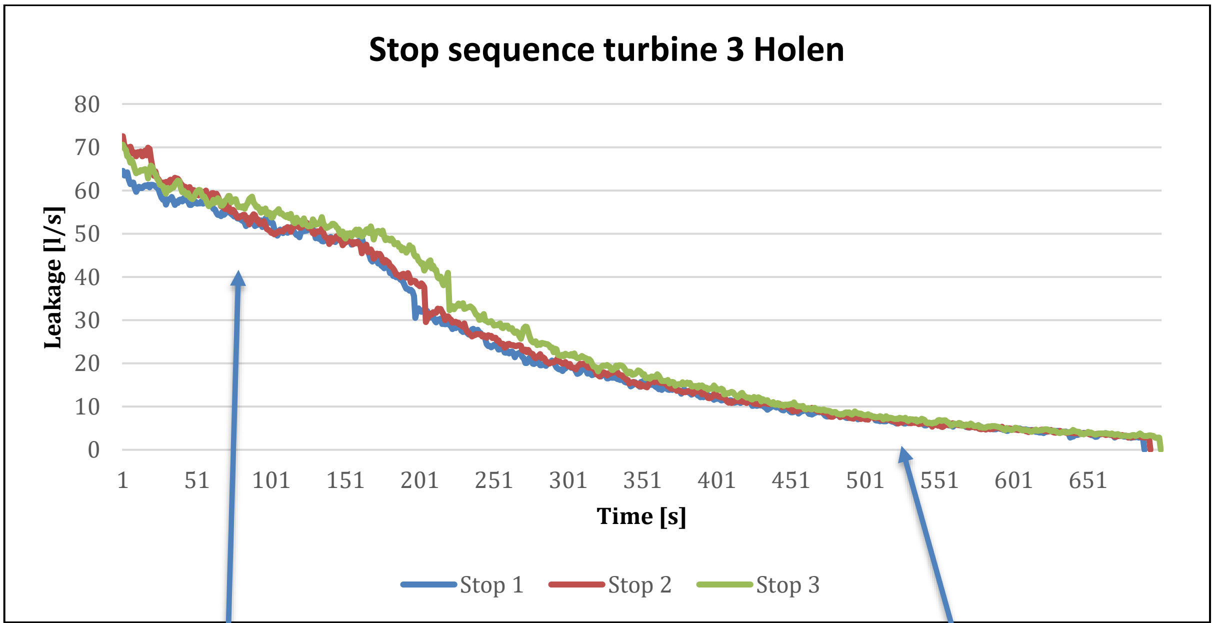


Figure 40: Stop sequence turbine 3 Holen.

6. Analysis

6.1 Analysis and comparison with operational parameters

For the analysis the following equations have been used or taken into consideration:

$$P_{turbine} = \rho * H_{net} * \eta * Q_{production} \tag{16}$$

$$H_{net} = H_a - H_b - H_f \tag{17}$$

Where:

H_a: Head from reservoir [m].

H_b: Head turbine [m].

H_f : Friction head losses [m].

For computing the friction head losses, the Darcy-Weisbach equation can be used:

$$h_f = f * \frac{L}{D} * \frac{U^2}{2g} \tag{18}$$

Where:

f: Darcy friction factor [-].

L: Length of pipe [m].

U: Cross section mean velocity [m].

The friction factor is computed using Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \tag{19}$$

Where:
ε: Absolute roughness of pipe [m].

D: Diamater of the pipe [m].

Re: Reynolds number [-].

Reynolds number is given by eq. (20):

$$Re = \frac{UD}{v} \tag{20}$$

Where:

v: Kinematic viscosity of water [m^2/s].

The specific speed of turbines can be calculated using eq. (21):

$$N_q = \frac{N\sqrt{P}}{H^{\frac{5}{4}}} \tag{21}$$

Where:
N: Rotation speed [rpm].

H: Net head [m].

P: Power [kW].

For the understanding, Bernoulli`s equation in Fig. 41 is a very important framework when it comes to fluids.

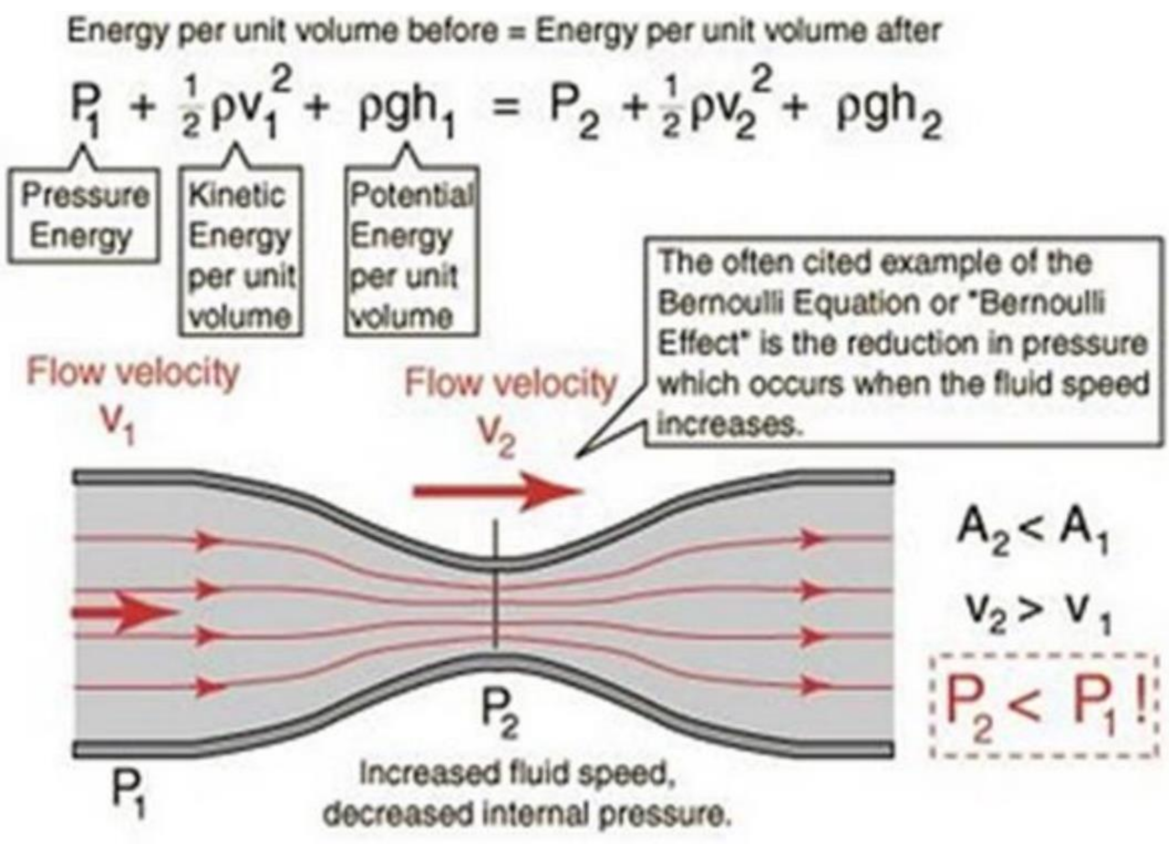


Figure 41: Description of Bernoulli Equation [25].

In Table 31, a comparison of the leakage in percentage of the production water can be seen for Brokke power plant. This is a common scale to corelate the leakage with, often found in the literature.

Table 31: Comparison of leakage in percentage of production water at Brokke power plant.

Active Power [MW]	Brokke 1 [%]	Brokke 2 [%]	Brokke 3 [%]	Brokke 4 [%]
35-40	0.23	Not measured	Not measured	Not measured
41-45	0.19	Not measured	Not measured	Not measured
46-50	0.17	0.21	Not measured	Not measured
51-55	0.17	0.19	0.29	0.44
56-60	0.16	0.18	0.27	0.44
61-65	Not measured	0.16	0.26	0.43
66-70	Not measured	0.16	0.25	0.43
71-80	Not measured	Not measured	Not measured	0.41
81-90	Not measured	Not measured	Not measured	0.35

From Table 31 it can be seen that the leakage for both turbines 1 and 2 are in the same range of percentage. While turbine 3 almost is 10 % greater in terms of the comparison with turbines 1 and 2. Turbine 4 is at a higher range in terms of leakage and stands out compared to the others. The overall turbine leakage with economical potential will be further discussed in in Chapter 6.2. The leakage percentage at Brokke is also presented in Fig. 42.

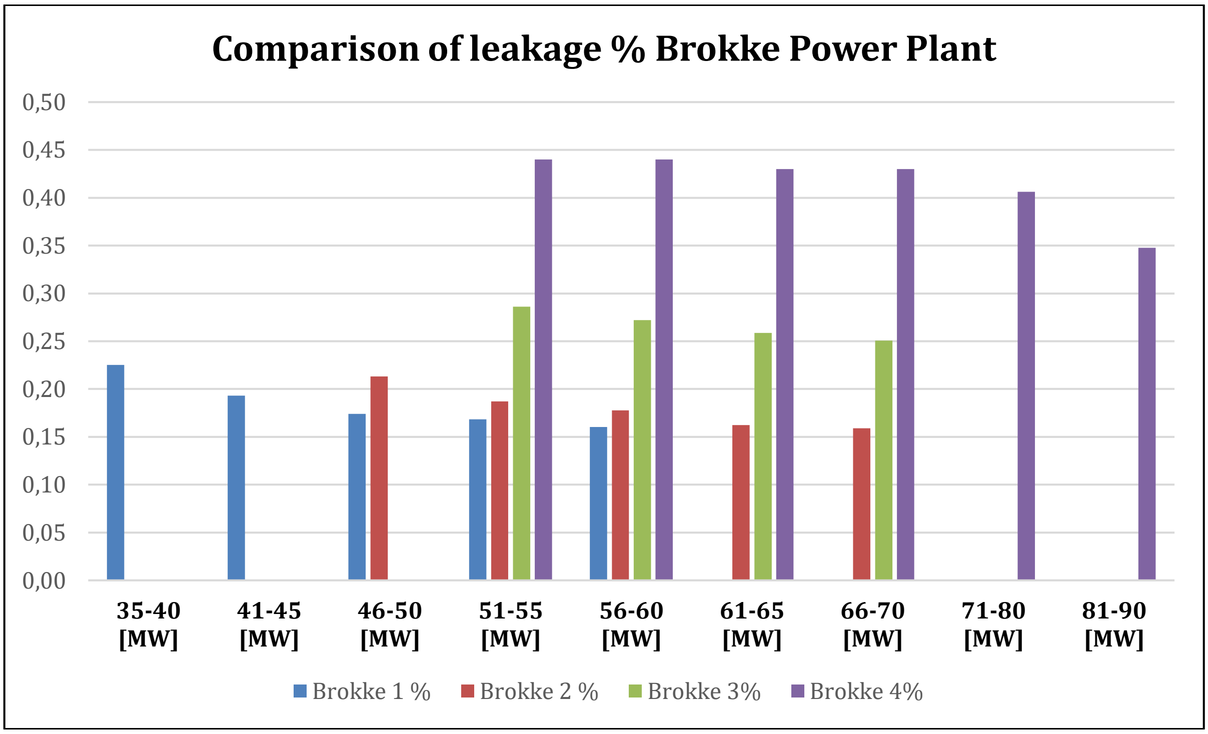


Figure 42: Comparison of leakage in percentage of production water at Brokke power plant.

In Table 32, the leakage percentage for both the turbines at Holen and turbine 4 at Brokke can be seen. Recall that turbines 1 and 2 at Holen are in the same size range, as turbine 4 at Brokke in terms of MVA and net head.

Table 32: Comparison of leakage in percentage of production water at Holen power plant and turbine 4 at Brokke.

Active Power [MW]	Holen 1 [%]	Holen 2 [%]	Holen 3 [%]	Holen 4 [%]
70-80	0.23	0.22	0.46	0.41
81-90	0.22	0.21	0.39	0.35
91-100	0.21	0.21	0.37	Not measured
101-110	0.19	0.19	0.35	Not measured
111-130	Not measured	Not measured	0.30	Not measured
131-150	Not measured	Not measured	0.28	Not measured

From Table 32 it can be seen that the leakage for both turbines 1 and 2 are in the same range of percentage. While turbine 3 almost is 20 % greater in terms of the comparison with turbine 1 and 2. The leakage percentage at Holen and compared with the percentage for turbine 4 at Brokke is also presented in Fig. 43. It is interesting to look at turbine 1 and 2 at Holen compared with turbine 4 at Brokke. They have all got the same size, but the figure shows that the percentage is a lot higher for turbine 4. It is also interesting to see that turbine 3 with the high head, also got high percentage. This is mainly because of much lesser production water and the high pressure, but also a sign that this turbine also has got a significant amount of leakage.

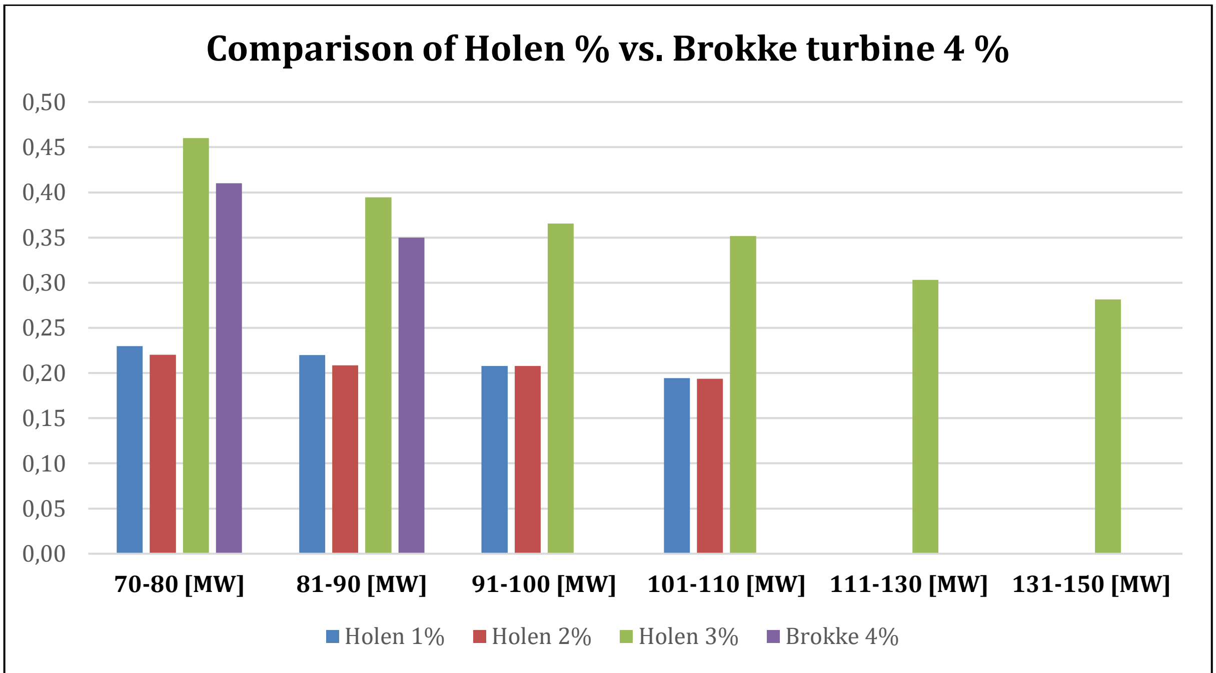


Figure 43: Comparison of leakage in percentage of production water at Holen power plant and turbine 4 at Brokke.

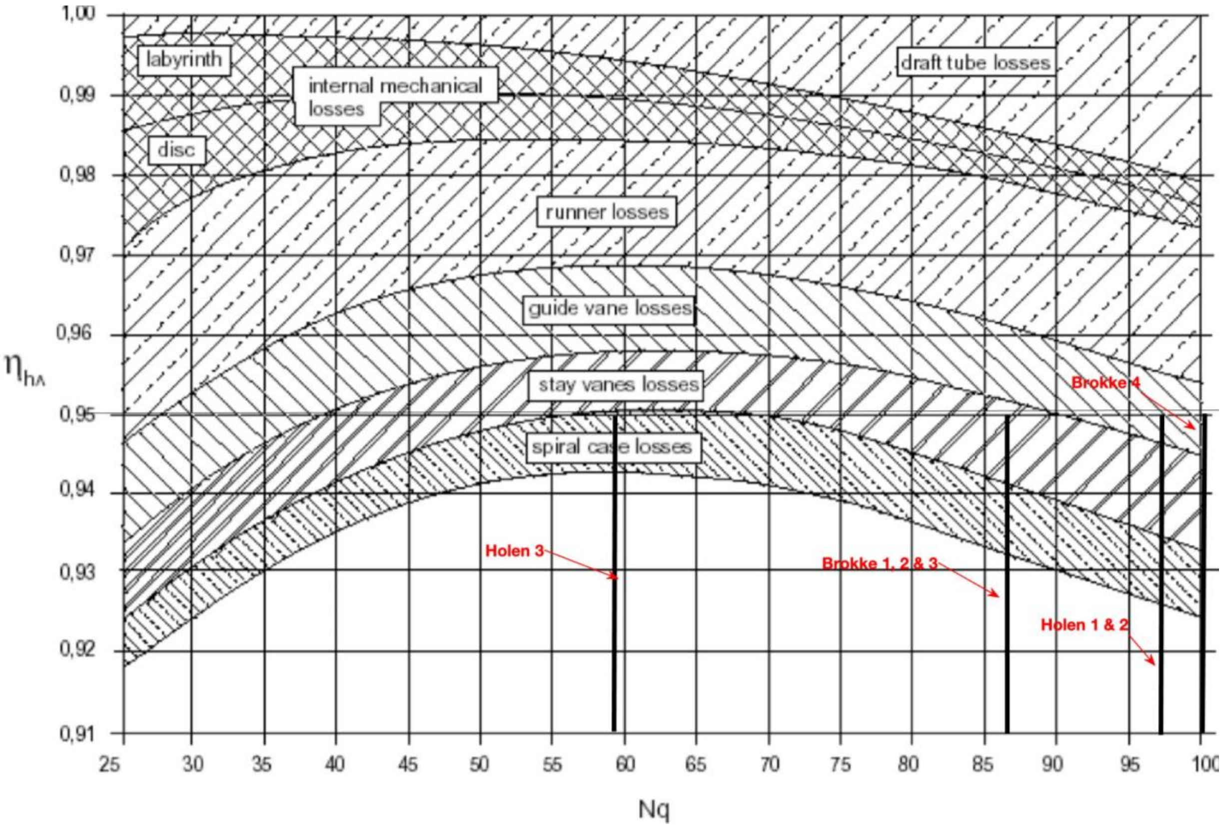


Figure 44: Specific speed for each turbine at Brokke and Holen power plants.

In Fig. 44 a calculation of the specific speed for each turbine (with the different nominal operational conditions) can be seen. From the graph it is interesting to see the distribution. Holen turbine 3 has a net head of 651 meters, and a rotational speed of 500 RPM, hence a smaller specific speed. As mentioned earlier Holen turbine 1, Holen turbine 2 and Brokke turbine 4 have approximately similar operational conditions, and a rotational speed of 375 RPM. Thus, the specific speeds are almost in the same range of size. Brokke 1, 2 and 3 also operate with similar conditions and a rotational speed of 375 RPM.

From this distribution it can be seen that Holen turbine 3 is expected to have a larger labyrinth loss, than the other turbines. Brokke turbines 1, 2 and 3 are all expected to have a labyrinth loss in the same range of size. As mentioned earlier, Brokke turbines 1 and 2 have almost the same leakage, while Brokke turbine 3 has a larger amount of leakage. Thus, Brokke turbine 3 can be rated worse than Brokke turbines 1 and 2 in terms of leakage conditions. Due to the specific speed at Brokke turbine 4, the leakage is not expected to be that high compared to the other turbines. This context has to be taken into consideration. Holen turbines 1 and 2 are probably within the expected leakage range. This could give an indication on a more stable leakage compared to Brokke turbine 4. Turbines 1 and 2 at Holen have a smaller number of operating hours through a year. This might have decreased the wear and tear of the turbines. When taking the leakage results into considerations it is important to have the leakage percentage in terms of production water in mind. All turbines are operating with different operational schedules, when the measurements have taken place.

6.2 Case analysis for estimation of total leakage loss

6.2.1 Case

An estimation of the total leakage for both upper and lower labyrinth leakage is found to be varying in the literature, see last column in Table 33. Therefore, an economic analysis has been carried out, to see how the potential varies with the different possibilities. When analyzing the total leakage eq. (1) has to be taken into consideration. For the analysis the following cases were considered and shown in Table 33.

Table 33: Analysis of the different cases.

Case	Leakage relation for lower labyrinth loss	Literature
1	Only the upper leakage (crown) is considered. Measured water at Brokke.	-
2	The lower leakage (band) is in the same size as the crown.	[7] and [8]
3	The lower leakage is twice the size as the upper leakage.	-
4	The lower leakage is three times the size as the upper leakage	[15]

For the calculation of the potential the average values of the leakage have been used. The net head was set to 303 meters, efficiency was set to 95 %, and that the turbines had an operation of 7000 hours [5] for the turbines at Brokke. For the calculations of the potential of Holen power plant, the operation hours from Table 3 have been used. With a respective 651-meter head, and 95 % efficiency. The leakages is also presented as a percentage of the production flow, for comparison. For the economical calculations the sales price is found in [26] and shown in Fig. 77 in appendix F.1. The sales price is then estimated to be average 41 EUR/MWh of Kristiansand day-ahead prices presented in Fig. 77 in appendix F.1. The EUR conversion is set at 1 EUR = 9,5 NOK [26].

The total estimation of the leakage is an important information to decide the total potential. In these calculations the average leakage for each turbine has been used. In appendix E.2 the same calculations have been carried out for both maximum and minimum leakage of each turbine. This to illustrate the differences in leakage potential. The calculations have been done for both Brokke and Holen power plants.

6.2.2 Case Analysis Brokke

In Table 34 an economical comparison of the calculated potentials from Brokke can be seen.

Table 34: Economical comparison of the calculated potentials from Brokke power plant.

	Turbine 1	Turbine 2	Turbine 3	Turbine 4
Measured Leakage crown labyrinth [l/s]	38	43	69	121
Prod. Water [l/s]	21250	24325	25854	30138
Leakage Case 1 [%]	0.2	0.2	0.3	0.4
Leakage Case 2 [%]	0.4	0.4	0.5	0.8
Leakage Case 3 [%]	0.5	0.5	0.8	1.2
Leakage Case 4 [%]	0.7	0.7	1.1	1.6
Potential leakage Case 1 [MWh]	681	771	1237	2169
Potential leakage Case 2 [MWh]	1362	1541	2473	4338
Potential leakage Case 3 [MWh]	2043	2312	3710	6506
Potential leakage Case 4 [MWh]	2724	3083	4947	8675
Case 1 [MNOK/year]	0.3	0.3	0.5	0.8
Case 2 [MNOK/year]	0.5	0.6	1.0	1.7
Case 3 [MNOK/year]	0.8	0.9	1.5	2.5
Case 4 [MNOK/year]	1.1	1.2	1.9	3.4

It can be seen that turbine 4 has a significant potential that are in the million NOK range. It is also interesting to see the potential from the leakage on turbine 3 at Brokke. The turbine runner was rehabilitated in 2007 and there is still an economical potential that is significant from the leakage. In [8] it is stated that it is normal for a new high head Francis turbine to increase the loss with 3-5 percentage points after 2-3 years. Thus, the potential for turbine 3 is also notable after only a couple of years after rehabilitation.

In the report [9] it can be seen that the labyrinth leakage is simulated to be in the region of 0.15-0.16% (band side labyrinth). In comparison to our results this is quite similar for turbine 1 and 2, but for turbine 3 and 4 with respective 0.3 % and 0.4 % there are a notable difference. In the report [9] the leakage is only considered for the lower band side, and that is important to take into consideration, since the measurements at Brokke is done for the crown side labyrinth leakage. The band side lower labyrinth leakage is decided through leakage relationship found in literature. It is interesting to see that the measured upper labyrinth loss has almost the same amount in percentage as found in [9] for the band side lower labyrinth, for turbines 1 and 2. Thus, there might be a relation to see that the lower band side leakage is in the same range of size as the upper labyrinth leakage.

When taking these potential calculations into consideration, an overview of the maximum and minimum leakage potential (in appendix E.2) accomplices the overall leakage extent.

6.2.3 Case Analysis Holen

In Table 35, an economical comparison for Holen power plant of the calculated potentials can be seen.

Table 35: Economical comparison of the calculated potentials from Holen power plant.

	Turbine 1	Turbine 2	Turbine 3
Measured Leakage crown labyrinth [l/s]	84	78	68
Prod. Water [l/s]	39723	38080	19526
Leakage Case 1 [%]	0.2	0.2	0.4
Leakage Case 2 [%]	0.4	0.4	0.7
Leakage Case 3 [%]	0.6	0.6	1.1
Leakage Case 4 [%]	0.9	0.8	1.4
Potential leakage Case 1 [MWh]	968	919	1104
Potential leakage Case 2 [MWh]	1936	1837	2207
Potential leakage Case 3 [MWh]	2904	2756	3311
Potential leakage Case 4 [MWh]	3872	3675	4414
Case 1 [MNOK/year]	0.4	0.4	0.4
Case 2 [MNOK/year]	0.8	0.7	0.9
Case 3 [MNOK/year]	1.1	1.1	1.3
Case 4 [MNOK/year]	1.5	1.4	1.7

For the potential calculations presented for Holen power plant, the operational time on each turbine is crucial. The yearly operational hours at Holen is at a fewer number of hours. Hence the deterioration of the machine might take lengthier time than the turbines at Brokke. When taking these results into reflection, wear and tear of the turbines might also have increased. This due to multiple start/stop sequences. In terms of head, it is important to see that the potential for both turbines 1 and 2 are approximately the same. Both turbines have a head around 300 meters. While turbine 3 has a net head more than twice the size, at 650 meters. Due to a very high head, the turbine needs a reduced amount of water in production.

In the report [9] it can be seen that the labyrinth leakage is simulated to be in the region of 0.15-0.16% (band side labyrinth). This corresponds to turbines 1 and 2 at Holen, and for turbine 3 it is twice the size.

When it comes to the economic loss, turbine 3 at Holen presents numbers that are roughly the same as for turbines 1 and 2. Hence, the very high head compensates and extracts a smaller volume of water for the MWh.

When taking these potential calculations into consideration, an overview of the max and min leakage potential (in appendix E.2.) accomplices the overall leakage extent.

Since turbines 1 and 2 at Holen are in the same size range, as turbine 4 in terms of MVA and net head. An extract from the potential tables can be seen for comparison in Table 36.

Table 36: Extract from the potential tables for comparison.

	Turbine 1 Holen	Turbine 2 Holen	Turbine 4 Brokke
Measured Leakage crown labyrinth [l/s]	38	43	121
Leakage Case 1 [%]	0.2	0.2	0.4
Potential leakage Case 1 [MWh]	968	919	2169

It can be seen that Brokke turbine 4 has a leakage 3 times the size of the leakage at both turbines 1 and 2 Holen. Turbines 1 and 2 Holen are almost equal when it comes to potential. This makes sense due to almost the same operational conditions in terms of MVA and the net head. Together with this, the overall economic potential is twice in Holen turbines 1 and 2. Turbine 4 Brokke also has a much higher number of operational hours, hence a superior MWh potential.

7. Discussion

7.1 Instrumentation

Through this report the PF220B was tested further and validated based on work done in [3] and this report. The device was tested with different pipes with different flows and compared to another acoustic instrument from Fuji Electrics. It was seen that the PF220B established accurate measurements in accordance to the reference that were made during the test period of the instrument. Hence it is possible to state that the letter of calibration for the device has a proven certainty. The developed logging program in LabVIEW has also been approved and programmed to its best purpose. The logger program was a fundamental part of this report, for the purpose of the long-time measuring sequences. In terms of instrumentation and method, this logging program was found to be very accurate and reliable. Minimal technical errors occurred. While monitoring the leakage for the turbines it was possible to see leakage behavior, both over time and when it comes to different operational conditions. For further work it will be recommended to do a further development for the logging program, to include the operational data from the turbines into the program. This to make the same resolution, and a comparison the most accurate as possible. Through the work of this report, the resolution in terms of comparing the operational data with the leakage, was found to be a time demanding part. This could be simply updated with including new measuring devices and sensors into the DAQ, and a reprograming in LabVIEW. This can be seen as a more expensive alternative, but it could strength the long-time monitoring sequences. As mentioned in the report Chapter 4.3, meter readings have been central to be reflected on. To get reliable measuring results the authors of this report have completed several tests and done the measuring sequences several times. The preferred measuring point was used for all 7 turbines. It was also an aim to try the best in terms of doing the measuring with equal circumstances.

7.2 Results and Analysis

7.2.1 Results Brokke

For the long-time measuring results at Brokke it was possible to see a good correlation in terms of that the leakage is proportional with the active power, and it follows the pattern of greater power changes. In Fig. 18 this is a great example on the correlation for Turbine 1 at Brokke. Turbine 1 at Brokke has been found to be a very stable turbine when it comes to leakage. This was also stated in [3]. It is recommended to make a new comparison in further work for turbines 2 and 3 at Brokke. This for a more accurate comparison versus the active power. For further comparison see appendix E.1. Turbine 3 has a notable leakage difference compared to turbines 1 and 2. Turbine 3 had a rehabilitation on the runner in 2007. Compared to the rehabilitation story in Table 2, this was a result of interest to see the difference compared to the other turbines. Only considering the rehabilitation story, a hypothesis would presume the opposite. In [3] turbine 3 was also rated at a more bad grading in terms of leakage. The long-time measuring has also stated that turbine 4 at Brokke is the turbine with the worst leakage grading, as presumed in [3]. When comparing the correlation between the leakage and the active power, it could be seen that this turbine had a higher grade of volumetric leakage throughout the time period.

It is possible to see that the leakage is high and stable through great active power adjustments, and the pattern is not that clear as for the others. Still with the help of the appendix E.1, It is possible to see the coloration pattern clearer. As well for the vibration, this is proportional on each turbine to the power change. When comparing the results found in this report with [3] it can be seen that the measuring results are in the same range for each turbine.

7.2.2 Results Holen

When comparing the leakage water versus production water for the turbines at Holen power plant it could be seen that Holen turbines 1 and 2 were about the same as found in literature, approximately 0.2 %. Holen 3 could be seen to an approximately 0.5 %, which can be seen as remarkable. As mentioned, it was crucial to take into consideration the very high head and the different production circumstances at Holen 3 compared to Holen 1 and Holen 2. Overall the results found from the measuring from Holen showed that turbines 1 and 2 behaved as expected. For further work it could be interesting to see the leakage flow pattern compared to other operational parameters.

For the potential calculations presented for Holen power plant the operational time on each turbine is crucial. The yearly operational hours at Holen is at a fewer number of hours. Hence the deterioration of the machine might take lengthier time than the turbines at Brokke. When taking these results into reflection, wear and tear of the turbines might also have increased. This due to multiple start/stop sequences. In terms of head it is important to see that the potential for both turbines 1 and 2 are approximately the same. Both turbines have a ca. head on approximately 300 meters. While turbine 3 has a net head more than twice the size, at 650 meters.

7.2.3 Start/stop sequences

The main reason why it is interesting to check out the start and stop sequence, is to look up on the leakage behavior in these periods. It is difficult know then the start/stop sequence are going to take place. Operational plans for the production next day, are made in the afternoon the day before. At Holen there is more starts and stops compared to Brokke. This increased the possibility of getting those measurements. In Chapter 5.4, the start and stops for each turbine at Holen is presented. In the measuring period, that took place for one week at each turbine, the PF220B collected values from two start sequences and three stop sequences from each turbine.

The start sequence between the three turbines were very similar. It was possible to see a good correlation in terms of that the leakage is proportional with the active power. Turbines 1 and 2 use the same fall height and have the same size. As Figs. 35 and 36 in Chapter 5.4.1 show, the curves are almost identical. After approximately 300 seconds, the guide vanes close to slow down the turbines to the normal operational speed. Over these seconds the leakage goes down to zero, before is goes back to 75-80 l/s when the guide vanes open again. The same can be seen at turbine 3. Because of its high pressure, the turbine speeds up to maximum speed much faster than turbines 1 and 2. The fall height is more than twice as big as for the other two turbines. The guide vanes close approximately at 50 seconds, to slow the turbine down before it reaches normal operational speed. Same procedure as for turbines 1 and 2. The leakage after the speed reducing period is approximately 60 l/s, and it is also possible to see correlation between the leakage and the increasing active power, but not that easy as for turbines 1 and 2. That refers to leakage behavior from turbine 3 at Holen. The increase in leakage water versus the increase in active power is not that big. The phenomena that the leakage water can be seen with good correlation in terms of that the leakage is proportional with the active power shows that the leakage behavior follows the same pattern for all the three turbines. With small pressures and lesser production water, the leakage still follows the active power.

The stop sequence between the three turbines are also similar to each other, just as the start sequences. It was also possible to see a good correlation in terms of that the leakage is proportional with the active power. When they stop the turbines, the valve closes and the water from the pipes drain out, and after a while the turbines stop. The sequence from all three turbines in Chapter 5.4.2 shows that that the amount of leakage reduces to zero. This takes approximately 600 seconds for turbine and it takes about 450 seconds for turbine 2. The reason why it is a difference, may be the different state of active power. Turbine 1 was running with the power of 95 MW when the stop sequence started and turbine 2 with the power of 85 MW. It takes up to 700 seconds from the stop sequence starts till the amount of leakage water reaches zero at turbine 3. Because of twice as much pressure and active power of 160 MW, should be the reason why this turbine uses that amount of time to stop. To sum up the results, the leakage behavior between the turbines at Holen is equal. The leakage decreases together with the decrease of active power. Unfortunately, no start or stops was collected from the measurements at Brokke power plant. It would have been very interesting to compare the sequences on the turbines at Brokke with Holen.

7.2.4 Potential and estimation of total leakage

In the literature the crown and band side leakage for the labyrinth seals varies a lot. In [7] and [8] it is assumed that the crown leakage is exactly the same in size as for the band side. This due to an assumed equivalent wear and tear over the same time. In [9] and [15] the band side leakage is assumed to be three times the size as the leakage from the crown. A further study on the estimation of this total loss would be of great interest. As seen in the economic analysis, this total loss can generate different MWh through a normal operation year. This loss has a potential that can be in a million NOK range. The numbers from the analysis depends on many factors, but a greater estimation for the total labyrinth loss would have given a greater reliability. For this report, the case analysis is made with different outcomes in terms of leakage relationship. The total leakage can only be decided with an actual measuring on both upper and lower labyrinth. Thus, it is an uncertainty to state the actual potential of the total leakage. Since the turbines do have a pump plate, the measured labyrinth leakage can be expected to be less than the actual lower band side leakage [7]. With the help of the pump plate, the crown leakage is utilized for machine cooling. This gives an overall better potential utilization compared to sending the leakage to the drain without any purpose.

The leakages that have been measured in this report have been compared to the literature in [9]. According to these numbers, turbines 1 and 2 at Brokke do have a leakage in the same range as found in [9]. This is also found to be the same relation for turbines 1 and 2 at Holen. For turbines 3 and 4 at Brokke the leakages are significant higher. Turbine 4 is the biggest turbine at Brokke, and this also needs to be taken into consideration. From the measurements done in this report it can be seen that a larger amount of production water gives a larger labyrinthic loss. Due to its size a larger amount of leakage water can be assumed. Turbine 4 at Brokke is also the elder turbine to get rehabilitated, and hence is the turbine with the largest amount of leakage. Turbines 1 and 2 at Brokke were rehabilitated respectively in 2004 and 2006. Turbine 3 at Brokke also has a slightly higher measured vibrations compared to turbines 1 and 2. At Brokke both vibration and pressure measurements are performed, since they have been proved to be important for both maintenance and rehabilitation of hydropower plants [10]. For further work it will be recommended to install appropriate pressure measurements nearby the labyrinths, for further analysis. This was not possible to analyze in this report and could have been of great importance both for Holen and Brokke power plant.

Through this report, it was also interesting to see the leakage behavior for turbine 3 at Holen with the very high head. This turbine exploits the water more efficient than the other turbines due to the corresponding pressure, given with the high head. Turbines 1 and 2 at Holen were compared with turbine 4 at Brokke, and it could be stated that leakage at turbine 4 Brokke was twice the size. Although the machines were similar and operating with the same head. At Holen power plant the operational hours through a normal year are almost half of the operational hours at Brokke. Hence the wear and tear of the machines have been greater at Brokke.

In [19] a thermodynamic method used to test the efficiency on a high head plant can be seen. With the help of such an efficiency test with inlet and outlet temperatures close to the labyrinth, a certain estimation of the lower labyrinthic leakage could be done. These tests are normal to carry out when assembling new turbines, to validate the given efficiency from the factory. Consultants companies as for example Sweco could perform test like this, but it follows with huge expenses [5].

7.3 Rehabilitation and further recommendations

From the results found in this report, it can be seen that turbines 1 and 2 at Brokke and Holen present results in accordance to the ones found in other scientific literature. Turbine 3 at Brokke is producing a high leakage although the turbine has had the newest revision. Turbine 4 at Brokke can be graded as the worst turbine due to a very high leakage, and hence a loss of economic potential. It is also important to notice that turbine 4 has the eldest revision. When comparing the leakage in percentage of the production water, turbine 3 at Holen is rated as bad as turbine 4 at Brokke. But due to the very high head and less operational hours, the economic loss potential is like turbine 3 at Brokke, turbines 1 and 2 at Holen. Since Holen power plant operates with almost half of the operational hours at Brokke, it is interesting to see that this clearly has affected the leakage grading.

An analysis comparing the measured leakage flows with numbers from the operation center was made to see the behavior of the leakage. It is also recommended in “Tilstandskontroll av vannkraftverk” [7], appendix G.1 to monitor the leakage over time over a year’s time, before examining it with a further analysis. It will then be possible to say more about when it is the most profitable to change/rehabilitate the turbine.

8. Conclusion

Through this report measuring of the labyrinth leakage from the upper crown has been carried out. Through numerous tests and reference measurements, the PF220B has been verified as a reliable acoustic device. This has been done with various types of pipes and flows, to increase the reliability within different conditions. The reference measurements confirm and validate the results from [3].

The programmed LabVIEW program has been proved and found to be an important tool to examine the leakage behavior over time. Hence it was possible to study the leakage compared to different operational parameters. The operational parameters were collected from the operational center at Brokke. For further work it is recommended to reprogram the logging program with the purpose of multiple sensors, hence a further possibility to examine the leakage.

The turbines at both Brokke and Holen show a pattern that follows the active power, due to the change in production water. The leakage is linear with the power change. Turbine 4 at Brokke can be seen as the worst graded turbine. This can be explained by multiple operational hours, and the eldest revision accomplished in 1998. Turbines 1 and 2 at both Brokke and Holen are stable in terms of leakage water compared with others found in the literature. Holen 3 did have a notable leakage, but in terms of the conditions for the high head turbine this potential is rated as a "healthier" turbine, than turbine 4 at Brokke.

The major outcome for this report is an establishment of the conditions and standards for monitoring the labyrinth leakage in Francis turbines.

9. Further work

9.1 Calibration and further verification of Portaflow 220B

The PF220B is delivered together with a letter of calibration, which have been done in 2016. In the project, this letter and a reference measurement at Spicheren has been the references or sources, telling that this instrument is measuring the correct values. The PF220B has also been reliability proved versus a Fuji electric ultrasonic instrument. With the help of further reference verifications, the results presented in this report would be further confirmed.

9.2 Logging program in LabVIEW

A further development of the logging program in LabVIEW could be of great importance for further work. Through this report, the logging program has been found to be a very important tool. In terms of monitoring the leakage over time. For further work, an extension of the logging program would be of interest. This could easily be carried out with the help of new sensors coupled to the DAQ device. It would be possible to install new sensors for vibration, pressure etc. Thus, monitor the behavior of the leakage and associated factors that affects the leakage.

When comparing the measured results with operational data, it has been important to have the same resolution. This to make the comparison clear. This has been time demanding through the project period. For further work, it is recommended to sample all results (leakage, active power, vibration etc.) in one program. This to avoid resolution differences, and equal time precision of the operational data vs. leakage. With the help of an ultrasonic device with logging possibilities, it would also be interesting to compare the logging program.

9.3 Further economic analysis with time for machine change/rehabilitation

Further economic analysis of the labyrinth leakage potential is an important aspect to take into consideration. For a more detailed analysis it could be interesting to get the knowledge from different turbine suppliers for a potential machine change/rehabilitation. Hence, a solution for when the leakage grading could be calculated. This to see when it is most profitable to do a possible machine change/ rehabilitation.

9.4 Confirmation of the total labyrinthic leakage

Through this report the total labyrinthic leakage (upper+lower) has some uncertainty, arising from the fact that the lower labyrinth leakage was not measured. An aim for future work has to be a confirmation of this actual loss. It would be interesting to find a relationship for the total leakage at the 7 turbines that this report has dealt with.

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Appendix A Portaflow 220B

A.1 Datasheets

micronics **Portaflow 220 Technical Datasheet**

Transducers

The PF220 system is supplied with one set of transducers with a temperature operating range of -20°C to +135°C. The PF220A is supplied with type 'A-ST' tranducers and the PF220B is supplied with type 'B-ST'.

PF220A standard transducers:

- 'A-ST' (2MHz) – used with 13mm 115mm pipe o.d.

PF220B standard transducers:

- 'B-ST' (1MHz) – used with 50mm 1000mm pipe o.d.

Transducer mounting

Type 'A' & 'B' transducers are fitted to adjustable guide rails which are secured to the pipe using wrap-around chains and mechanically connected together by a steel separation bar. The separation bar also acts as a ruler to allow the distance between the transducers to be set to the value calculated by the Portaflow instrument.

A thumb-wheel is used to adjust the chain tension until the assembly is held firmly in place. The transducers are then inserted into the guide rails and secured in place by a knurled screw. This illustration shows a completed assembly with a transducer fitted to the left-hand guide rail only.

The transducers are connected to the PF220 instrument by means of two 2m mini-coaxial cable.

Control Outputs

The PF220 provides analogue and pulse outputs that are designed to be used in conjunction with external control and site monitoring applications such as those typically found in building management systems. These outputs can be calibrated to suit a required flow operating range and a high-flow alarm level.

Both outputs are connected to a single (green), 7-pin LEMO socket located on the top of the PF220 instrument. A single 2 metre cable is provided that can be adapted for use for either of these output functions. The 'tails' on the free end of the cable must be terminated to suit the intended application

Cable termination	
Red –	4-20mA positive
Black –	4-20mA negative
White –	Pulse output (+)
Green –	Pulse return (-)
Brown –	Set Point (not in present use)
Blue –	Set Point return (not in present use)
Thick Black –	Cable screen

Analogue output:	
Range –	4–20mA 0–20mA 0–16mA
Resolution –	0.1% of full scale
Alarm current –	Adjustable between 0–26mA
Isolation –	1500V Opto-isolated
Maximum load –	620 Ohms

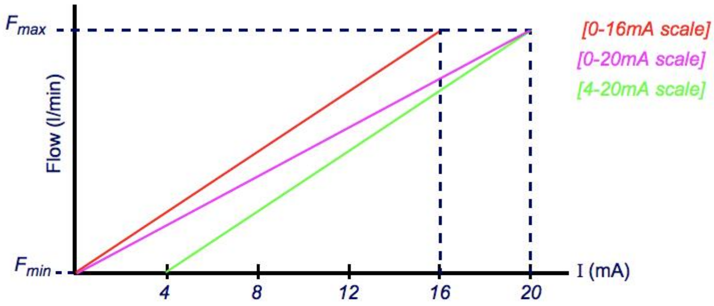
Pulse output:	
Output type –	One open collector opto-isolated digital output
Pulse repetition –	Up to 500 pulses/sec (depending on pulse width)
Pulse width –	500ms for 1pulse/s 5ms for 100 pulses/s
Max current –	150mA

Portaflow 220 Technical Datasheet
(Issue 1.0) **5**

Figure 45: Transducers and control outputs PF220B.

3.7.3 How to convert the measured current to flow rate

Assume the maximum flow rate is F_{max} (l/min) and the minimum flow rate F_{min} is '0' (l/min), as shown.



To calculate the flow rate (l/min) for a measured current I(mA) then:

0-20mA	0-16mA	4-20mA
Flow rate $= \frac{I \times (F_{max} - F_{min})}{20} + F_{min}$	Flow rate $= \frac{I \times (F_{max} - F_{min})}{16} + F_{min}$	Flow rate $= \frac{(I-4) \times (F_{max} - F_{min})}{(16)} + F_{min}$

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Figure 46: How to convert the measured current to flow rate PF220B.

Portaflow 220 Technical Datasheet

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Technical data

General specification:	
DSP measurement technique –	The PF220 uses 'transit time' measurement with a sampling resolution of 50 pico-second, with a continuous signal level indication to the display
Flow velocity range (bi-directional) –	• Minimum velocity 0.1m/s • Max velocity 20m/s
Flow measurement accuracy –	• ±0.5% to ±2% of flow reading for flow rate >0.2m/s and Pipe ID >75mm • ±3% of flow reading for flow rate >0.2m/s and Pipe ID in range 13mm - 75mm • ±6% of flow reading for flow rate < 0.2m/s • Flow velocity corrected for Reynolds number over entire velocity range
Repeatability –	• ±0.5% of measured value or ±0.02m/s whichever is the greater
Response time –	• < 500ms depending on pipe diameter
Selectable flow units –	• VELOCITY: m/sec, ft/sec • VOLUME: l/s, l/min, l/h, gal/min, gal/h, USgals/min, USgals/h, Barrel/h, Barrel/day, m³/s, m³/min, m³/h
Selectable volume units –	• l, gal, USgals, Barrel, m³
Total volume –	• 12 Digits - forward and reverse
Display languages –	The following operator languages can be selected from the PF220 set-up menu • English • Italian • Russian • French • Spanish • Norwegian • German • Portuguese • Dutch

Electrical

Supply voltage:	
Input voltage range –	9–24Vdc
Power consumption –	10.5W

Battery:	
Technology –	5-cell NiMH
Capacity –	3.8AHr
Operating time –	Typically 20 hours continuous with backlight and 4-20mA output OFF
Recharge time –	6.5 Hours
Service life –	>500 charge/discharge cycles

Power supply charger:	
Manufacturer –	Model ECO-181WP12
Input voltage range –	90–264Vac
Input frequency range –	47–63Hz
Output voltage –	12Vdc
Max. Output current –	1.5A
Approvals –	UL, CUL, TUV, CB & CE

6 ***Portaflow 220 Technical Datasheet (Issue 1.0)***

Figure 47: Technical data PF220B.

Portaflow 220 Technical Datasheet micronics

Principles of Operation

When ultrasound is transmitted through a liquid the speed at which the sound travels is accelerated slightly when transmitted in the same direction as the liquid flow and decelerated slightly when transmitted against it. The difference in time taken by the sound to travel over the same distance but in opposite directions is therefore proportional to the flow velocity of the liquid and can be used to calculate the flow rate.

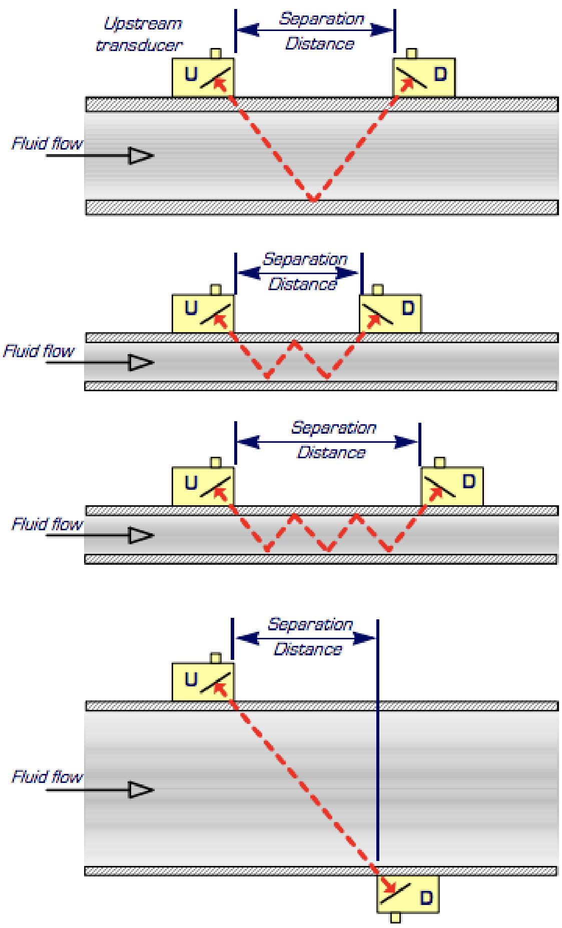
Transit time technique

This technique is known as 'transit time' measurement and is the method used by the Portaflow 220 system to calculate the liquid flow rate. Once the flow velocity is known it is a simple matter for the PF220 to calculate the volumetric flow.

Operating modes

The Portaflow sensors can be set to operate in one of four modes determined mainly by the pipe diameter and the transducer set in use. The diagram below illustrates these modes and shows the importance of applying the correct separation distance between the transducers to obtain the best possible signal.

In practice, the PF220 determines the operating mode and calculates the appropriate transducer separation distance in response to site application data entered by the user.



Reflex mode
This is the mode most commonly used. The two transducers (U & D) are attached to the pipe in line with each other and the signals passing between them are reflected by the opposite pipe wall. The Separation Distance is calculated by the instrument in response to entered data concerning the pipe and fluid characteristics.

Reflex mode (double bounce)
In this mode the separation distance is calculated to give a 'double bounce. This is most likely to occur if the pipe diameter is so small that the calculated reflex mode Separation Distance would be impractical for the transducers in use.

Reflex mode (triple bounce)
This illustration goes one step further to show a 'triple bounce situation. This would normally apply when working with very small pipes relative to the transducer range in use.

Diagonal mode
This mode might be selected by the instrument where relatively large pipes are concerned. In this mode the transducers are located on opposite sides of the pipe but the Separation Distance is still critical in order for the signals to be received correctly.

2 *Portaflow 220 Technical Datasheet (Issue 1.0)*

Figure 48: Principle of operation PF220B.

A.2 Method and placement of PF220B

A.2.1 Transducers

In many applications an even flow velocity profile over a full 360° is unattainable due, for example, to the presence of air turbulence at the top of the flow and possibly sludge in the bottom of the pipe. Experience has shown that the most consistently accurate results are achieved when the transducer guide rails are mounted at 45° with respect to the top of the pipe.

The PF220B equipment expects a uniform flow profile as a distorted flow will produce unpredictable measurement errors. Flow profile distortions can result from upstream disturbances such as bends, tees, valves, pumps and other similar obstructions. To ensure a uniform profile the transducers must be mounted far enough away from any cause of distortion such that it no longer has an effect [20]. This can be seen in Fig. 49.

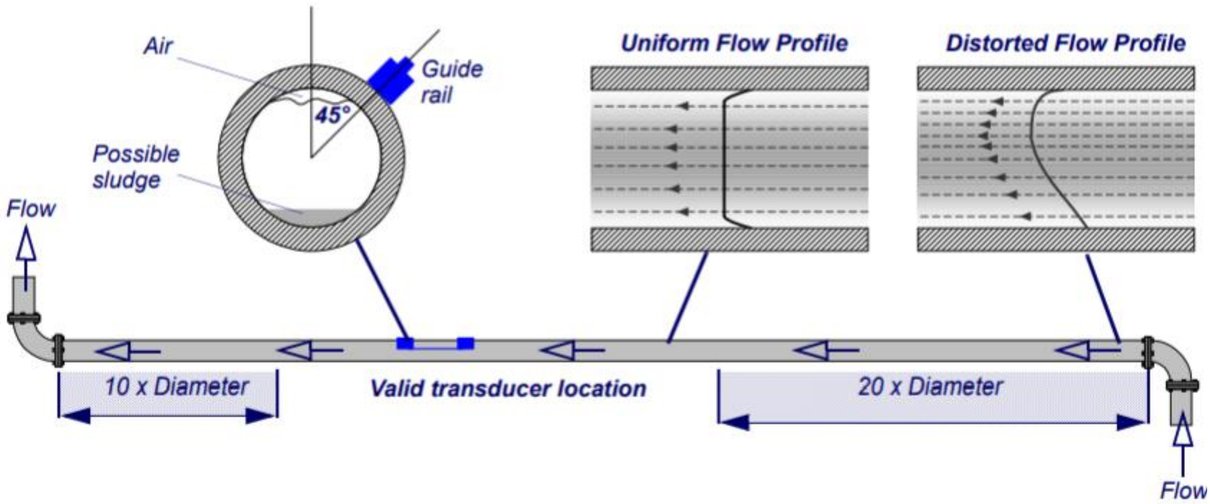


Figure 49: Positioning of the transducers [20].

A.2.2 Attachment

The transducers are fitted to adjustable guide rails which are secured to the pipe using wrap-around chains and mechanically connected together by a steel separation bar. The separation bar also acts as a ruler to allow the distance between the transducers to be accurately set to the value determined by the PF220B instrument.

When fitting the guide rails, it is easiest to assemble them onto the separation bar and adjust to the required separation distance before attaching them to the pipe. Fig. 50 is showing how attaching the guide rails [20].

The procedure for transducer attachment is the following:

1. Slide the separation bar (D) into the front of the left-hand guide rail, align the front edge of the guide rail with "0" on the ruler scale (E) and secure it in place by tightening the thumbscrew (C).
2. Slide the other end of the separation bar into the front of the right-hand guide rail, align the front edge of the guide rail to the required separation distance on the ruler (F), then secure it in place by tightening the thumbscrew.
3. On each guide rail, attach one end of a securing chain to a hook on the tensioning bar (B), wrap the chain (G) around the pipe and then attach it to the hook on the other end of the tensioning bar whilst keeping the chain as tight as possible.
4. Rotate the complete guide rail assembly so that is approximately 45° with respect to the top of the pipe. Then tighten the chain by turning the tensioning thumb-wheel (A) on each guide block until the assembly is securely attached to the pipe [20].

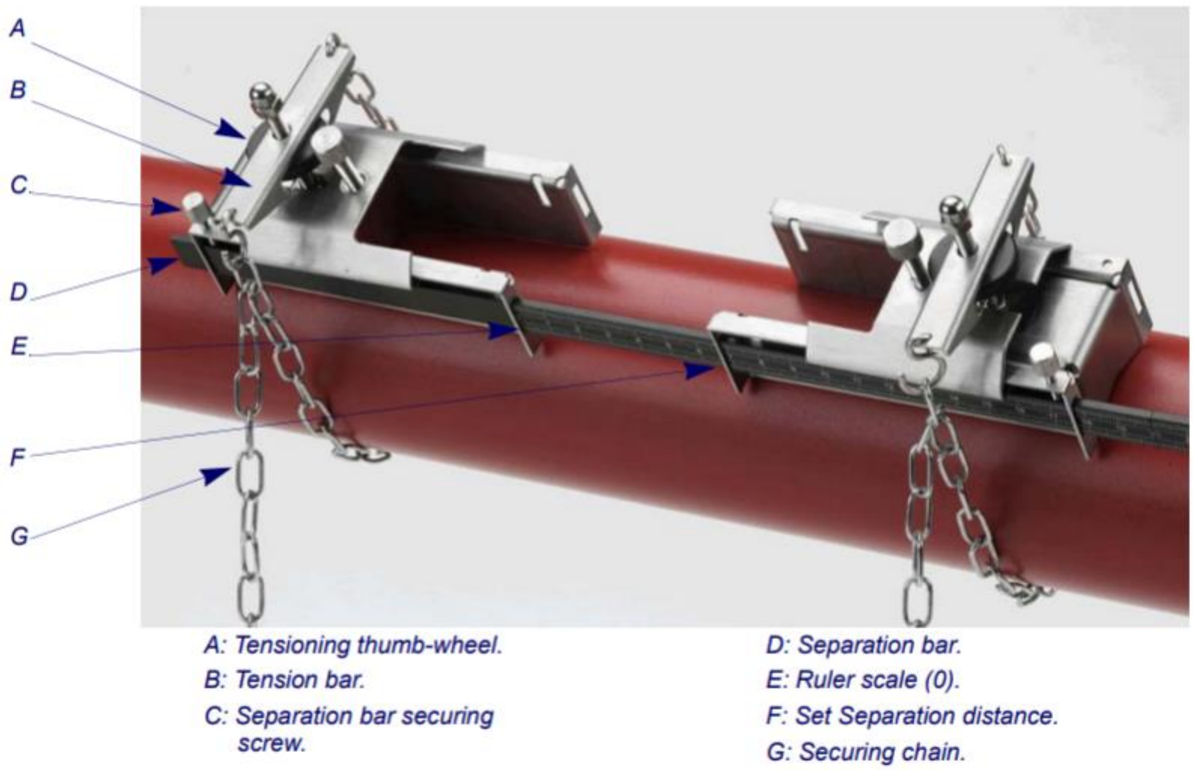


Figure 50: Transducer attachment [20].

A.2.3 Fitting the transducers

The fitting of the transducers (see Fig. 51) has the following procedures:

1. Slide the transducer cover plate (A) fully towards the outside of the guide assembly to allow sufficient access to fit the transducer.
2. Clean the face of the transducer, removing all traces of dirt and grease.
3. Apply a 3mm bead of ultrasonic couplant along the centre length of the transducer (E).
4. Fit the transducer into the guide block – ensuring the lugs on the sides of the transducer are correctly located into the slots on the sides of the guide block (B).
5. Slide the transducer cover plate (A) over the top of the transducer and tighten the thumbscrew (C) finger tight to secure the transducer in place. When securing the cover plate take care to leave sufficient room around the transducer connector (D) to connect the cable.
6. Repeat the above steps for the second transducer.
7. Connect the transducers to the PF220B instrument using the coaxial cable provided. The red cable must be connected to the upstream transducer and the blue cable to the downstream transducer. If you observe negative flow, swap the red and blue cables at the sensors [20].

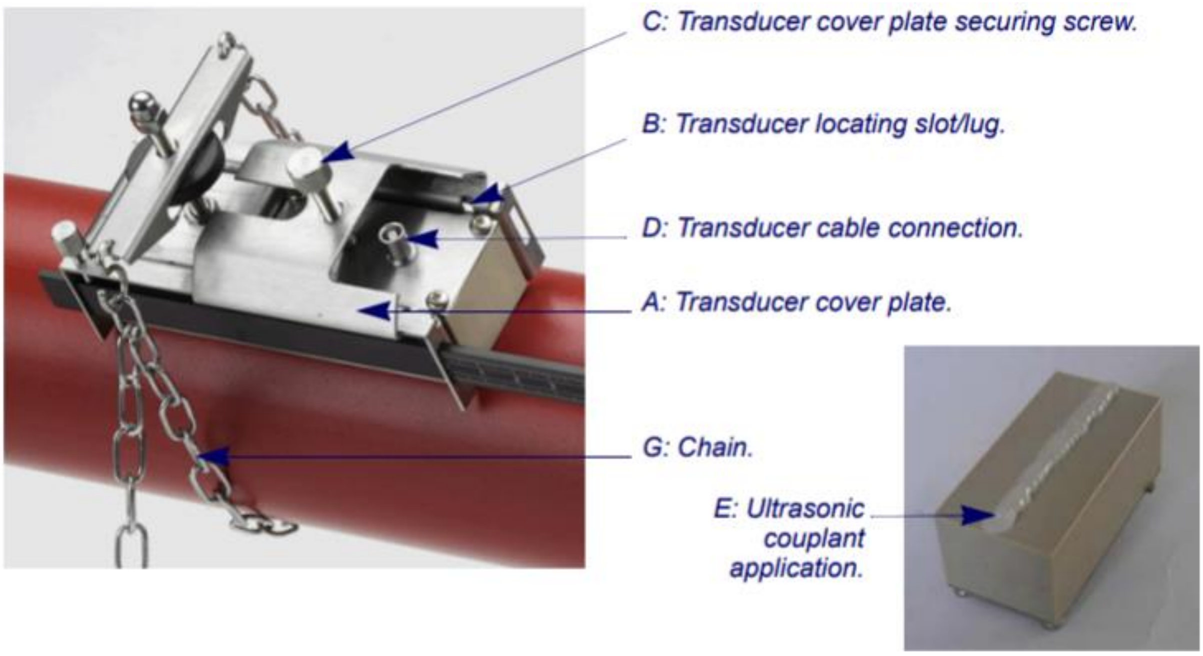


Figure 51: Fitting the transducers [20].

A.2.4 Equipment

The list of the equipment (see Fig. 52) is as follows:

- PF220B instrument with backlit graphic display.
- Power supply – with UK, US, European adaptors. 110/240VAC.
- 4-20 mA/Pulse output cable.
- 2 lengths of chain.
- Test block.
- Two transducer cables (one red and one blue) 2 meters long.
- Two transducers (Type A or type B depending on model).
- Set of guide rails used for mounting the transducers.
- Ruled separation bar (2-piece).
- Ultrasonic couplant with syringe dispenser used when mounting the transducers.
- Manual [20].

Figure 52: Overview of the equipment [20].

A.3 Letter of calibration Micronics

micronics

Certificate of Calibration

Micronics Ltd certifies that, at the time of manufacture/service, the instrument detailed below was calibrated and verified using an Electromagnetic Flow Meter of known accuracy, which is traceable to National and International Standards in accordance with Micronics Ltd calibration procedures (TP-011). These procedures are in compliance with the relevant clauses of ISO 9001.

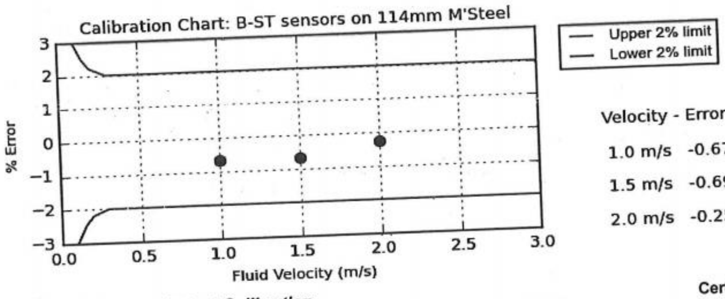
Description of Instrument Calibrated

These are portable ultrasonic 'clamp-on' flowmeters, designed for measuring flow in 'clean' liquids.

Uncertainty in Reference Measurement Equipment: Flowmeter: ±0.2%

Model:	PF220B
Serial No:	12862
Condition:	New
Software Version:	02.07.007

Air Temperature:		13.73
Fluid Temperature:		13.1
A Sensor Serial:		
B Sensor Serial:	48245	48766



Velocity - Error

1.0 m/s -0.67%

1.5 m/s -0.69%

2.0 m/s -0.25%

4-20mA Current Output Calibration

Load (Ohm)	Set I (mA)	DAC Value	Measured	Deviation (%)
120	4.000	8176	3.999	0.025
120	20.000	40816	20.001	0.005

Pulse Output Check

Vol/Pulse (litres)	Measured Vol (litres)	Expected No Pulses	Measured No Pulses	Result
10.00	1056.2	105	104	Pass

Certified:

Dated:

27/04/2016

Registered Office: Micronics Limited, Knaves Beech Business Centre, Davies Way, Loudwater, Buckinghamshire, HP10 9QR

Web site: www.micronicsflowmeters.com Tel: +44 (1628) 810456 Fax: +44 (1628) 531540

Directors: E.J. Farnon, E. Farnon, M.A. Farnon, D.B. Leigh, W.K. Reidie

Registration No. 1289680 V.A.T. Registration No. 303 6190 91

Figure 53: Letter of calibration PF220B.

Appendix B Datalogger

B.1 Datasheets National Instruments

Connecting the NI 9215

The NI 9215 provides connections for four differential analog input channels.

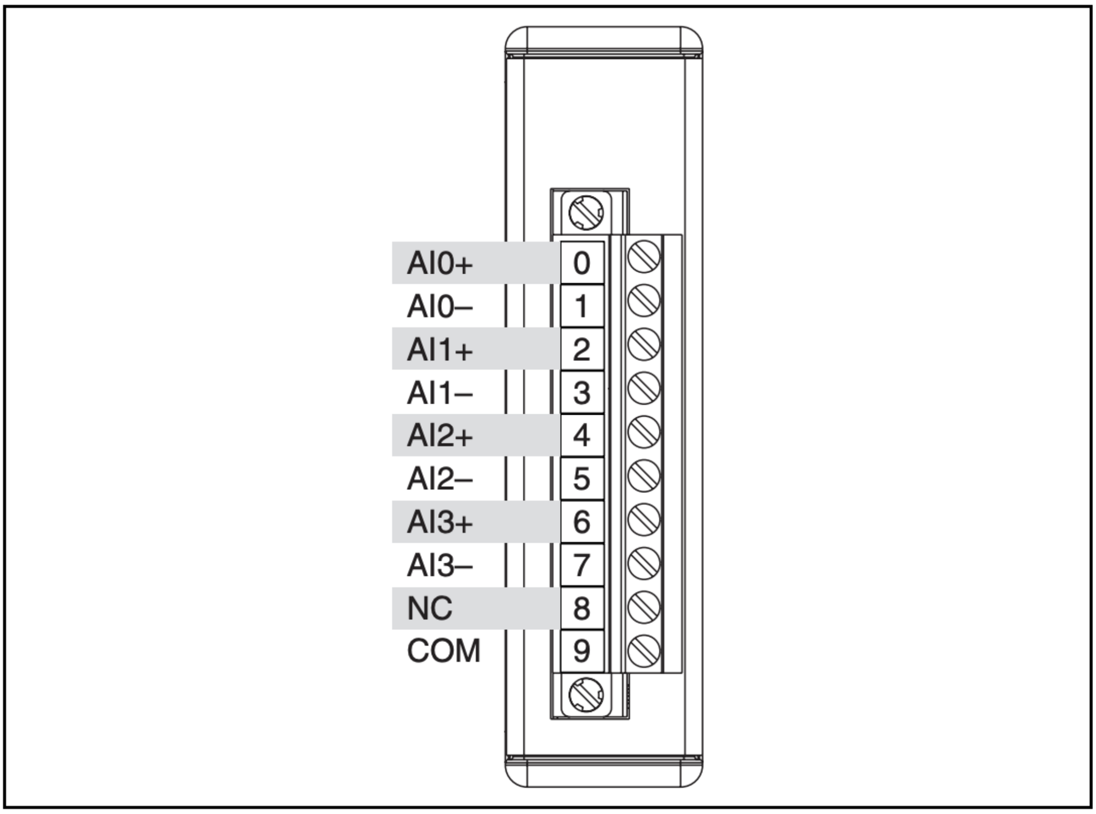


Figure 54: Terminal Assignments of the NI 9215 with Screw Terminal [22].

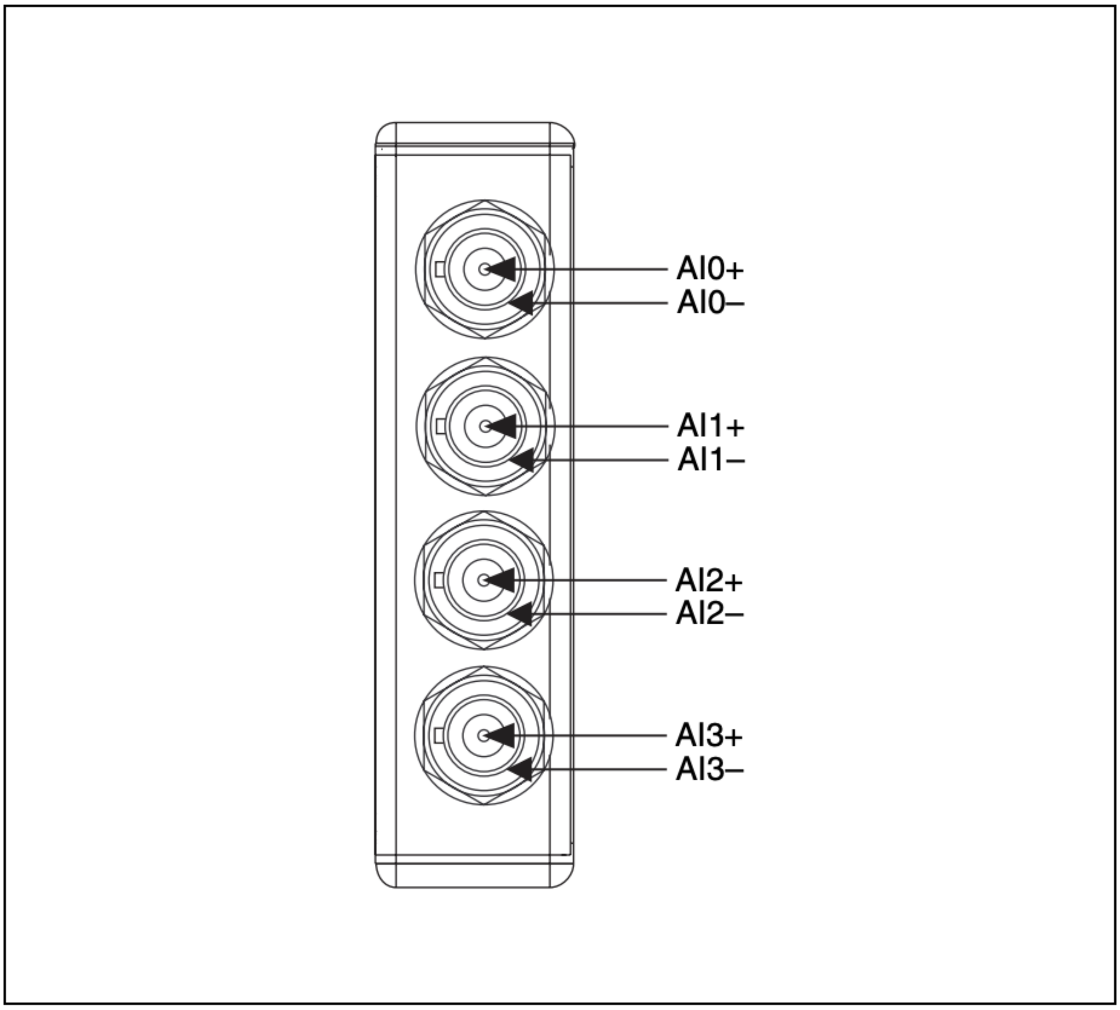


Figure 55: Connector Assignments of the NI 9215 with BNC [22].

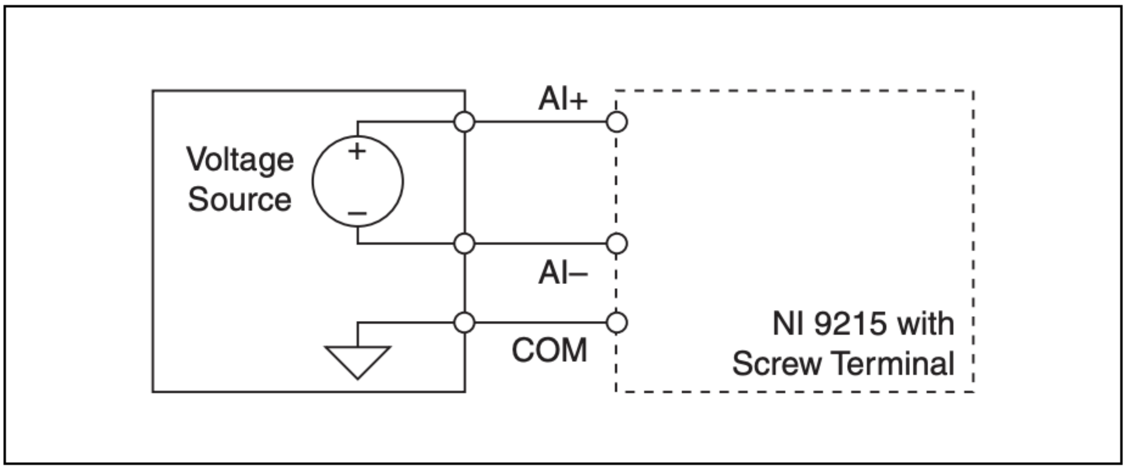


Figure 56: Connecting a Grounded Differential Voltage Signal to the NI 9215 with Screw Terminal.

B.2 LabVIEW

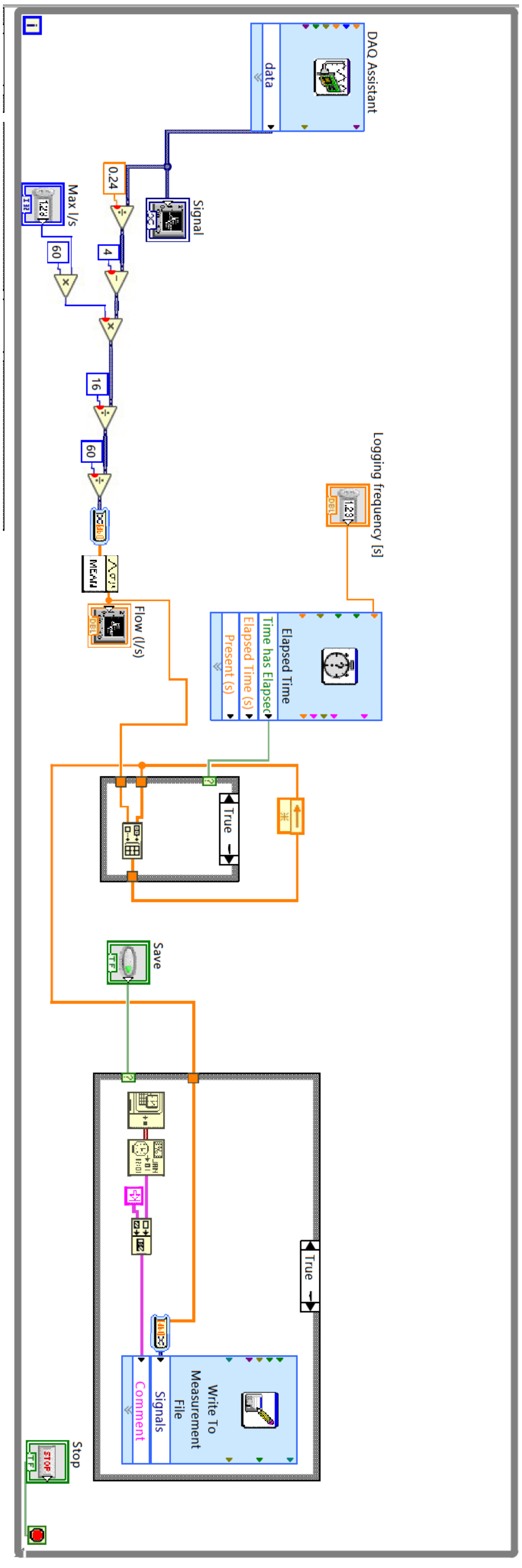


Figure 57: Programming scheme in LabVIEW.

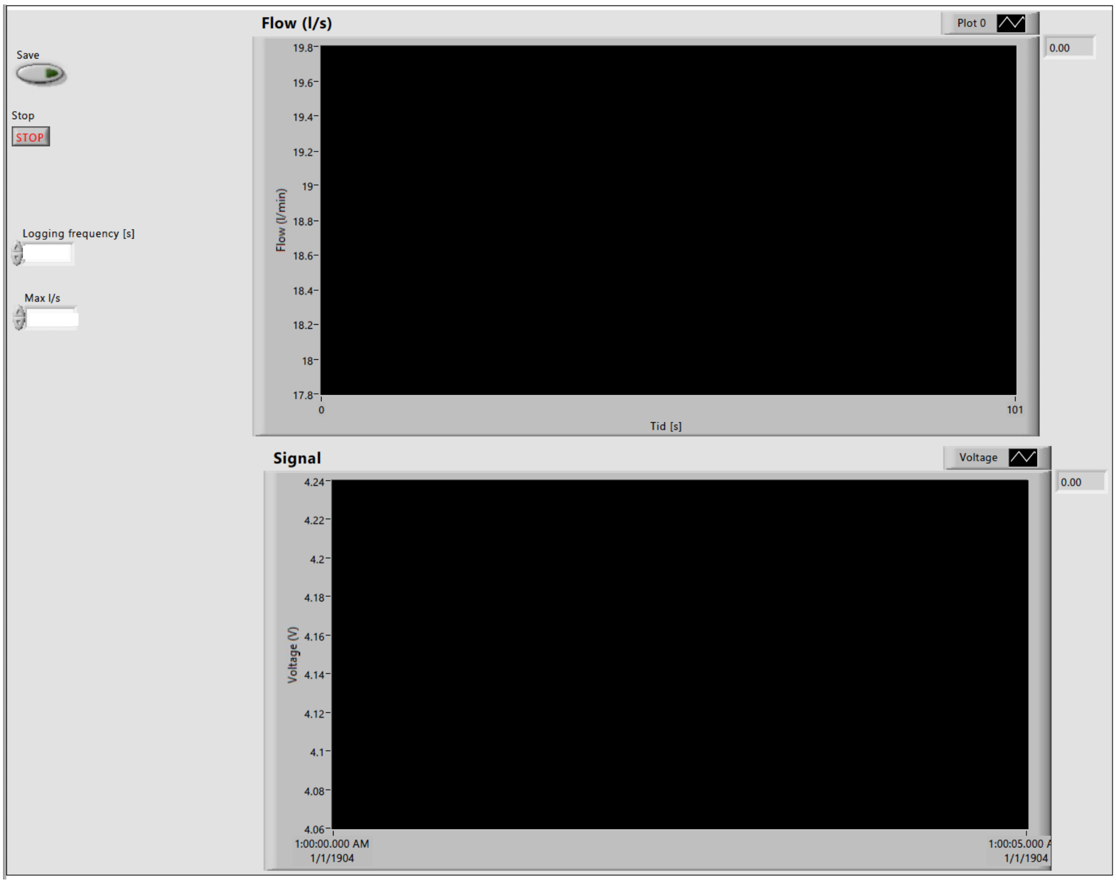


Figure 58: Control screen LabVIEW.

B.3 Set up and equipment for data logging

National Instruments has developed a compact USB-chassis for use with different of the modules available. For this system an NI cDAQ-9174, 4-slots chassis is used which communicating with the computer using USB. The chassis is capable of fast measuring and has high resolution [21]. The chassis is shown in Fig. 59.

Figure 59: NI cDAQ-9174.

The voltage output module to collect the voltage signal, a voltage module named NI-9215 [21] is used. This is a voltage output module which works with a wide range of components. Since the PF220B is producing an active current pulse, a resistance is coupled in series to develop a voltage signal.

Figure 60: NI-9215.

When coupling the cables, the following coupling (Fig. 61) scheme was used. NOTE, with a resistance in series with the current loop (Fig.11).

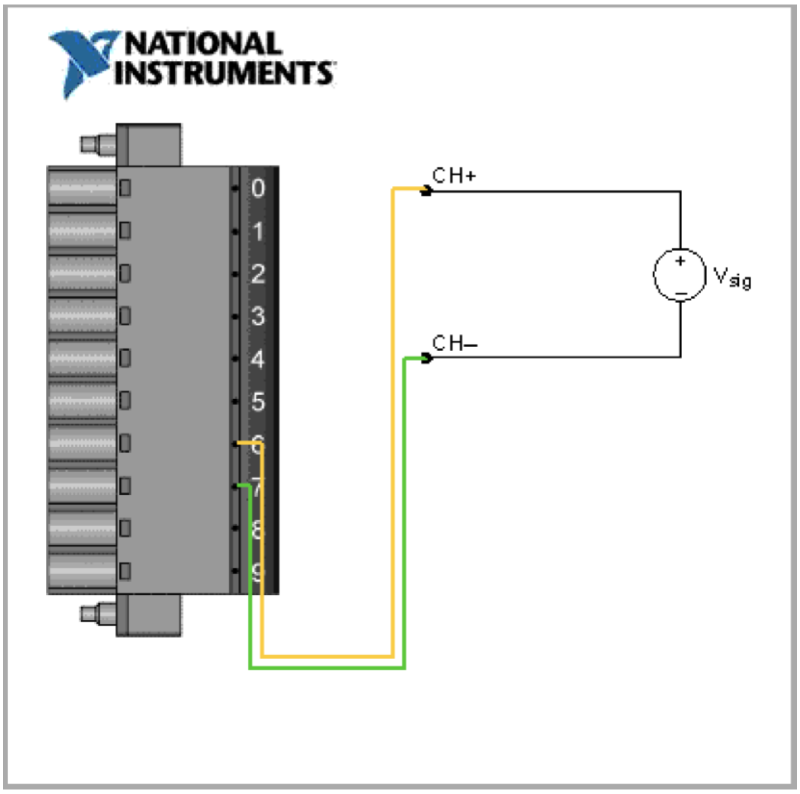


Figure 61: Coupling scheme.

Appendix C Test measurements

C.1 Reference measurements Spicheren Swimming

This section presents some reference measurements that has been done to validate our measurements and, the to confirm the reliability for the PF220B.

It is beneficial to perform both assembly and testing of the PF220B. It was hard to find a pipe with the flow close to 200 [l/s]. Spicheren swimming do have a purification system for both the swimming pool and the whirlpool. In this system there are instruments that measure the flow. There was therefore a possibility to compare the flow from the instruments there, with the measurements from the PF220B. This is to get a scale or a reference on the measurements.

C.1.1 Reference measurements purification system for swimming pool

The first test that was done, was with the purification system for the swimming pool. The size of the pipe is almost the same as in Brokke and Holen, but in plastic and also a bit thicker. The parameters that were put into the PF220B are listed up in Table 37.

Table 37: Input parameters PF220B swimming pool.

Parameters	Values
Pipe outside diameter	200 mm
Pipe wall thickness	8.00 mm
Pipe wall material	Plastic
Fluid type	Water
Fluid temperature	27.5℃
Sensor mode	Reflex
Sensor separation distance	109.56 mm

The totalizer function[3] in the PF220B was used and tested over several different time intervals.

The test has been done with time intervals 1, 5, 15, 30 and 60 seconds. The reason for this, was to find the best or the better intervals to use in our measurement. In Table 38 results from the measurements for each of the five different intervals are presented. The same results are presented in different plots in Fig. 62.

[3] The Totalizer function for the PF220B is an inbuilt function. The flow is then summarized over a selected amount of time, to see how the average flow was over the selected time. A handy function when studying flows over time. See PF220B manual in [20] for more information.

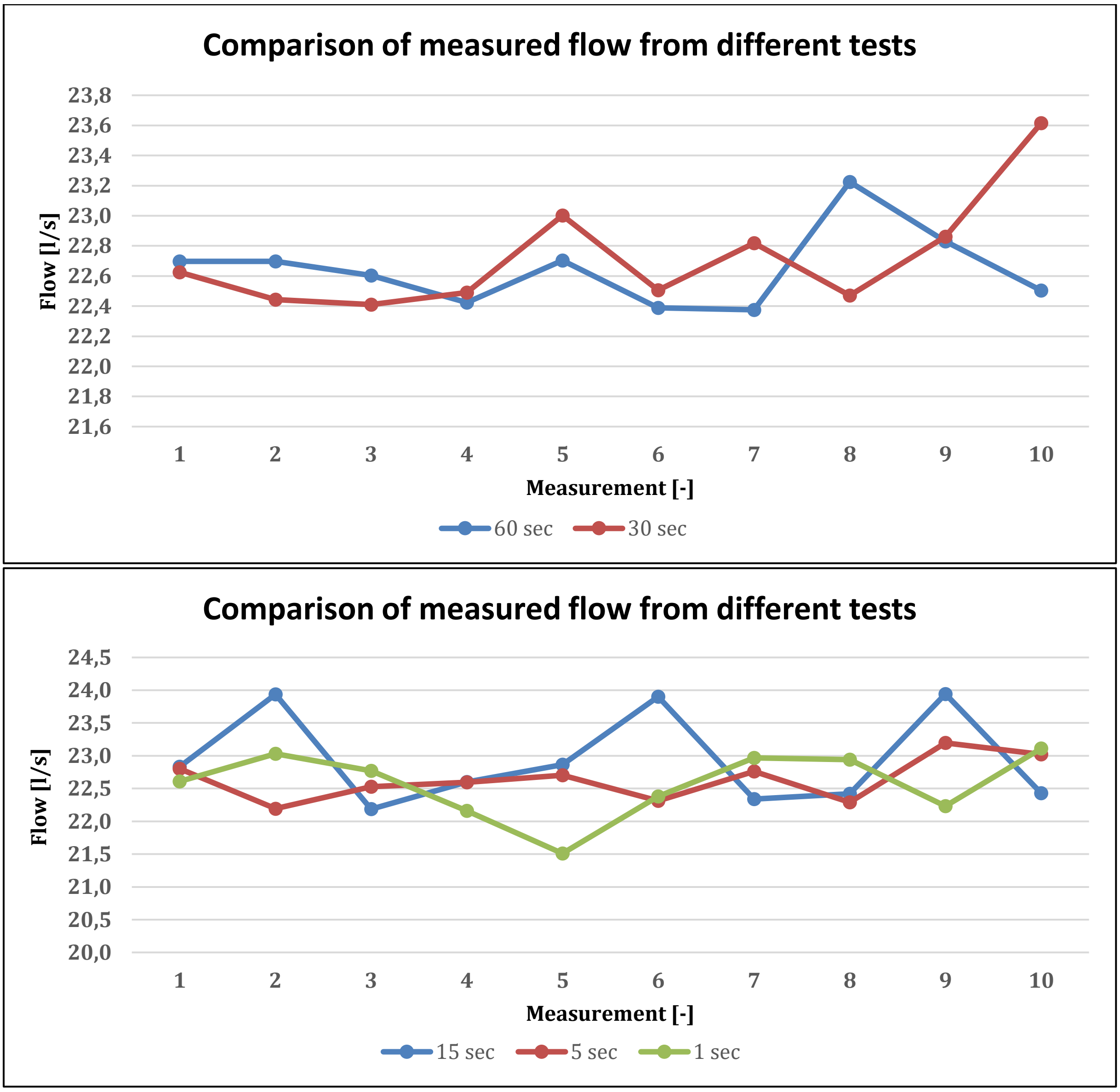


Figure 62: Plots from measurements done with different time intervals.

The different plots in Fig. 62, are showing 10 of the 30 measurements that have been done. By comparing the different results, there were minimal difference between the results from the different time intervals. The average measurement from each of the different time intervals are presented in Table 38. The table show that measurements done in time interval 30 seconds and 60 seconds are reliable, because of the least deviation. Although the averaged values for time interval 1 and 5 seconds seem to be good, their variability throughout the test (Fig. 62) is high, implying that reliable measurements will require lots of tests.

Through the test it was also cleared out that with a pipe of approximately 200 mm in diameter, it was reasonable to set the transducers in reflex mode. For a pipe at that size, diagonal mode was also considered. The results for the test showed that the reflex mode gave a better signal, better setup and more reasonable numbers.

Table 38: Average values from test with different time intervals, including the deviation.

Test interval	1 sec	5 sec	15 sec	30 sec	60 sec
Average value PF220B [l/s]	22.6	22.6	23.0	22.7	22.6
Average value Spicheren instrument [l/s]	25.3	24.6	24.3	24.0	23.8
Deviation [%]	10.7	8.1	5.3	5.4	5.0

C.1.2 Reference measurements purification system for whirlpool

The purification system for the whirlpool consisted of a pipe that was around half the size of the pipe from the swimming pool. A test was also done there, and all the input parameters are listed up in Table 39. There was a big difference in both temperature and sensor separation distance, compared with the tests using the swimming pool purification system (Table 37). Sensor mode were also tested, but the best mode to use was still the reflex mode.

Table 39: Input parameters PF220B whirlpool.

Parameters	Values
Pipe outside diameter	90 mm
Pipe wall thickness	4.30 mm
Pipe wall material	Plastic
Fluid type	Water
Fluid temperature	37.5°C
Sensor mode	Reflex
Sensor separation distance	94.67 mm

Since test intervals using 30 and 60 seconds gave the results with the lowest deviation with the system for the swimming pool, those intervals have also been used in this test. The deviation was of course a bit higher in these tests because of smaller flowrate. The results gave an indication compared with the measured value from the instruments installed there. The results are presented in Table 40. A source of error in this measurement was amongst other the fluid velocity. The flow corresponded to a flow that is under minimum velocity 0.1 [m/s] for the PF220B. This means that the results from the measurements could be unclear or inaccurate.

Table 40: Average values from test with different time intervals, including the deviation.

Test interval	30 sec	60 sec
Average value PF220B [l/s]	5.4	5.5
Average value Spicheren instrument [l/s]	6.4	6.1
Deviation [%]	15.6	9.8

C.1.3 Fuji Electrics Portaflow test whirlpool

Table 41: Average values from test with deviation between PF220B and Fuji Electrics Portaflow.

Test interval	30 sec	60 sec
Average value Fuji Electrics Portaflow [l/s]	5.3	5.4
Average value PF220B [l/s]	5.4	5.5
Average value Spicheren instrument [l/s]	6.4	6.1
Deviation Fuji Electrics Portaflow [%]	17.2	11.5
Deviation PF220B [%]	15.6	9.8
Deviation between them [%]	-1.6	-1.7

C.1.4 Portaflow 220B logger test

Table 42: Average values from test with deviation between PF220B and PF220B with logger.

Test interval	30 sec	60 sec
Average value PF220B [l/s]	22.7	22.6
Average value PF220B with logger [l/s]	22.5	22.6
Average value Spicheren instrument [l/s]	24.0	23.8
Deviation PF220B [%]	5.4	5.0
Deviation PF220B with logger [%]	6.3	5.0
Deviation between them [%]	-0.9	0

C.1.5 Complete table with test results Spicheren 200 mm diameter pipe

Table 43: Test results Spicheren 200 mm diameter pipe.

60 sec (l)	(l/s)	30 sec (l)	(l/s)	15 Sec (l)	(l/s)	5 sec (l)	(l/s)	1 sec (l/s)
1361.8	22.70	678.78	22.63	342.5	22.83	114.01	22.80	22.61
1361.81	22.70	673.3	22.44	359.07	23.94	110.97	22.19	23.03
1356.25	22.60	672.31	22.41	332.79	22.19	112.65	22.53	22.77
1345.42	22.42	674.71	22.49	339.01	22.60	112.98	22.60	22.16
1362.16	22.70	690.08	23.00	342.95	22.86	113.52	22.70	21.51
1343.38	22.39	675.15	22.51	358.54	23.90	111.57	22.31	22.38
1342.54	22.38	684.55	22.82	335.07	22.34	113.81	22.76	22.97
1393.5	23.23	674.15	22.47	336.28	22.42	111.46	22.29	22.94
1369.77	22.83	685.85	22.86	359.15	23.94	115.98	23.20	22.23
1350.22	22.50	708.45	23.62	336.47	22.43	115.1	23.02	23.11
1393.5	23.23	672.31	22.41	332.79	22.19	110.97	22.19	21.51
1393.5	23.23	672.31	22.41	332.79	22.19	110.97	22.19	22.16
1369.77	22.83	673.3	22.44	335.07	22.34	111.46	22.29	22.23
1369.77	22.83	673.3	22.44	335.07	22.34	111.46	22.29	22.38
1362.16	22.70	674.15	22.47	336.28	22.42	111.57	22.31	22.61
1362.16	22.70	674.15	22.47	336.28	22.42	111.57	22.31	22.77
1361.81	22.70	674.71	22.49	336.47	22.43	112.65	22.53	22.94
1361.81	22.70	674.71	22.49	336.47	22.43	112.65	22.53	22.97
1361.8	22.70	675.15	22.51	339.01	22.60	112.98	22.60	23.03
1361.8	22.70	675.15	22.51	339.01	22.60	112.98	22.60	23.11
1356.25	22.60	678.78	22.63	342.5	22.83	113.52	22.70	23.11
1356.25	22.60	678.78	22.63	342.5	22.83	113.52	22.70	23.03
1350.22	22.50	684.55	22.82	342.95	22.86	113.81	22.76	22.97
1350.22	22.50	684.55	22.82	342.95	22.86	113.81	22.76	22.94
1345.42	22.42	685.85	22.86	358.54	23.90	114.01	22.80	22.77
1345.42	22.42	685.85	22.86	358.54	23.90	114.01	22.80	22.61
1343.38	22.39	690.08	23.00	359.07	23.94	115.1	23.02	22.38
1343.38	22.39	690.08	23.00	359.07	23.94	115.1	23.02	22.23
1342.54	22.38	708.45	23.62	359.15	23.94	115.98	23.20	22.16
1342.54	22.38	708.45	23.62	359.15	23.94	115.98	23.20	21.51
Average	**22.64**		**22.72**		**22.95**		**22.64**	**22.57**

C.1.6 Rig for test measuring

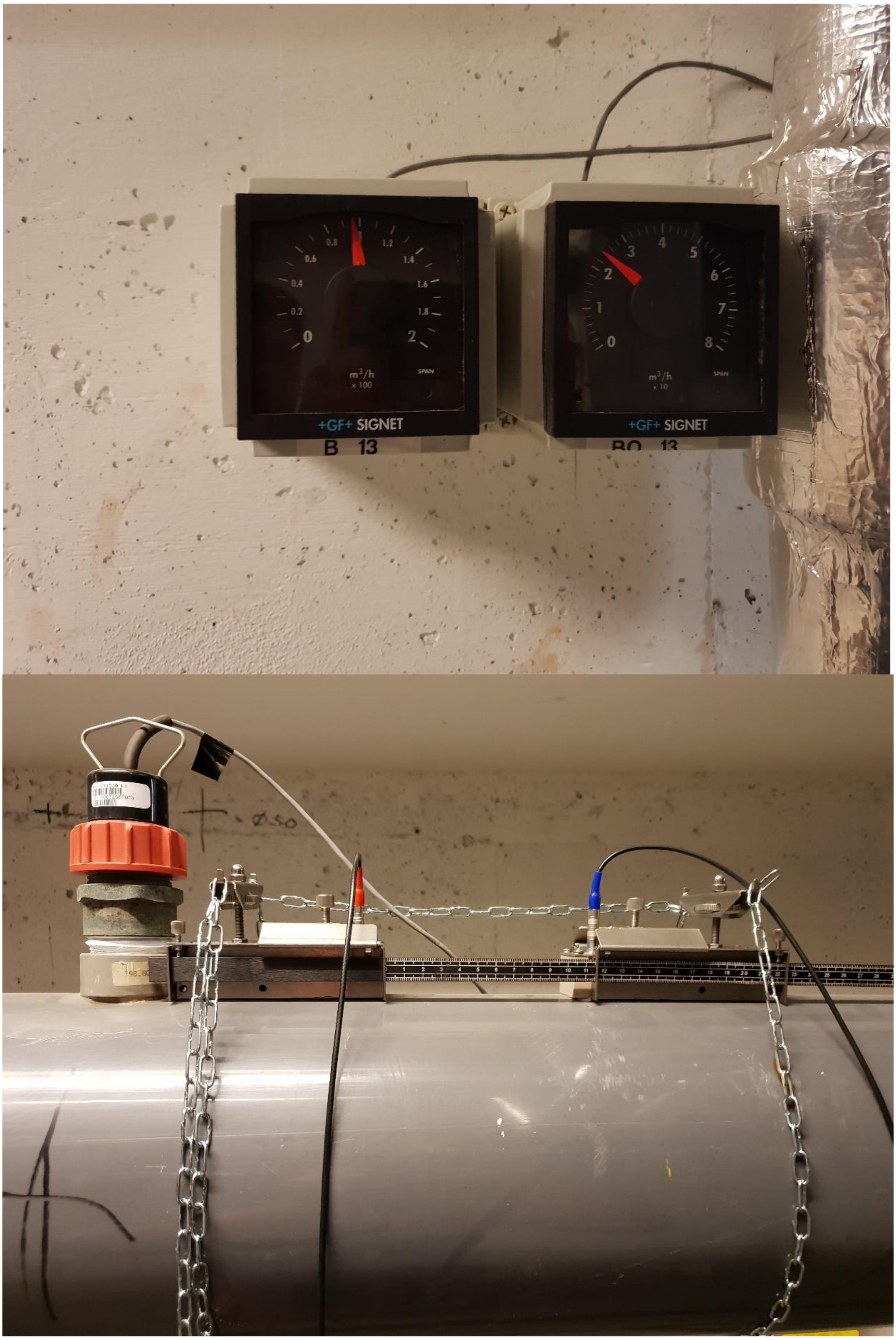


Figure 63: Both measuring instruments at Spicheren and measuring point for PF220B at Spicheren.

C.2 Selection of the best measuring point Francis Turbines

C.2.1 Measurements and results

There were two different places to attach the transducers that were tested on turbine 4. On the top of the runner, a pipe is following the runner circularly. This pipe does collect leakage water from the labyrinth in the runner sealings. Otrakraft wanted to mount the transducers close to the output of this pipe. In this area there was a lot of vibrations in the pipe and also very unstable flow. The other area to mount the transducers was about to meters from the first point. At that location there were no noticeable vibrations or unstable flow. In Figs. 65-67 in appendix C.2.2, pictures of the installation measuring points are shown. Fig. 65 and Fig. 66 are from the measuring point nr. 1, close to the output of the pipe mentioned above. Fig. 67 is showing the measuring point nr. 2.

The measuring method used in these measurements is the same method as described in the tests at Spicheren. The summarizer function in PF220B is used to sum the flow for one minute, and then an average value in [l/s] is found. This method was repeated fifteen times. This was at first done on turbine 4 on both different measuring points.

The results of these measurements are shown in Table 44 [3]. It can be seen that the flow is much more unstable and changing between the measurements at measuring point nr. 1. Comparing with measuring point nr. 2 the flow is here higher and much more stable.

Table 44: Measurements from different locations.

Measurement	Measuring point 1 $\overline{(l/s]}$	Measuring point 2 $\overline{(l/s)}$
1	104.4	136.0
2	106.1	135.6
3	111.9	136.0
4	107.6	136.1
5	102.4	135.7
6	106.6	135.8
7	108.6	135.9
8	101.1	135.5
9	78.6	135.4
10	98.8	135.0
11	110.8	135.3
12	113.8	135.1
13	96.5	135.7
14	96.4	135.2
15	98.3	135.2

With the results from the measurements done in the different locations on the pipe, a conclusion is made. The values from measuring point nr. 2 are more stable and also the closest to the assumptions made by Otrakraft. Fig. 64 also shows how stable the measurements at measuring point nr. 2 are, compared with the measurements from measuring point nr. 1. With reference to the measurements done at turbine 4, measuring point nr. 2 has been used in the measurements of the other three turbines.

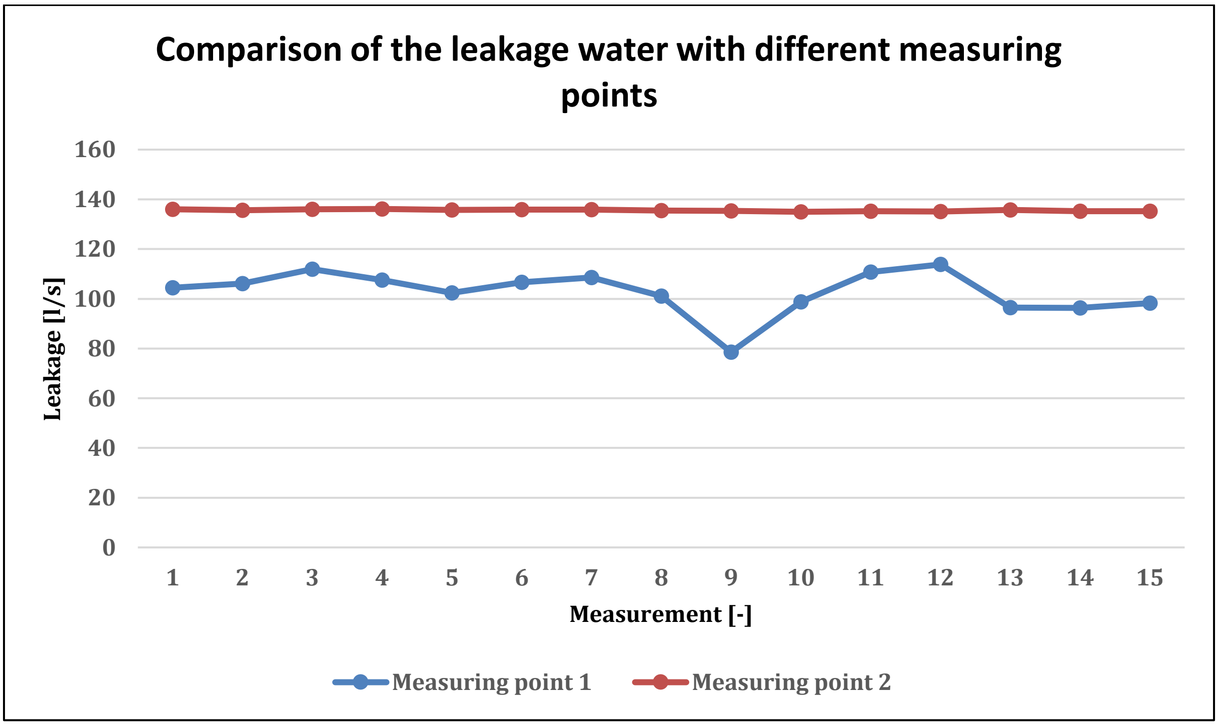


Figure 64: Comparison of the leakage water with different measuring points.

C.2.2 Measuring point location

The first measuring point that the PF220B was set to is shown with the circle in Fig. 65. The measuring point was first set close to the outlet from the runner, shown in Fig. 66.

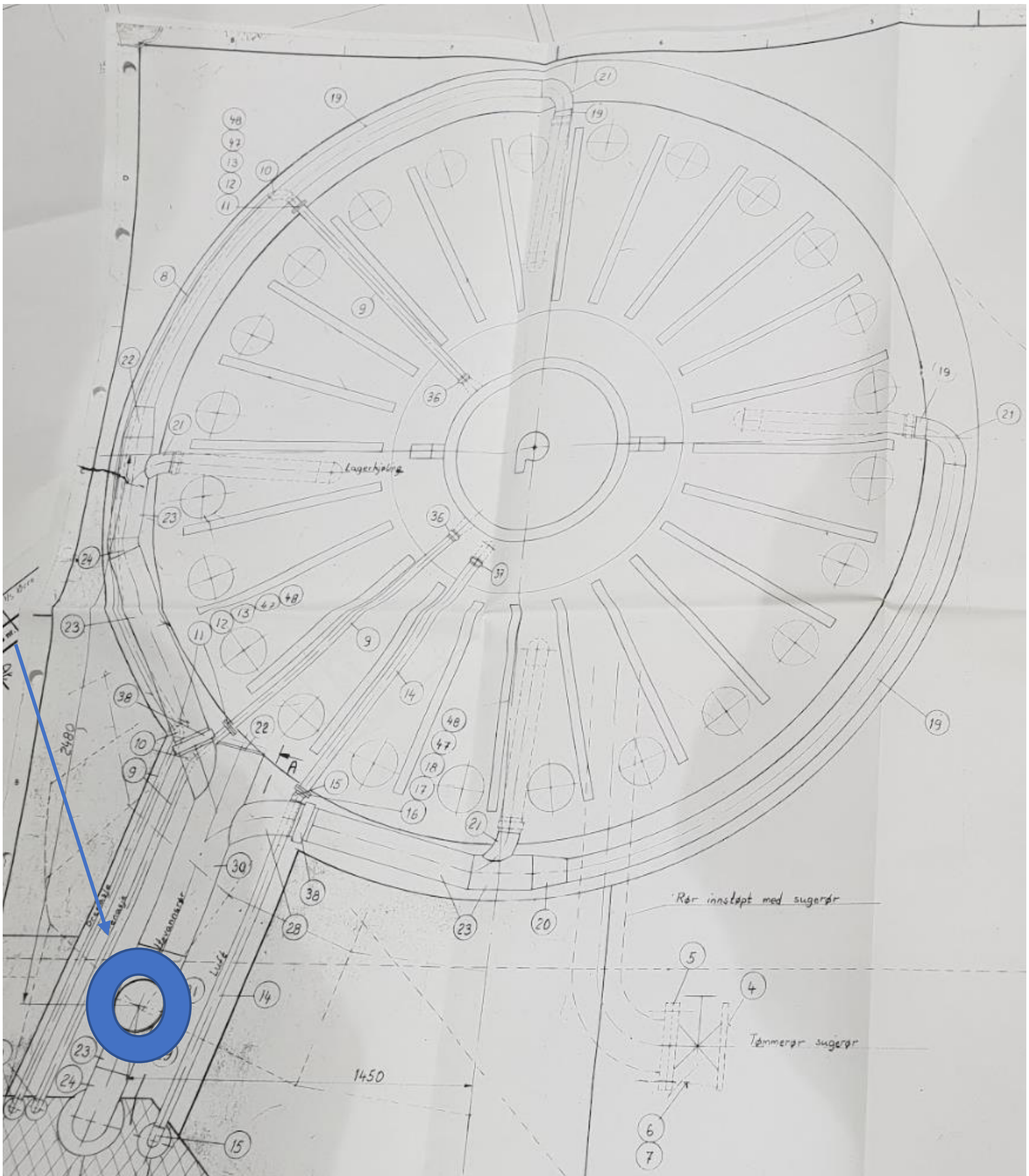


Figure 65: Measuring point 1 PF220B at Brokke.

Figure 66: Measuring point 1 PF220B at Brokke.

Figure 67: Measuring point 2 PF220B at Brokke.

Fig. 67 shows the final rig for the best measuring. This point was preferred because it gave a steadier flow and more correctly picture of the measurement. The measuring point was set approx. 2 meters further out on the pipe, away from the outlet of the runner and the band.

C.3 Stability testing on Francis Turbines Brokke

As can be seen in Chapter 4.5 - the operational central at Brokke are monitoring the different turbines and logging the operational parameters for each turbine. The data sets that are collected from each turbine can be expressed in either seconds, minutes or hours. Thus, it is an aim for this test to see how the coloration between the leakage expressed in seconds vs. min behaves. The testing period of time is set to 15 minutes for each turbine. The purpose of this test is to see how the leakage is over time.

Table 45: Operational parameters at stated testing periods.

	Turbine 1	Turbine 2	Turbine 3	Turbine 4
Test period	8th March at 09:58	30th January at 08:34-08:49	23rd January at 08:22-08:37	6th February at 08:42-08:57
Power [~MW]	58	68	59	79
Speed [~RPM]	375	375	375	375

C.3.1 Turbine 1 – Test 1 Second and 1 Minute

Test 1 Second:

For turbine 1, a testing of first one second was chosen. The results can be seen in both Fig. 68 and Table 46.

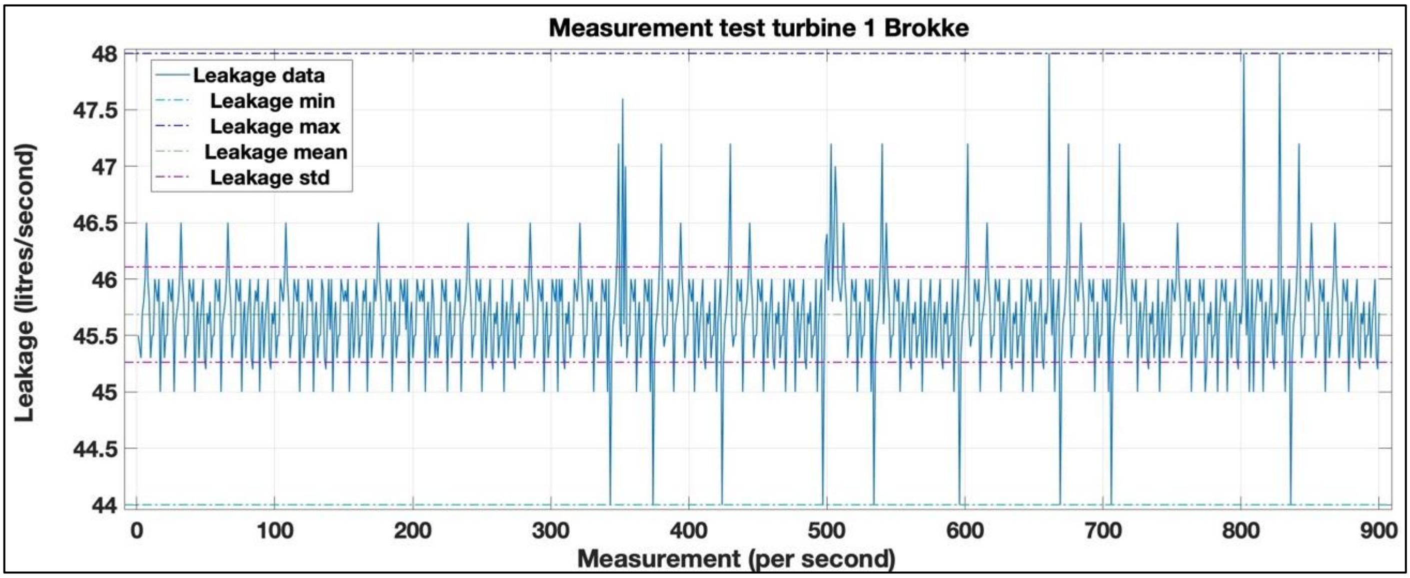


Figure 68: Measurement test at turbine 1 Brokke at every second.

Table 46: Data statistics turbine 1 Brokke - at 1 second.

Data statistics	Leakage (liters/second)
Min	44
Max	48
Mean	45.7
Standard deviation	0.42

Test 1 Minute:

In Fig. 69 and Table 47, the results when using an average of 1 minute can be seen.

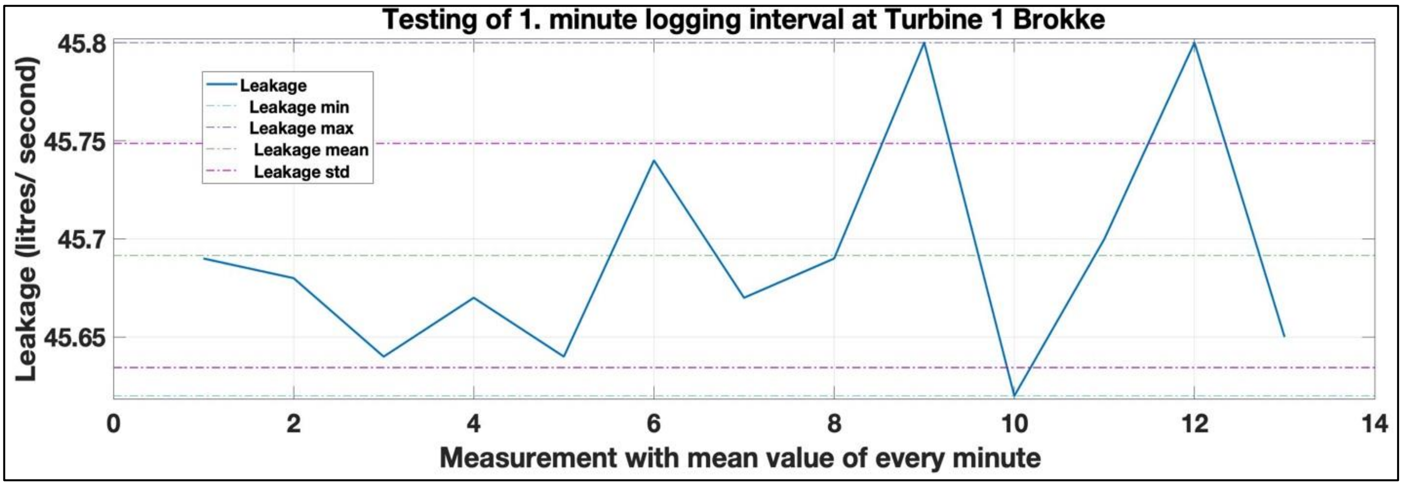


Figure 69: Measurement test at turbine 1 Brokke with mean value of every minute.

Table 47: Data statistics turbine 1 Brokke - at 1 minute.

Data statistics	Leakage (liters/second)
Min	45.6
Max	45.8
Mean	45.68
Standard deviation	0.18

C.3.2 Turbine 2 – Test 1 Second and 1 Minute

Test 1 Second:

For turbine 2, a testing of first one second was chosen. The results can be seen in both Fig. 70 and Table 48.

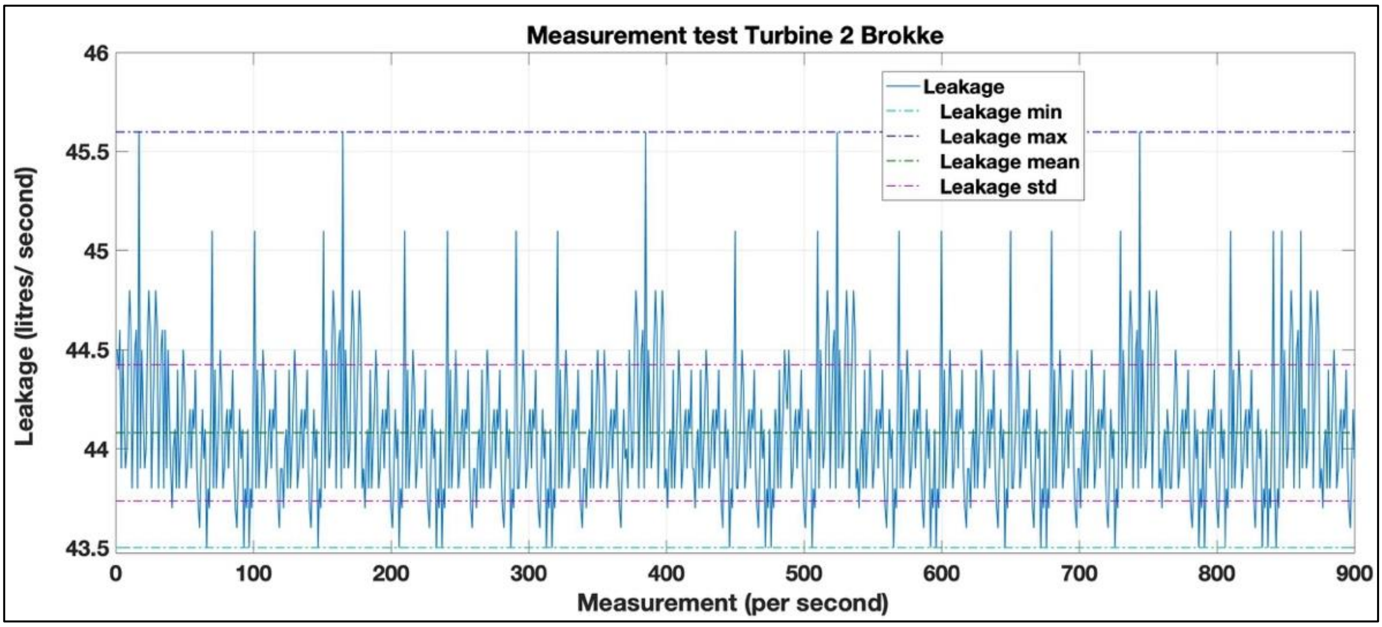


Figure 70: Measurement test at turbine 2 Brokke at every second.

Table 48: Data statistics turbine 2 Brokke - at 1 second.

Data statistics	Leakage (liters/second)
Min	43.5
Max	45.6
Mean	44.1
Standard deviation	0.34

Test 1 Minute:

In Fig. 71 and Table 49 the results when using an average of 1 minute can be seen.

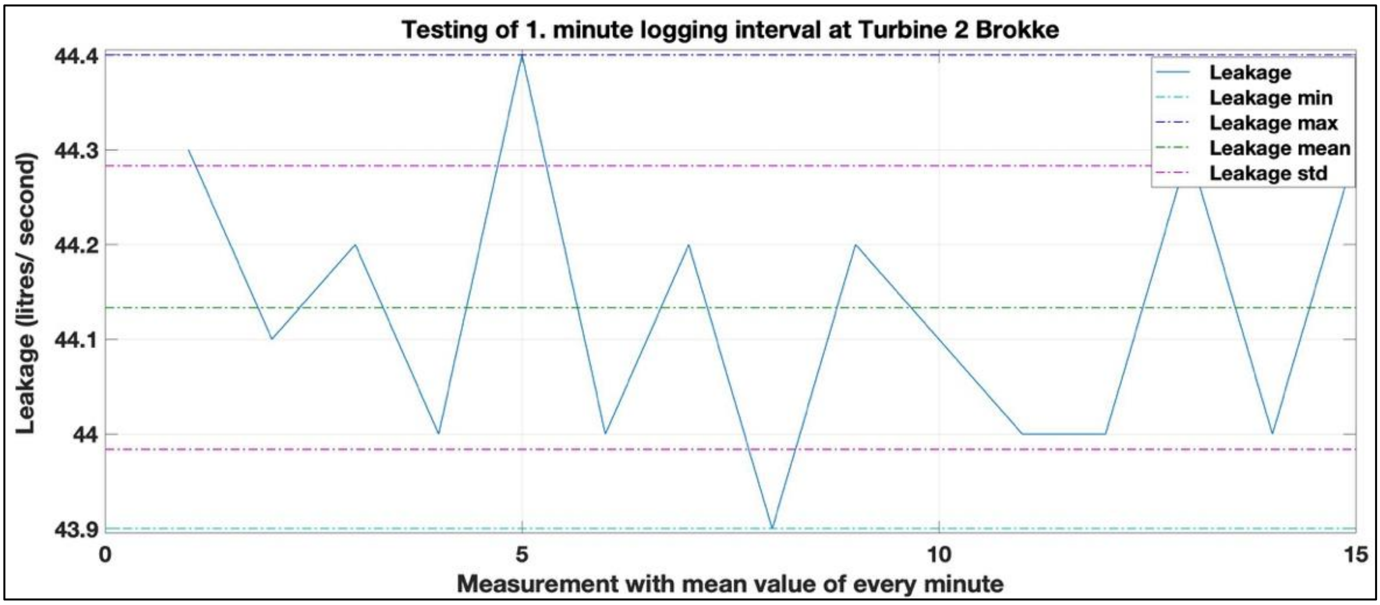


Figure 71: Measurement test at turbine 2 Brokke with mean value of every minute.

Table 49: Data statistics turbine 2 Brokke - at 1 minute.

Data statistics	Leakage (liters/second)
Min	43.9
Max	44.4
Mean	44.1
Standard deviation	0.15

C.3.3 Turbine 3 – Test 1 Second and 1 Minute

Test 1 Second:

For turbine 3, a testing of first one second was chosen. The results can be seen in both Fig. 72 and Table 50.

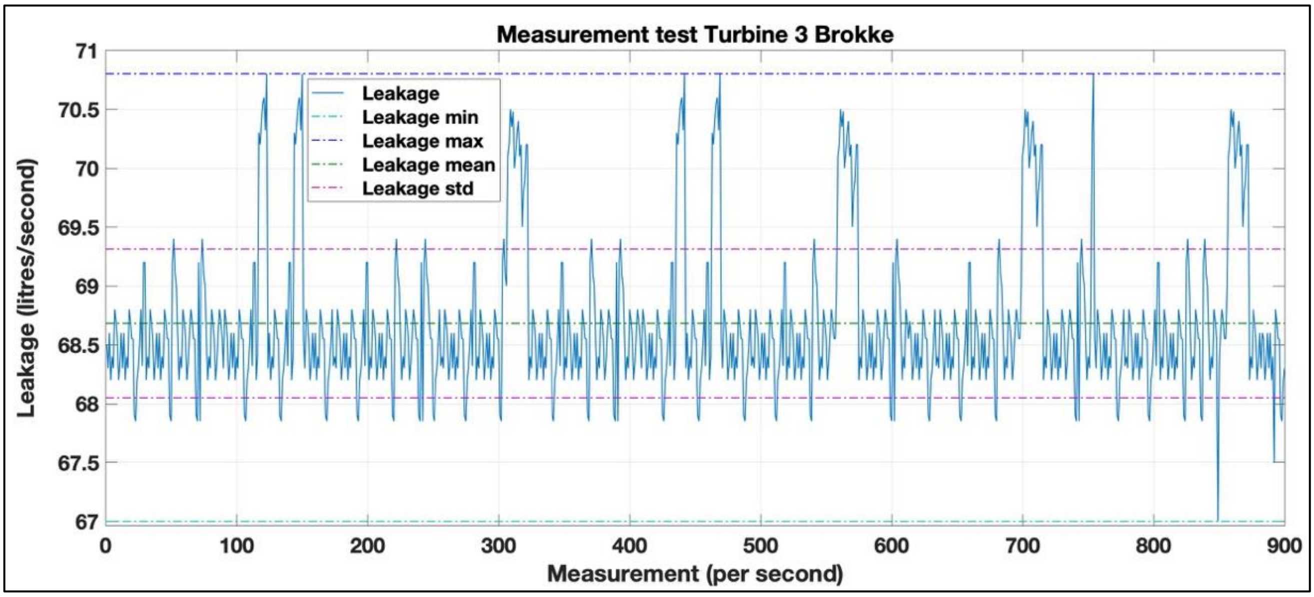


Figure 72: Measurement test at turbine 3 Brokke at every second.

Table 50: Data statistics turbine 3 Brokke - at 1 second.

Data statistics	Leakage (liters/second)
Min	67
Max	70.8
Mean	68.7
Standard deviation	0.63

Test 1 Minute:

In Fig. 73 and Table 51 the results when using an average of 1 minute can be seen.

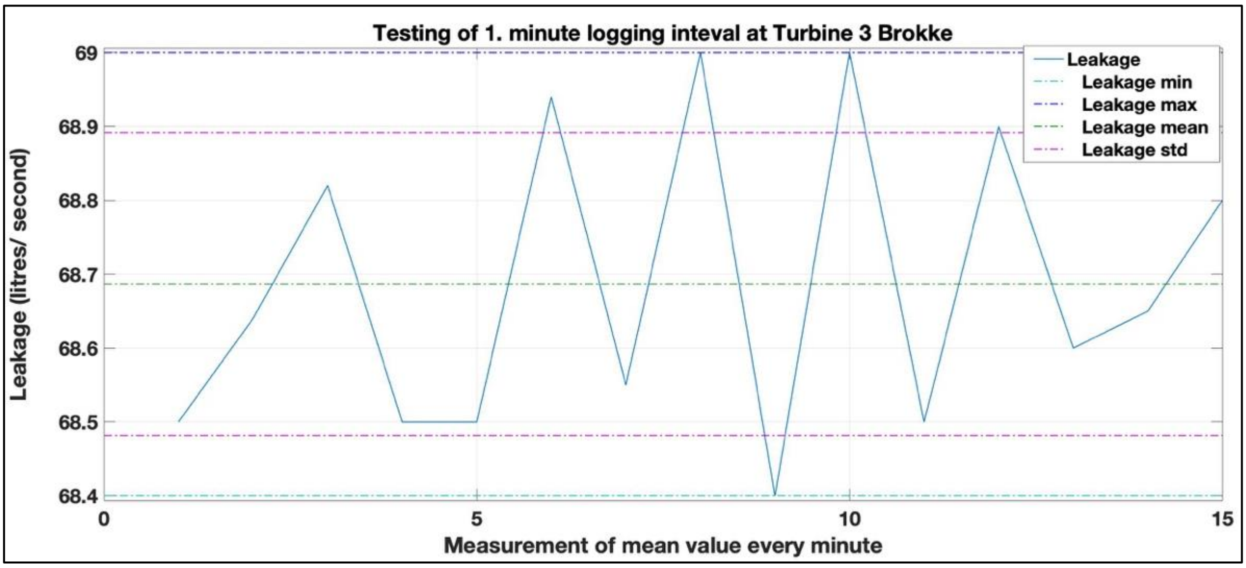


Figure 73: Measurement test at turbine 3 Brokke with mean value of every minute.

Table 51: Data statistics turbine 3 Brokke - at 1 minute.

Data statistics	Leakage (liters/second)
Min	68.4
Max	69
Mean	68.7
Standard deviation	0.21

C.3.4 Turbine 4 - Test 1 Second and 1 Minute

Test 1 Second:

For turbine 4, a testing of first one second was chosen. The results can be seen in both Fig. 74 and Table 52.

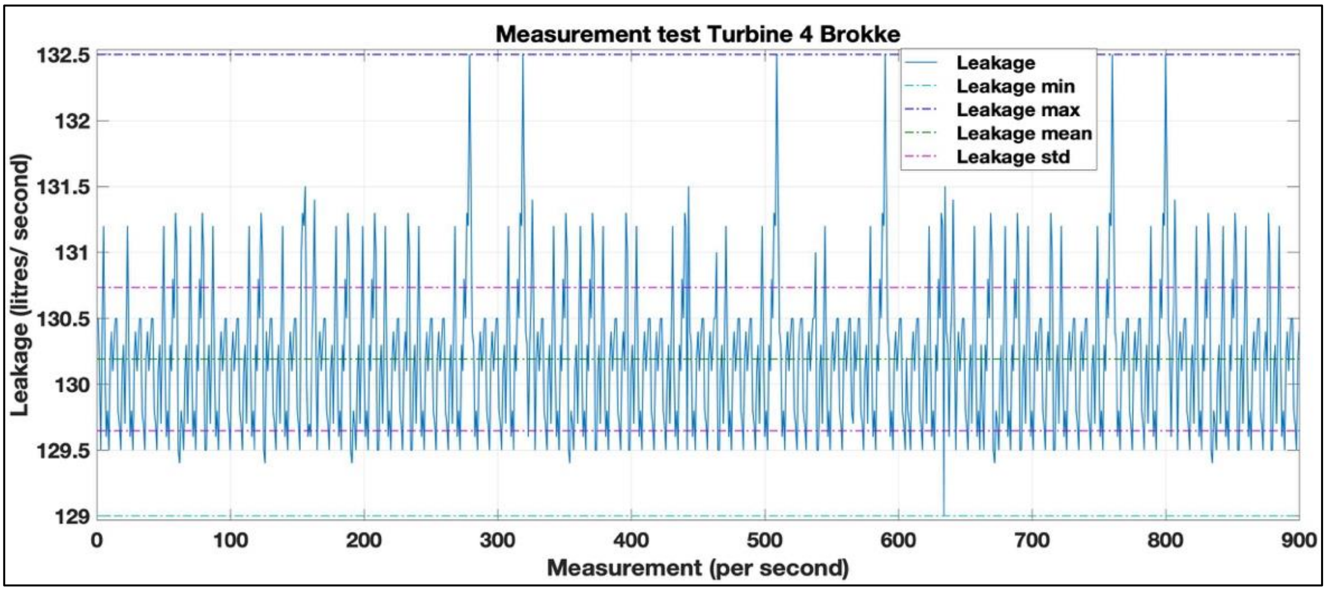


Figure 74: Measurement test at turbine 4 Brokke at every second.

Table 52: Data statistics turbine 4 Brokke - at 1 second.

Data statistics	Leakage (liters/second)
Min	129
Max	132.5
Mean	130.2
Standard deviation	0.54

Test 1 Minute:

In Fig. 75 and Table 53 the results when using an average of 1 minute can be seen.

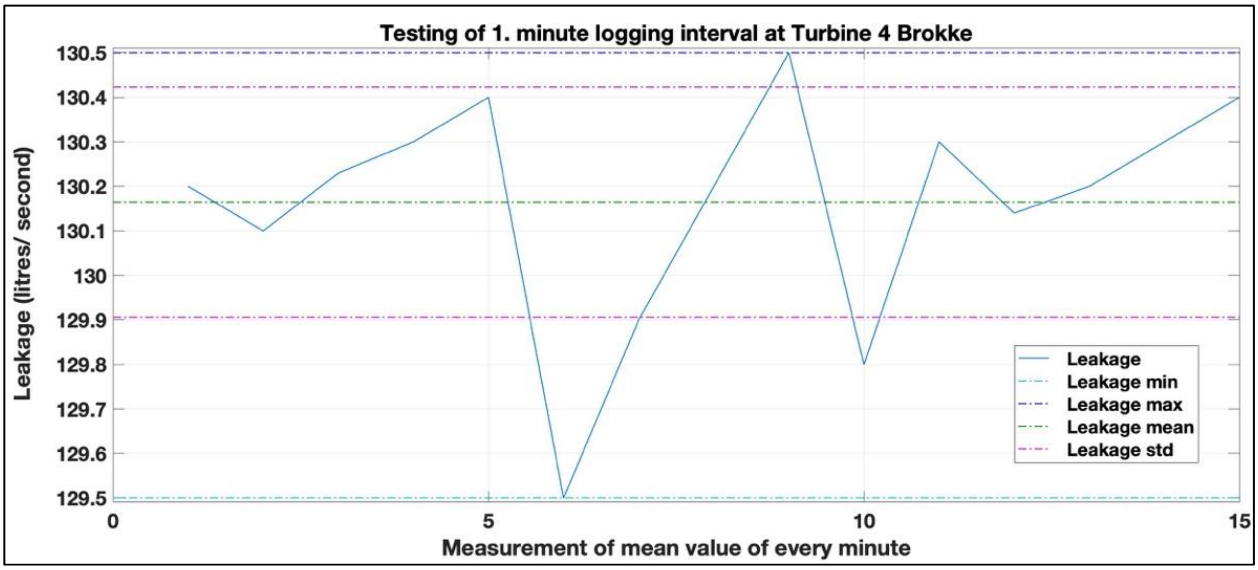


Figure 75: Measurement test at turbine 4 Brokke with mean value of every minute.

Table 53: Data statistics turbine 4 Brokke - at 1 minute.

Data statistics	Leakage (liters/second)
Min	129.5
Max	130.5
Mean	130.2
Standard deviation	0.26

Appendix D Energy Research Project

D.1 Calculations and measurements for analysis

Calculations turbine 1

Table 54: Relevant calculations and measurements for analysis Turbine 1 computed in Energy Research Project.

Time:	Leakage (l/s)	Prod. Water (l/s)	Leakage Case 1 (%)	Leakage Case 2 (%)	Leakage Case 3 (%)	Leakage Case 4 (%)	Potential (kW) Case 1	Potential (kWh) Case1	(MNOK/year) Case 1	(MNOK/year) Case 2	(MNOK/year) Case 3	(MNOK/year) Case 4
15,07,00	40,71	23956	0,17	0,34	0,51	0,68	104	729753	0,28	0,57	0,85	1,14
15,08,30	40,80	24003	0,17	0,34	0,51	0,68	104	731229	0,28	0,57	0,85	1,14
15,10,0	40,71	24142	0,17	0,34	0,51	0,67	104	729750	0,28	0,57	0,85	1,14
15,11,30	40,96	24072	0,17	0,34	0,51	0,68	105	734219	0,29	0,57	0,86	1,14
15,13,0	41,25	24072	0,17	0,34	0,51	0,69	106	739318	0,29	0,58	0,86	1,15
15,14,30	40,89	24142	0,17	0,34	0,51	0,68	105	732940	0,29	0,57	0,86	1,14
15,16,00	40,99	24188	0,17	0,34	0,51	0,68	105	734700	0,29	0,57	0,86	1,14
15,17,30	40,94	24119	0,17	0,34	0,51	0,68	105	733884	0,29	0,57	0,86	1,14
15,19,00	40,85	24188	0,17	0,34	0,51	0,68	105	732137	0,29	0,57	0,86	1,14
15,20,30	41,24	24188	0,17	0,34	0,51	0,68	106	739157	0,29	0,58	0,86	1,15
15,22,00	41,11	24188	0,17	0,34	0,51	0,68	105	736836	0,29	0,57	0,86	1,15
15,23,30	40,70	24049	0,17	0,34	0,51	0,68	104	729460	0,28	0,57	0,85	1,14
15,25,00	40,69	24142	0,17	0,34	0,51	0,67	104	729311	0,28	0,57	0,85	1,14
15,26,30	41,06	24142	0,17	0,34	0,51	0,68	105	735952	0,29	0,57	0,86	1,15
15,28,00	40,58	24072	0,17	0,34	0,51	0,67	104	727330	0,28	0,57	0,85	1,13
Average	**40,90**	**24111**	**0,17**	**0,34**	**0,51**	**0,68**	**105**	**733065**	**0,29**	**0,57**	**0,86**	**1,14**

Calculations turbine 2

Table 55: Relevant calculations and measurements for analysis Turbine 2 computed in Energy Research Project.

Time:	Leakage (l/s)	Prod. Water (l/s)	Leakage Case 1 (%)	Leakage Case 2 (%)	Leakage Case 3 (%)	Leakage Case 4 (%)	Potential (kW) Case 1	Potential (kWh) Case1	(MNOK/year) Case 1	(MNOK/year) Case 2	(MNOK/year) Case 3	(MNOK/year) Case 4
14,26,30	43,82	24304	0,18	0,36	0,54	0,72	112	785451	0,31	0,61	0,92	1,22
14,29,00	43,53	23956	0,18	0,36	0,55	0,73	111	780289	0,30	0,61	0,91	1,22
14,30,30	43,75	24188	0,18	0,36	0,54	0,72	112	784176	0,31	0,61	0,92	1,22
14,32,00	44,12	24049	0,18	0,37	0,55	0,73	113	790882	0,31	0,62	0,92	1,23
14,33,30	43,72	23863	0,18	0,37	0,55	0,73	112	783587	0,31	0,61	0,92	1,22
14,35,00	43,62	23863	0,18	0,37	0,55	0,73	112	781762	0,30	0,61	0,91	1,22
14,36,30	43,55	23956	0,18	0,36	0,55	0,73	112	780525	0,30	0,61	0,91	1,22
14,38,00	43,40	23956	0,18	0,36	0,54	0,72	111	777866	0,30	0,61	0,91	1,21
14,39,30	43,20	24165	0,18	0,36	0,54	0,72	111	774276	0,30	0,60	0,90	1,21
14,41,00	43,78	24142	0,18	0,36	0,54	0,73	112	784680	0,31	0,61	0,92	1,22
14,43,00	43,98	24188	0,18	0,36	0,55	0,73	113	788268	0,31	0,61	0,92	1,23
14,44,30	43,75	24072	0,18	0,36	0,55	0,73	112	784241	0,31	0,61	0,92	1,22
14,46,00	43,75	24304	0,18	0,36	0,54	0,72	112	784205	0,31	0,61	0,92	1,22
14,47,30	43,69	24142	0,18	0,36	0,54	0,72	112	783002	0,30	0,61	0,91	1,22
14,49,00	43,85	24188	0,18	0,36	0,54	0,73	112	786010	0,31	0,61	0,92	1,22
Average	**43,70**	**24089**	**0,18**	**0,36**	**0,54**	**0,73**	**112**	**783281**	**0,31**	**0,61**	**0,92**	**1,22**

Calculations turbine 3

Table 56: Relevant calculations and measurements for analysis Turbine 3 computed in Energy Research Project.

Time:	Leakage (l/s)	Prod. Water (l/s)	Leakage Case 1 (%)	Leakage Case 2 (%)	Leakage Case 3 (%)	Leakage Case 4 (%)	Potential (kW) Case 1	Potential (kWh) Case1	(MNOK/year) Case 1	(MNOK/year) Case 2	(MNOK/year) Case 3	(MNOK/year) Case 4
13,44,00	66,83	23330	0,29	0,57	0,86	1,15	171	1197866	0,47	0,93	1,40	1,87
13,45,30	65,64	23168	0,28	0,57	0,85	1,13	168	1176549	0,46	0,92	1,37	1,83
13,47,00	65,90	23214	0,28	0,57	0,85	1,14	169	1181095	0,46	0,92	1,38	1,84
13,48,30	66,35	23122	0,29	0,57	0,86	1,15	170	1189212	0,46	0,93	1,39	1,85
13,50,00	66,23	23098	0,29	0,57	0,86	1,15	170	1187040	0,46	0,92	1,39	1,85
13,51,30	65,90	23098	0,29	0,57	0,86	1,14	169	1181119	0,46	0,92	1,38	1,84
13,53,00	65,96	23005	0,29	0,57	0,86	1,15	169	1182201	0,46	0,92	1,38	1,84
13,54,30	65,97	23075	0,29	0,57	0,86	1,14	169	1182350	0,46	0,92	1,38	1,84
13,56,00	66,35	23098	0,29	0,57	0,86	1,15	170	1189263	0,46	0,93	1,39	1,85
13,57,30	66,07	23075	0,29	0,57	0,86	1,15	169	1184169	0,46	0,92	1,38	1,84
13,59,00	65,99	23075	0,29	0,57	0,86	1,14	169	1182774	0,46	0,92	1,38	1,84
14,00,30	66,48	23354	0,28	0,57	0,85	1,14	170	1191658	0,46	0,93	1,39	1,86
14,02,00	66,43	23354	0,28	0,57	0,85	1,14	170	1190640	0,46	0,93	1,39	1,86
14,03,30	65,98	23261	0,28	0,57	0,85	1,13	169	1182538	0,46	0,92	1,38	1,84
14,05,00	66,02	23354	0,28	0,57	0,85	1,13	169	1183270	0,46	0,92	1,38	1,84
Average	**66,14**	**23179**	**0,29**	**0,57**	**0,86**	**1,14**	**169**	**1185450**	**0,46**	**0,92**	**1,39**	**1,85**

Calculations turbine 4

Table 57: Relevant calculations and measurements for analysis Turbine 4 computed in Energy Research Project.

Time:	Leakage (l/s)	Prod. Water (l/s)	Leakage Case 1 (%)	Leakage Case 2 (%)	Leakage Case 3 (%)	Leakage Case 4 (%)	Potential (kW) Case 1	Potential (kWh) Case1	(MNOK/year) Case 1	(MNOK/year) Case 2	(MNOK/year) Case 3	(MNOK/year) Case 4
12.59.00	136,01	32013	0,42	0,85	1,27	1,70	348	2437832	0,95	1,90	2,85	3,80
13.00.30	135,64	31689	0,43	0,86	1,28	1,71	347	2431114	0,95	1,89	2,84	3,79
13.02,20	136,01	31981	0,43	0,85	1,28	1,70	348	2437778	0,95	1,90	2,85	3,80
13.05.000	136,12	31753	0,43	0,86	1,29	1,71	349	2439834	0,95	1,90	2,85	3,80
13.06,30	135,73	31785	0,43	0,85	1,28	1,71	348	2432804	0,95	1,90	2,84	3,79
13,08,00	135,82	31818	0,43	0,85	1,28	1,71	348	2434358	0,95	1,90	2,84	3,79
13,09,30	135,86	31818	0,43	0,85	1,28	1,71	348	2435164	0,95	1,90	2,85	3,79
13,11,00	135,47	31623	0,43	0,86	1,29	1,71	347	2428159	0,95	1,89	2,84	3,78
13,12,30	135,39	31526	0,43	0,86	1,29	1,72	347	2426660	0,95	1,89	2,84	3,78
13,14,00	134,98	31363	0,43	0,86	1,29	1,72	346	2419320	0,94	1,88	2,83	3,77
13,15,30	135,26	31525	0,43	0,86	1,29	1,72	346	2424413	0,94	1,89	2,83	3,78
13,17,00	135,09	31590	0,43	0,86	1,28	1,71	346	2421342	0,94	1,89	2,83	3,77
13,18,30	135,70	31428	0,43	0,86	1,30	1,73	347	2432341	0,95	1,89	2,84	3,79
13,20,00	135,17	31363	0,43	0,86	1,29	1,72	346	2422728	0,94	1,89	2,83	3,77
13,21,30	135,18	31460	0,43	0,86	1,29	1,72	346	2423024	0,94	1,89	2,83	3,78
Average	**135,56**	**31649**	**0,43**	**0,86**	**1,29**	**1,71**	**347,11**	**2429791**	**0,95**	**1,89**	**2,84**	**3,79**

Table 58: Measured leakage water from upper crown labyrinth compared with operational parameters at stated times turbine 1 Energy Research Project.

Time:	Qleakage (l/s)	Prod. Water (m3/s)	Prod. Water (l/s)	Active power (MW)	Shaft motion low. guide bearing (µm)	Shaft motion up. guide bearing (µm)	Shaft motion turbine bearing (µm)	Vibration low. guide bearing (mm/s)	Vibration up. guide bearing (mm/s)
15,07,00	40,71	23,96	23956	60,5	70,80	117,68	50,29	0,12	0,39
15,08,30	40,80	24,00	24003	60,6	72,27	115,72	52,25	0,12	0,41
15,10,0	40,71	24,14	24142	61,0	72,27	117,19	52,25	0,12	0,39
15,11,30	40,96	24,07	24072	60,8	72,27	117,19	50,78	0,12	0,39
15,13,0	41,25	24,07	24072	60,8	72,27	117,19	50,78	0,12	0,39
15,14,30	40,89	24,14	24142	61,1	71,29	116,21	51,76	0,12	0,39
15,16,00	40,99	24,19	24188	61,1	71,29	116,21	51,76	0,12	0,39
15,17,30	40,94	24,12	24119	61,1	72,75	114,26	51,76	0,12	0,39
15,19,00	40,85	24,19	24188	61,1	72,75	116,70	49,80	0,12	0,39
15,20,30	41,24	24,19	24188	61,1	73,73	117,68	51,76	0,12	0,39
15,22,00	41,11	24,19	24188	61,1	70,80	117,68	51,76	0,12	0,39
15,23,30	40,70	24,05	24049	60,8	70,80	116,21	51,76	0,12	0,39
15,25,00	40,69	24,14	24142	61,0	70,80	116,21	51,76	0,12	0,39
15,26,30	41,06	24,14	24142	60,8	72,27	116,21	52,73	0,12	0,41
15,28,00	40,58	24,07	24072	60,6	72,27	116,21	52,73	0,12	0,39
Average:	**40,90**	**24,11**	**24111**	**60,9**	**71,91**	**116,57**	**51,60**	**0,12**	**0,39**

Table 59: Measured leakage water from upper crown labyrinth compared with operational parameters at stated times turbine 2 Energy Research Project.

Time:	Qleakage (l/s)	Prod. Water (m3/s)	Prod. Water (l/s)	Active power (MW)	Shaft motion low. guide bearing (µm)	Shaft motion up. guide bearing (µm)	Shaft motion turbine bearing (µm)	Vibration low. guide bearing (mm/s)	Vibration up. guide bearing (mm/s)
14,26,30	43,82	24,30	24304	61,4	31,74	139,65	62,50	0,19	0,38
14,29,00	43,53	23,96	23956	61,1	31,74	142,09	63,96	0,21	0,37
14,30,30	43,75	24,19	24188	61,3	31,74	139,65	62,99	0,18	0,37
14,32,00	44,12	24,05	24049	60,7	31,74	142,09	64,94	0,20	0,37
14,33,30	43,72	23,86	23863	60,3	31,74	140,14	63,48	0,20	0,37
14,35,00	43,62	23,86	23863	60,6	31,74	142,09	63,48	0,18	0,37
14,36,30	43,55	23,96	23956	60,5	31,74	141,60	63,48	0,21	0,39
14,38,00	43,40	23,96	23956	60,5	31,74	144,53	63,48	0,21	0,39
14,39,30	43,20	24,16	24165	61,3	33,20	140,63	64,94	0,19	0,39
14,41,00	43,78	24,14	24142	61,1	33,20	140,63	62,99	0,19	0,39
14,43,00	43,98	24,19	24188	61,3	33,20	143,55	62,99	0,19	0,39
14,44,30	43,75	24,07	24072	61,4	33,20	143,55	64,45	0,20	0,39
14,46,00	43,75	24,30	24304	61,3	33,20	139,16	62,50	0,18	0,37
14,47,30	43,69	24,14	24142	61,2	31,74	144,53	63,48	0,18	0,37
14,49,00	43,85	24,19	24188	61,3	31,74	144,53	64,94	0,20	0,37
Average:	**43,70**	**24,09**	**24089**	**61,0**	**32,23**	**141,89**	**63,64**	**0,19**	**0,38**

Table 60: Measured leakage water from upper crown labyrinth compared with operational parameters at stated times turbine 3 Energy Research Project.

Time:	Qleakage (l/s)	Prod. Water (m3/s)	Prod. Water (l/s)	Active power (MW)	Shaft motion low. guide bearing (µm)	Shaft motion up. guide bearing (µm)	Shaft motion turbine bearing (µm)	Vibration low. guide bearing (mm/s)	Vibration up. guide bearing (mm/s)
13,44,00	66,83	23,33	23330	58,9	81,05	207,03	28,81	0,20	0,38
13,45,30	65,64	23,17	23168	58,8	82,03	207,03	28,81	0,20	0,38
13,47,00	65,90	23,21	23214	58,4	82,03	196,78	27,34	0,20	0,38
13,48,30	66,35	23,12	23122	58,4	82,03	205,08	27,34	0,20	0,38
13,50,00	66,23	23,10	23098	58,4	82,03	205,08	27,34	0,20	0,38
13,51,30	65,90	23,10	23098	58,4	82,03	198,73	27,34	0,20	0,38
13,53,00	65,96	23,01	23005	58,3	80,57	195,31	27,34	0,20	0,38
13,54,30	65,97	23,07	23075	58,4	81,54	205,08	27,34	0,20	0,38
13,56,00	66,35	23,10	23098	58,4	81,54	205,08	27,34	0,20	0,38
13,57,30	66,07	23,07	23075	58,3	81,54	209,96	28,81	0,20	0,38
13,59,00	65,99	23,07	23075	58,3	81,54	205,57	28,81	0,20	0,38
14,00,30	66,48	23,35	23354	59,2	81,54	199,71	27,34	0,19	0,39
14,02,00	66,43	23,35	23354	59,0	82,52	205,08	27,34	0,20	0,39
14,03,30	65,98	23,26	23261	59,0	81,54	195,80	28,81	0,20	0,39
14,05,00	66,02	23,35	23354	59,0	81,54	203,13	26,86	0,20	0,39
Average:	**66,14**	**23,18**	**23179**	**58,6**	**81,67**	**202,96**	**27,80**	**0,20**	**0,38**

Table 61: Measured leakage water from upper crown labyrinth compared with operational parameters at stated times turbine 4 Energy Research Project.

Time:	Qleakage (l/s)	Prod. Water (m3/s)	Prod. Water (l/s)	Active power (MW)	Shaft motion low. guide bearing (µm)	Shaft motion up. guide bearing (µm)	Shaft motion turbine bearing (µm)	Vibration low. guide bearing (mm/s)	Vibration up. guide bearing (mm/s)
12.59.00	136,01	31,43	31428	79,4	125,98	308,59	67,87	1,09	0,34
13.00.30	135,64	31,30	31299	79,7	127,44	307,13	67,87	1,13	0,35
13.02,20	136,01	31,69	31688	80,2	123,54	310,06	69,34	1,15	0,35
13.05.000	136,12	31,69	31688	80,6	124,51	308,59	67,87	1,25	0,34
13.06,30	135,73	31,46	31461	80,6	124,51	307,13	67,87	1,28	0,32
13,08,00	135,82	31,75	31753	79,3	124,51	308,59	67,87	1,10	0,32
13,09,30	135,86	31,27	31266	78,0	123,54	308,11	65,92	1,05	0,32
13,11,00	135,47	31,56	31558	78,8	123,54	308,11	65,92	1,05	0,32
13,12,30	135,39	31,14	31136	79,2	125,00	308,11	67,87	1,05	0,32
13,14,00	134,98	31,20	31201	79,5	125,98	308,11	66,41	1,10	0,32
13,15,30	135,26	31,04	31038	78,4	125,98	306,64	67,87	1,06	0,35
13,17,00	135,09	31,20	31201	78,6	125,98	306,64	67,87	1,07	0,33
13,18,30	135,70	31,30	31298	79,1	125,49	310,06	66,41	1,10	0,33
13,20,00	135,17	31,30	31298	78,9	125,49	310,06	66,41	1,08	0,33
13,21,30	135,18	30,97	30974	79,1	125,49	307,13	68,36	1,04	0,33
Average:	**135,56**	**31,35**	**31352**	**79,3**	**125,13**	**308,20**	**67,45**	**1,11**	**0,33**

D.2 Results and Analysis

D.2.1 Results

The same method used on turbine 4 has also been used for the three other turbines. In Table 62, the results of the average value of the measurements from turbine 1-4 are presented. It can be seen that the leakage water that has been measured is very stable at the selected measuring point. This is also confirmed in Fig. 76, where plots from the leakage water per turbine is presented.

Table 62: Results of measurements from the turbines Energy Research Project.

Measurement	Turbine 1 $\overline{(l/s)}$	Turbine 2 $\overline{(l/s)}$	Turbine 3 $\overline{(l/s)}$	Turbine 4 $\overline{(l/s)}$
1	40.7	43.8	66.8	136.0
2	40.8	43.5	65.6	135.6
3	40.7	43.8	65.9	136.0
4	41.0	44.1	66.4	136.1
5	41.3	43.7	66.2	135.7
6	40.9	43.6	65.9	135.8
7	41.0	43.6	66.0	135.9
8	40.9	43.4	66.0	135.5
9	40.9	43.2	66.4	135.4
10	41.2	43.8	66.1	135.0
11	41.1	44.0	66.0	135.3
12	40.7	43.8	66.5	135.1
13	40.7	43.8	66.4	135.7
14	41.1	43.7	66.0	135.2
15	40.6	43.9	66.0	135.2

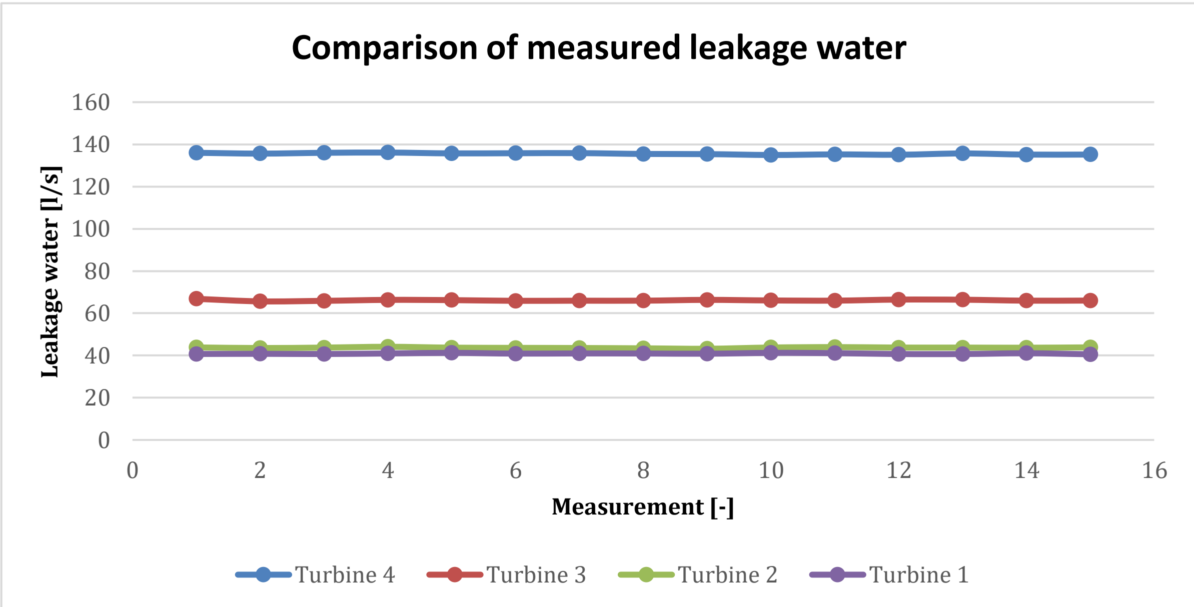


Figure 76: Comparison of measured leakage water Energy Research Project.

The plots above confirm that the choice of measuring point has been good. The plots look very stable over the fifteen tests and are also an indication on how the operational conditions is when the measurements took place. Because the almost constant amount of leakage, corresponds to the operational conditions on every one of the four turbines which were the same in the measurement intervals.

In Table 63, the average values of the measured leakage water from all tests are presented. The biggest loss comes from the biggest turbine, and the loss is an average value of 135.6 [l/s]. There is also a significant loss from turbine 3 and the loss from turbine 1 and 2 are lower and about the same value.

Table 63: Average values of measurements from turbines.

Turbine nr.	Average $\overline{(l/s)}$
1	40.9
2	43.7
3	66.1
4	135.6

Some of the operational parameters that where measured on the different turbines are presented in Table 64. At the operational conditions that took place when our measurements have been done, the rotational speed is held constant on 375 rpm. The load is set between 61-67 % on the different turbines. This describes how big the opening for the guide vanes are. These values correspond to normal operation. Active power produced by the turbine and generator is also presented in Table 64. The power is similar for turbines 1, 2 and 3. The biggest turbine is producing nearly 80 MW.

Table 64: Different operational parameters from the different turbines.

	Turbine 1	Turbine 2	Turbine 3	Turbine 4
Power [~MW]	60.7	60.2	59.2	78.4
Load [~%]	63.9	61	67.4	64
Speed [~RPM]	375	375	375	375

D.2.2 Analysis

Table 65: Economic analysis for the potential of the leakage water Energy Research Project [3].

	Turbine 1	Turbine 2	Turbine 3	Turbine 4
Measured Leakage crown labyrinth [l/s]	40.9	43.7	66.1	135.6
Prod. Water [l/s]	24110.9	24089.1	23178.7	31649.0
Leakage Case 1 [%]	0.17	0.18	0.29	0.43
Leakage Case 2 [%]	0.34	0.36	0.57	0.86
Leakage Case 3 [%]	0.51	0.54	0.86	1.29
Leakage Case 4 [%]	0.68	0.73	1.14	1.71
Potential leakage Case 1 [MWh]	734	783	1186	2430
Potential leakage Case 2 [MWh]	1466	1567	2371	4860
Potential leakage Case 3 [MWh]	2199	2350	3556	7289
Potential leakage Case 4 [MWh]	2932	3133	4742	9719
Case 1 [MNOK/year]	0.29	0.31	0.46	0.95
Case 2 [MNOK/year]	0.57	0.61	0.92	1.89
Case 3 [MNOK/year]	0.86	0.92	1.39	2.84
Case 4 [MNOK/year]	1.14	1.22	1.85	3.79

Appendix E Measurements and Calculations

E.1 Measurements and operational data for analysis on turbines at Holen and Brokke

Measurements turbine 1 Holen

Table 66: Measurements and operational data for analysis turbine 1 Holen.

	Active Power [MW]							
	70-80		81-90		91-100		101-110	
Nr.	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]
1	75.2	32.8	81.8	37.0	87.1	41.0	94.1	47.5
2	76.2	32.9	81.9	37.0	86.1	41.2	93.8	47.5
3	74.7	32.9	81.8	37.0	86.5	41.2	94.0	48.2
4	76.6	32.9	82.4	37.1	86.9	41.2	92.6	48.2
5	75.4	32.8	81.1	37.1	86.6	41.3	92.8	48.2
6	75.1	32.8	78.8	37.1	86.7	41.3	92.6	47.7
7	74.4	32.8	80.0	37.2	85.3	41.3	92.6	47.7
8	75.2	32.8	79.5	37.2	85.7	41.3	93.3	47.5
9	76.3	32.8	81.3	36.9	85.1	41.3	92.8	47.5
10	76.0	32.8	82.4	36.9	84.6	41.3	92.7	47.5
11	76.6	32.9	81.8	36.9	83.6	41.2	93.2	48.0
12	75.2	32.9	81.9	36.8	83.7	41.2	91.6	48.0
13	73.7	32.8	81.8	36.8	86.5	41.2	91.8	48.1
14	75.5	32.8	82.4	36.9	86.0	41.2	92.4	48.1
15	74.9	32.9	81.1	36.9	85.1	41.2	94.8	48.1
Average:	**75.4**	**32.8**	**81.3**	**37.0**	**85.7**	**41.2**	**93.0**	**47.9**

Measurements turbine 2 Holen

Table 67: Measurements and operational data for analysis turbine 2 Holen.

	Active Power [MW]							
	71-80		81-90		91-100		101-110	
Nr.	Leakage [l/s]	Prod.water [m^3/s]	Leakage [l/s]	Prod.water [m^3/s]	Leakage [l/s]	Prod.water [m^3/s]	Leakage [l/s]	Prod.water [m^3/s]
1	70.5	31.1	75.2	35.7	84.1	40.8	84.3	44.4
2	71.0	31.1	74.8	35.7	82.8	40.8	85.0	44.4
3	70.6	31.8	75.4	35.7	83.7	40.8	84.3	44.0
4	70.1	31.8	73.5	35.5	83.2	40.8	85.1	44.0
5	70.0	32.0	74.9	35.7	83.6	40.6	87.4	43.9
6	70.1	32.0	73.8	36.0	85.2	40.6	86.6	43.9
7	71.3	31.8	73.1	36.0	84.2	40.5	87.1	43.5
8	71.3	31.8	74.7	35.9	84.8	40.5	85.2	43.7
9	70.6	32.1	76.4	35.9	85.2	40.6	82.1	44.0
10	70.2	32.0	77.1	35.9	85.3	40.6	83.4	44.0
11	70.3	32.0	75.9	35.9	85.5	40.5	83.9	43.9
12	71.0	32.0	74.4	36.1	85.8	40.5	85.9	43.9
13	68.3	32.4	75.0	36.1	84.9	40.7	85.4	43.7
14	70.1	32.4	73.6	35.7	83.8	40.7	86.1	43.8
15	68.8	32.3	72.0	35.7	83.9	40.6	85.4	43.8
Average:	**70.3**	**31.9**	**74.7**	**35.8**	**84.4**	**40.6**	**85.1**	**43.9**

Measurements turbine 3 Holen

Table 68: Measurements and operational data for analysis turbine 3 Holen.

Active Power

	70-80		**81-90**		**91-100**		**101-110**		**111-130**		**131-150**	
Nr.	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]	Leakage [l/s]	Prod.water [m³/s]
1	65.0	13.9	65.3	16.5	67.8	18.2	68.4	19.4	70.0	23.2	71.6	25.6
2	65.8	13.9	65.5	16.5	67.7	18.2	68.8	19.5	69.9	23.2	70.8	25.6
3	65.7	14.0	65.1	16.6	66.9	18.2	68.2	19.5	70.5	23.2	71.4	25.6
4	64.4	14.0	65.4	16.6	67.5	18.2	68.2	19.5	69.7	23.2	71.4	25.7
5	63.8	13.9	64.5	16.4	66.3	18.2	68.8	19.5	69.7	23.1	72.9	25.7
6	64.8	13.9	64.8	16.4	67.4	18.2	68.9	19.5	69.0	23.1	73.0	25.8
7	64.5	14.0	65.8	16.7	66.5	18.2	68.4	19.5	69.0	23.0	72.5	25.8
8	64.3	14.0	65.0	16.7	66.4	18.2	67.9	19.5	69.0	23.0	72.9	25.9
9	64.3	13.9	64.0	16.8	65.5	18.3	68.2	19.5	68.8	23.0	73.3	25.9
10	63.8	13.9	65.6	16.8	64.5	18.3	68.2	19.5	69.3	23.0	74.1	25.9
11	64.0	13.9	66.6	16.5	65.4	18.3	68.5	19.5	69.5	23.0	73.1	26.1
12	63.4	13.9	66.3	16.5	66.5	18.3	68.5	19.5	69.6	23.0	73.5	26.1
13	63.8	14.0	66.5	16.5	65.7	18.3	69.1	19.5	70.0	22.9	73.9	26.1
14	63.4	14.0	66.6	16.5	66.4	18.3	69.5	19.5	70.0	22.9	74.6	26.1
15	65.0	14.1	65.8	16.4	67.6	18.3	70.2	19.5	71.0	23.0	74.1	26.0
Average:	**64.4**	**14.0**	**65.5**	**16.6**	**66.5**	**18.2**	**68.6**	**19.5**	**69.7**	**23.0**	**72.9**	**25.9**

Measurements turbine 1 Brokke

Table 69: Measurements and operational data for analysis turbine 1 Brokke.

Active Power [MW]

	35-40			41-45			46-50			51-55		
Nr.	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
1	36.1	16.0	0.103	37.0	18.8	0.107	39.2	21.9	0.112	39.0	23.3	0.117
2	35.9	16.0	0.103	36.4	18.8	0.107	39.2	21.9	0.112	38.9	23.3	0.117
3	36.1	16.3	0.103	38.3	18.9	0.107	39.0	22.0	0.112	39.4	23.4	0.117
4	35.9	16.1	0.103	36.1	18.9	0.107	37.8	22.0	0.112	39.4	23.4	0.117
5	36.1	16.1	0.103	37.2	19.0	0.107	38.4	22.0	0.112	38.9	23.1	0.117
6	36.6	15.9	0.103	35.8	19.0	0.107	37.8	21.9	0.112	39.6	23.2	0.117
7	35.7	16.1	0.103	35.9	19.1	0.107	37.7	22.0	0.112	39.8	23.6	0.117
8	36.1	15.8	0.103	36.5	19.1	0.107	36.8	21.9	0.112	39.0	23.6	0.117
9	36.5	15.8	0.103	36.8	19.0	0.107	38.3	21.9	0.112	40.6	23.8	0.117
10	35.6	15.8	0.103	36.3	19.0	0.107	37.5	21.9	0.112	39.4	23.8	0.117
11	36.4	15.6	0.103	37.2	19.0	0.107	38.0	21.9	0.112	39.9	24.0	0.117
12	36.0	15.6	0.103	36.8	19.1	0.107	37.7	21.9	0.112	40.6	24.0	0.117
13	35.6	15.5	0.103	36.2	19.1	0.107	37.4	21.9	0.112	40.4	24.2	0.117
14	33.9	15.9	0.103	36.9	19.1	0.107	38.3	21.9	0.112	41.1	24.2	0.117
15	34.5	15.5	0.103	36.5	19.2	0.107	38.3	21.8	0.112	41.9	24.0	0.117
Average:	**35.8**	**15.9**	**0.103**	**36.7**	**19.0**	**0.107**	**38.1**	**21.9**	**0.112**	**39.9**	**23.7**	**0.117**

Active Power [MW]		
56-60		
Leakage [l/s]	Prod.water [m³/s]	Vibration [mm/s]
41.5	26.0	0.127
40.7	26.0	0.127
42.4	25.9	0.127
41.7	25.9	0.127
41.6	25.8	0.127
40.5	25.8	0.127
41.1	25.7	0.127
40.9	25.7	0.127
40.2	25.8	0.127
41.6	25.8	0.127
41.9	25.7	0.127
41.6	25.7	0.127
42.4	25.6	0.127
41.4	25.6	0.127
41.6	25.6	0.127
41.4	**25.8**	**0.127**

Leakage Leakage Leakage Potential Potential

Measurements turbine 2 Brokke

Table 70: Measurements and operational data for analysis turbine 2 Brokke.

	Active Power [MW]											
	45-50			**51-55**			**56-60**			**61-65**		
Nr.	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
1	39.7	19.1	0.186	42.8	22.3	0.181	41.7	24.4	0.161	43.8	26.0	0.186
2	40.0	19.0	0.186	42.3	22.6	0.181	44.3	24.2	0.161	43.8	26.4	0.186
3	40.1	19.0	0.200	42.1	22.6	0.181	43.3	24.2	0.161	43.1	26.4	0.171
4	40.9	18.7	0.200	41.8	22.4	0.181	43.9	24.4	0.161	42.7	26.5	0.186
5	40.3	18.7	0.181	43.0	22.5	0.181	43.6	24.4	0.161	44.6	26.4	0.161
6	40.7	18.5	0.195	41.5	22.4	0.181	43.2	24.3	0.161	43.8	27.3	0.190
7	40.2	18.6	0.176	43.4	22.4	0.181	44.7	24.3	0.161	43.7	27.3	0.176
8	40.6	19.0	0.190	42.1	22.3	0.200	42.5	24.4	0.161	44.1	27.0	0.176
9	39.9	19.0	0.190	41.7	22.5	0.166	43.1	24.4	0.161	43.9	27.6	0.195
10	41.8	19.1	0.190	42.3	22.6	0.166	43.3	24.3	0.161	43.0	27.2	0.176
11	39.8	19.1	0.176	40.9	22.5	0.190	42.6	24.2	0.161	42.6	27.2	0.176
12	40.1	19.2	0.176	41.6	22.5	0.166	43.8	24.4	0.161	43.6	27.3	0.176
13	40.4	19.2	0.195	41.6	22.7	0.195	43.5	24.4	0.161	44.0	27.3	0.176
14	42.0	19.3	0.210	42.6	22.7	0.195	43.0	24.2	0.161	45.0	27.2	0.176
15	40.4	19.3	0.190	42.1	22.8	0.181	41.9	24.2	0.161	44.1	27.2	0.176
Average:	**40.5**	**19.0**	**0.189**	**42.1**	**22.5**	**0.182**	**43.2**	**24.3**	**0.161**	**43.7**	**26.9**	**0.179**

Active Power [MW]		
66-70		
Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
46.0	28.9	0.190
46.0	28.8	0.190
45.3	28.9	0.200
46.5	28.7	0.200
45.6	28.9	0.200
45.2	28.6	0.200
45.7	28.6	0.200
44.8	28.8	0.181
46.2	28.8	0.181
46.2	28.8	0.200
46.4	28.7	0.200
46.3	29.1	0.186
45.3	29.1	0.186
46.4	29.0	0.186
46.1	29.0	0.200
45.9	**28.9**	**0.193**

Measurements turbine 3 Brokke

Table 71: Measurements and operational data for analysis turbine 3 Brokke.

Active Power [MW]

	50-55			**56-60**			**61-65**			**66-70**		
Nr.	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
1	65.0	22.9	0.186	68.7	25.2	0.176	69.4	26.6	0.200	71.8	28.2	0.244
2	63.5	22.8	0.186	67.6	25.1	0.176	69.5	26.8	0.200	70.9	28.1	0.244
3	65.4	22.9	0.186	68.3	25.1	0.176	69.1	26.7	0.200	72.4	28.5	0.229
4	66.7	22.8	0.195	68.9	25.2	0.176	69.9	26.9	0.200	71.1	28.5	0.229
5	65.4	22.8	0.195	68.5	25.2	0.176	71.8	26.9	0.200	70.5	28.4	0.254
6	65.4	22.8	0.195	67.7	25.1	0.176	70.9	27.2	0.200	70.6	28.5	0.254
7	66.0	22.8	0.195	70.0	25.1	0.176	67.4	27.2	0.200	70.6	28.4	0.278
8	65.3	22.9	0.195	70.4	25.2	0.176	71.1	27.3	0.200	71.0	28.5	0.278
9	64.9	22.9	0.195	69.6	25.2	0.176	70.5	27.2	0.200	72.0	28.2	0.249
10	63.9	22.7	0.181	67.6	25.2	0.176	70.6	27.4	0.200	72.1	28.2	0.273
11	65.6	22.7	0.181	67.5	25.2	0.176	70.6	27.4	0.200	70.8	28.5	0.244
12	66.6	22.8	0.181	68.5	25.2	0.176	71.0	27.3	0.200	70.7	28.5	0.244
13	65.0	22.8	0.181	67.6	25.2	0.176	69.0	27.3	0.200	71.0	28.4	0.244
14	65.7	22.7	0.181	67.5	25.1	0.176	70.1	27.0	0.200	72.3	28.4	0.273
15	63.0	22.7	0.181	69.9	25.1	0.176	70.8	27.0	0.200	70.7	28.5	0.229
Average:	**65.2**	**22.8**	**0.187**	**68.6**	**25.2**	**0.176**	**70.1**	**27.1**	**0.200**	**71.2**	**28.4**	**0.251**

Measurements turbine 4 Brokke

Table 72: Measurements and operational data for analysis turbine 4 Brokke.

	Active Power [MW]											
	50-60			**61-70**			**71-80**			**81-90**		
Nr.	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]	Leakage [l/s]	Prod.water [m^3/s]	Vibration [mm/s]
1	103.1	24.7	0.630	112.0	26.0	0.698	129.6	31.6	1.128	132.3	38.0	2.441
2	103.1	23.7	0.630	112.0	26.0	0.698	129.6	31.6	1.128	133.6	38.0	1.963
3	103.2	23.9	0.630	112.0	26.0	0.679	127.4	31.6	1.338	133.6	38.5	2.305
4	103.2	23.7	0.630	115.5	26.9	0.679	127.4	31.8	1.084	133.6	38.5	1.958
5	100.3	23.7	0.630	115.5	26.9	0.679	127.4	31.8	1.396	133.6	38.0	2.144
6	101.6	23.9	0.605	115.5	27.6	0.713	127.7	31.6	1.318	133.6	38.0	1.885
7	107.7	23.9	0.605	115.5	27.6	0.713	129.2	31.5	1.172	133.6	38.4	1.938
8	103.1	23.7	0.620	115.5	27.9	0.747	129.2	31.7	1.299	133.6	38.4	2.144
9	97.3	23.7	0.620	115.5	27.9	0.747	129.2	31.7	1.069	133.6	38.2	1.899
10	107.7	23.9	0.596	115.5	26.3	0.713	129.2	31.7	1.318	133.6	38.4	2.163
11	107.8	23.9	0.596	115.5	26.3	0.713	129.2	31.6	1.187	133.6	38.2	1.899
12	107.7	23.7	0.625	115.5	27.1	0.728	129.2	31.6	1.196	133.2	38.2	2.183
13	107.7	23.7	0.625	119.7	27.1	0.728	129.2	32.0	1.157	132.2	38.3	1.919
14	107.7	23.3	0.625	119.7	26.7	0.693	129.2	32.0	1.289	132.4	38.3	2.241
15	107.7	23.3	0.605	119.7	26.7	0.693	129.2	31.5	1.294	132.4	38.4	2.188
Average:	**104.6**	**23.8**	**0.618**	**115.6**	**26.8**	**0.708**	**128.8**	**31.7**	**1.225**	**133.2**	**38.3**	**2.085**

E.2 Calculations for analysis on turbines at Holen and Brokke

Table 73: Relevant calculations for analysis of the potential Brokke and Holen, min values.

	Leakage (l/s)	Prod. Water (l/s)	Leakage Case 1 (%)	Leakage Case 2 (%)	Leakage Case 3 (%)	Leakage Case 4 (%)	Potential Case 1 (kW)	Potential Case1 (kWh)	(MNOK/year) Case 1	(MNOK/year) Case 2	(MNOK/year) Case 3	(MNOK/year) Case 4
Brokke Turbine 1	34.00	15500	0.22	0.44	0.66	0.88	87	609409	0.24	0.47	0.71	0.95
Brokke Turbine 2	38.00	18500	0.21	0.41	0.62	0.82	97	681105	0.27	0.53	0.80	1.06
Brokke Turbine 3	63.00	22800	0.28	0.55	0.83	1.11	161	1129200	0.44	0.88	1.32	1.76
Brokke Turbine 4	100.00	23700	0.42	0.84	1.27	1.69	256	1792381	0.70	1.40	2.09	2.79
Holen Turbine 1	72.00	32700	0.22	0.44	0.66	0.88	184	829616	0.32	0.65	0.97	1.29
Holen Turbine 2	68.00	32000	0.21	0.43	0.64	0.85	174	800938	0.31	0.62	0.94	1.25
Holen Turbine 3	60.00	13900	0.43	0.86	1.29	1.73	325	973728	0.38	0.76	1.14	1.52

Table 74: Relevant calculations for analysis of the potential Brokke and Holen, max values.

	Leakage (l/s)	Prod. Water (l/s)	Leakage Case 1 (%)	Leakage Case 2 (%)	Leakage Case 3 (%)	Leakage Case 4 (%)	Potential Case 1 (kW)	Potential Case 1 (kWh)	(MNOK/year) Case 1	(MNOK/year) Case 2	(MNOK/year) Case 3	(MNOK/year) Case 4
Brokke Turbine 1	42.00	26000	0.16	0.32	0.48	0.65	108	752800	0.29	0.59	0.88	1.17
Brokke Turbine 2	39.00	18700	0.21	0.42	0.63	0.83	100	699029	0.27	0.54	0.82	1.09
Brokke Turbine 3	73.00	28500	0.26	0.51	0.77	1.02	187	1308438	0.51	1.02	1.53	2.04
Brokke Turbine 4	134.00	38000	0.35	0.71	1.06	1.41	343	2401790	0.94	1.87	2.81	3.74
Holen Turbine 1	95.00	48000	0.20	0.40	0.59	0.79	243	1094633	0.43	0.85	1.28	1.71
Holen Turbine 2	86.00	44500	0.19	0.39	0.58	0.77	220	1012951	0.39	0.79	1.18	1.58
Holen Turbine 3	75.00	26500	0.28	0.57	0.85	1.13	406	1217160	0.47	0.95	1.42	1.90

Appendix F Prices

F.1 Prices in EUR/MWh

Ref: [26]

- **1 Euro = 9,5 NOK** [27].

Day-ahead prices in EUR/MWh	SYS	SE1	SE2	SE3	SE4	FI	DK1	DK2	Oslo	Kr.sand	Bergen	Molde	Tr.heim	Tromsø	EE	LV	LT
08.11.2018	48,68	47,54	47,54	54,96	61,08	54,96	60,58	61,61	46,37	46,37	46,36	46,66	46,66	46,66	54,96	60,82	61,08
07.11.2018	48,07	47,31	47,31	52,6	54,91	52,6	55,11	55,32	45,63	45,63	45,34	47,14	47,14	46,62	52,47	54,64	54,78
06.11.2018	48,19	47,31	47,31	51,2	57,04	51,2	57,89	57,89	47,2	47,2	47,1	47,16	47,16	45,71	50,98	56,95	56,95
05.11.2018	45,83	45,3	45,3	47,52	55,11	47,52	56,62	56,62	45,11	45,11	45,11	45,11	45,11	45,11	47,52	55,11	55,07
04.11.2018	43,6	43,55	43,55	43,55	44,7	43,55	46,65	46,65	43,55	43,55	43,55	43,55	43,55	43,55	43,55	45,94	45,94
03.11.2018	43,82	43,71	43,71	43,71	47,19	43,71	50,72	50,72	43,71	43,71	43,71	43,71	43,71	43,71	43,71	47,19	47,19
02.11.2018	44,5	44,83	44,83	44,83	44,83	45,22	44,83	46,21	44,3	44,3	44,3	44,56	44,56	44,56	45,22	48,37	47,76
01.11.2018	44,67	45,35	45,35	45,35	45,35	45,35	47,22	47,23	44,23	44,23	44,23	44,93	44,93	44,61	45,35	45,35	45,21
31.10.2018	43,16	42,58	42,58	42,58	48,4	46,33	47,9	48,45	42,78	42,78	42,78	42,78	42,78	42,78	46,33	53,08	53,67
30.10.2018	42,78	42,58	42,58	42,58	42,58	42,58	35,02	35,93	42,93	42,93	42,93	43,25	43,25	43,25	42,58	47,77	47,77
29.10.2018	44,93	44,65	44,65	44,65	47,05	49,98	40,65	42,1	44,62	44,62	44,62	44,65	44,65	44,15	49,98	51,5	51,5
28.10.2018	44,06	44,27	44,27	44,27	44,27	44,29	43,78	43,81	44,01	44,01	44,01	44,14	44,14	44,03	44,29	44,29	44,29
27.10.2018	44,15	44,17	44,17	44,17	46,75	44,17	41,66	43,58	44,17	44,17	44,17	44,17	44,17	44,12	44,17	46,75	46,75
26.10.2018	49,04	50,52	50,52	50,52	56,98	55,73	55,61	57,23	46,99	46,99	46,91	46,91	46,91	46,43	55,73	57,65	58,79
25.10.2018	44,46	44,05	44,05	44,05	45,85	49,46	41,95	43,76	44,05	44,05	44,05	44,05	44,05	44,05	49,46	50,03	50,03
24.10.2018	41,65	41,22	41,22	41,22	46,34	45,92	35,89	40,33	41,98	41,98	41,98	41,45	41,45	41,45	45,92	46,8	46,65
23.10.2018	36,04	35,63	35,63	35,63	35,63	42,25	32,17	32,4	35,63	35,63	35,63	35,63	35,63	35,63	42,25	42,55	42,55
22.10.2018	38,05	37,81	37,81	37,81	41,96	42,2	37,81	41,96	37,81	37,81	37,81	37,81	37,81	37,81	42,2	47,17	47,17
21.10.2018	40,59	40,57	40,57	40,57	45,67	40,57	42,39	46,42	40,57	40,57	40,57	40,57	40,57	40,57	40,77	46,69	46,69
20.10.2018	42,12	43,6	43,6	43,6	52	43,6	52,41	53,87	40,76	40,76	40,76	42,71	42,71	42,71	43,6	52	52
19.10.2018	43,33	45,25	45,25	45,25	65,7	47,86	67,54	67,59	40,47	40,47	40,47	42,84	42,84	42,84	47,86	63,43	66,36
18.10.2018	43,25	44,11	44,11	44,11	59,68	52,46	61,7	62,46	40,55	40,55	40,55	42,87	42,87	42,87	52,46	59,34	61,08
17.10.2018	43,52	44,55	44,55	44,55	67,09	49,37	70,83	71,09	39,85	39,85	39,85	44,14	44,14	44,14	49,37	61,9	66,55
16.10.2018	44,26	47,62	47,62	47,62	67,9	49,97	72	72,22	41,69	41,69	6,43	44,91	44,91	44,94	49,97	65,13	68,13
15.10.2018	37,27	39,74	39,74	39,74	51,61	41,38	54	54,15	34,15	34,15	6,51	38,54	38,54	44,41	41,38	55,93	55,93
14.10.2018	20,07	18,09	18,09	18,09	18,09	18,09	18,09	19,89	18,09	18,09	18,09	18,09	18,09	38,39	18,09	33,98	33,98
13.10.2018	34,56	34	34	34	34	34	34	34	34	34	33,83	34	34	38,86	34	51,57	51,57
12.10.2018	44,35	45,53	45,53	45,53	55,09	50,15	44,34	55,21	42,07	42,07	41,91	44,77	44,77	45,15	50,15	58,3	58,38
11.10.2018	43,69	45,13	45,13	45,13	52,56	49,44	42	52,56	41	41	41	44,57	44,57	46,54	49,44	61,81	61,81
10.10.2018	46,76	49,97	49,97	49,97	59,87	49,97	58,55	59,94	43,81	43,81	43,81	47,13	47,13	47,13	49,97	67,74	67,81
09.10.2018	44,79	45,91	45,91	45,91	62,2	45,91	43,63	66,09	43,63	43,63	43,63	45,91	45,91	46,74	45,91	65,34	65,34
Average										**41**							

Figure 77: Day-ahead prices.

Appendix G Maintenance and Rehabilitation

G.1 Condition monitoring scheme of leakage water in labyrinth seals

Tilstandskontroll av vannkraftverk **Francisturbin**

Løpehjulstetninger

5.3 Målemetoder

Visuell inspeksjon

Visuell inspeksjon av løpehjulstetningene vil bare kunne skje gjennom en omfattende demontasje av turbinen. Metoden gir en sikker bestemmelse av skadeomfang og -type, og det er derfor viktig at løpehjulstetningene kontrolleres visuelt og med måleutstyr når turbinen, av ulike årsaker, er demontert. Resultatet vil være et referansemål for senere kontroller.

Karaktersettingen vil være basert på en skjønnsmessig vurdering av inspektøren. Observeres rivningsskader må årsaken til disse kartlegges og utbedres sammen med selve skadene, før videre drift.

Måling av spaltvannsmengde

Jevnlig måling av spaltvannsmengden gir et godt bilde av slitasjeforløpet. Det er i første rekke der spaltvannet tappes av og brukes til kjøling av aggregatet, at mulighetene er gode for å kunne måle spaltvannsmengden. Spaltvannsmengden måles på en egnet strekning av spaltvannsrøret hvor strømningen ikke er forstyrret av f.eks. oppstrøms og nedstrøms bend.

Det finnes flere ulike måleprinsipper, hvorav de mest benyttede er:

- pitotmåling
- ultralydmåling

Disse to prinsippene er nærmere beskrevet i Prinsipper for måling av spaltevannsmengden.

Siden slitasjeforløpet for øvre og nedre løpehjulstetning antas å følge samme utvikling, er det tilstrekkelig å bare måle vannføringen fra de øvre spaltene.

Kriterier for karaktersetting er gitt i Tabell 5.3. Økningen i spaltvannsmengden regnes ut fra den verdien som ble registrert ved nye løpehjulstetninger.

Tabell 5.3 Løpehjulstetninger – Spaltvannsmåling

Karakter	Kriterier for karaktersetting
1	Spaltvannsøkning ≤ 30 %
2	30 % < Spaltvannsøkning ≤ 100 %
3	Spaltvannsøkning > 100 %
4	-

Kriteriene i Tabell 5.3 gjelder i første rekke høytrykksturbiner. For turbiner hvor det ikke er praktisk mulig å måle spaltvannsmengden, bør en undersøke om det lar seg gjøre å lage inspeksjonshull for spaltklaringsmåling hvis dette ikke allerede eksisterer.

Figure 78: Condition monitoring scheme of leakage water in labyrinth seals.

Tilstandskontroll av vannkraftverk — **Francisturbin**

Flytdiagrammer

V1.6 Løpehjulstetninger – Spaltevannsmengde, Spaltklaring, Utløpskurve, Trykkmåling på øvre lokk

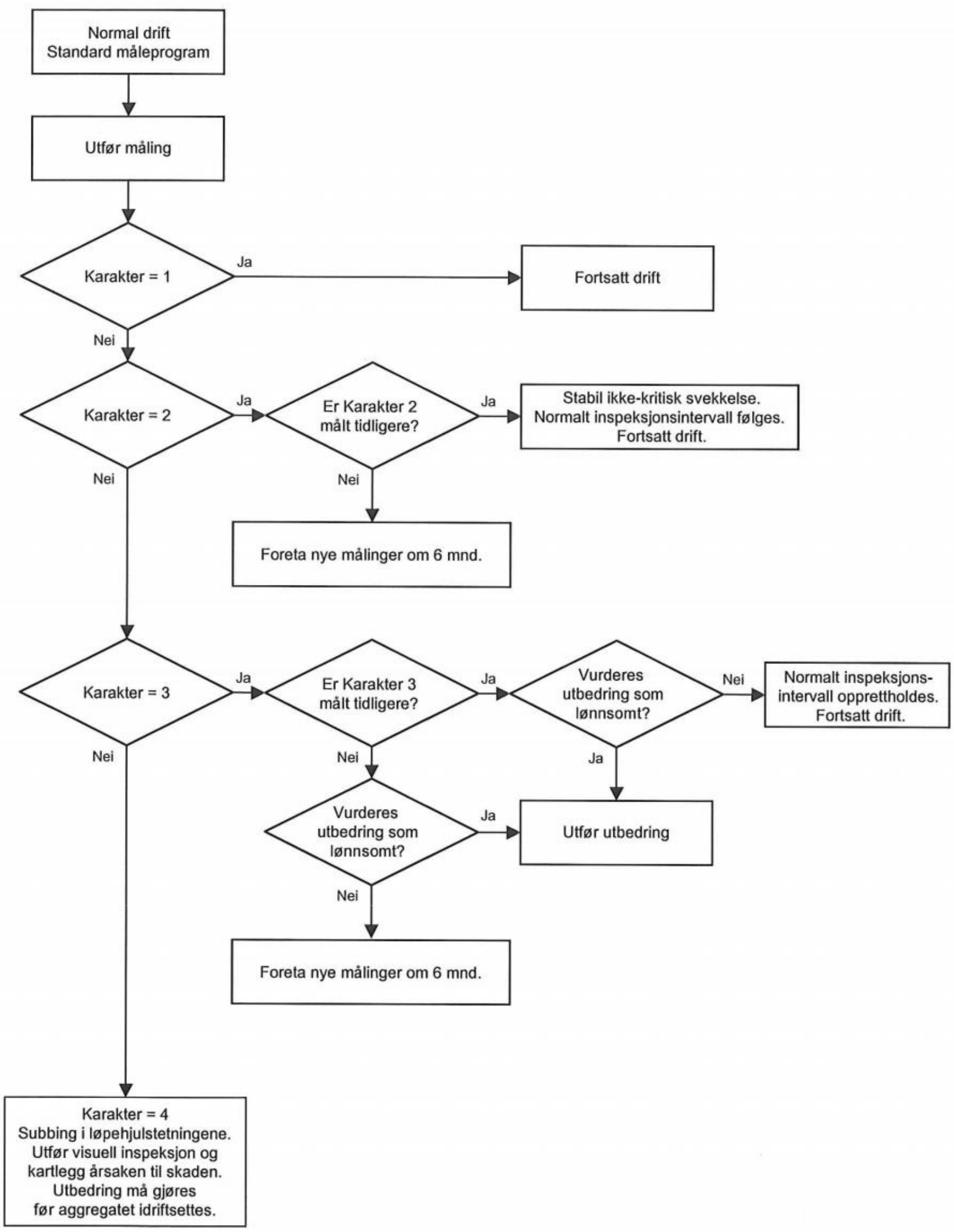


Figure 79: Condition monitoring scheme of leakage water in labyrinth seals [5].