NTNU – Trondheim
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Design of a Francis Model Test Rig at Kathmandu University

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MASTER THESIS

for

Inger Johanne Rasmussen

Spring 2014

Design of a Francis model test rig at Kathmandu University
Design av Francis modell test rig ved Kathmandu University

Background

The Turbine Testing Laboratory at Kathmandu University is designed to handle performance testing of model turbines. Model tests should be performed according to the specifications of IEC 60193 which is the standard used in such model tests. In order to achieve required accuracy, one of the most important issues is to establish proper test rig for the model tests of Francis turbines.

The Francis test rig at the Waterpower Laboratory, NTNU will be used as the initial design. The adaptations needed for the installation at Kathmandu University will be evaluated, designed and documented in this thesis.

Objective:

Design the Francis model test rig in the Turbine Testing Laboratory at Kathmandu University

The following tasks shall be considered in the project work:

1. Literature survey
    a. Model test of Francis turbines
    b. IEC 600193
    c.
2. Software knowledge
    a. Get familiar with the CAD-program, Inventor
    b.
3. Design the test rig at Kathmandu University with the following components
    a. Detail design of the following components:
        i. Inlet high pressure tank
        ii. Guide vane control system
        iii. Main shaft, bearing and system for the measurement of friction torque in the bearings and axial load
        iv. Low pressure tank
        v. Measurement of pressure, flow rate, speed and torque
    b. Overview of the following components and systems:
        i. Measurement of temperature and oxygen level in the water
        ii. Generator
        iii. Frequency transformer
        iv. Electrical system to feed the produced energy back to the main system

4. Development of procedures for efficiency measurement

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in the Waterpower laboratory
☒ Field work

Department of Energy and Process Engineering, 14. January 2014

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Abstract

Due to the growing energy demand in Nepal and its neighbouring countries, the focus on hydropower development in Nepal has increased. As a consequence, the Turbine Testing Laboratory (TTL) at Kathmandu University (KU) has been developed to handle performance testing of model turbines. However, the laboratory is not yet equipped with a test rig which can handle model tests according to the specifications of the international standard for model tests of hydraulic turbines, *IEC 60193* [1]. This master's thesis is one of the first stages towards the aim of developing turbine model test rigs in compliance with *IEC 60193* [1] at TTL.

The objective of this project is to design a Francis model test rig for TTL, using the Francis test rig at the Waterpower Laboratory at NTNU as the initial design. The rig must fulfil the accuracy requirements of *IEC 60193* [1] and it should be capable of a complete performance test for different sized turbines.

The pressure tank and the draft tube tank are designed to have the same shape as the tanks at the Waterpower Laboratory, but with some difference in volume. The main shaft and bearing block will include systems to measure the speed of rotation, axial thrust, generator torque, and friction torque without the need of a hydraulic system. The guide vane angles are manually controlled and measured by a rotary encoder.

The pressure difference between inlet and outlet is measured by differential pressure transducers, calibrated by a deadweight manometer. The flow rate is measured by an electromagnetic flowmeter which is calibrated using the volumetric method. At the outlet to the pumps, the temperature, oxygen level and pressure of the water is measured.

3D CAD drawings of the final design are presented in this thesis. The most practical and space efficient placement of the test rig in the laboratory has been chosen based on discussions with the staff at NTNU and KU. The rig has been integrated in the main pipe system, and designed for both open and closed loop modes. Procedures for efficiency measurements have also been developed.

The work done in this thesis is an input to the *EnergizeNepal* project on developing a Francis model test rig at TTL.

Sammendrag

På grunn av det voksende energibehovet i Nepal og landene rundt, har fokuset på vannkraftutviklingen i landet økt. Som en konsekvens av dette, har Turbine Testing Laboratory (TTL) på Kathmandu University (KU) blitt opprettet for å kunne teste vannkraftturbiner. Laboratoriet har enda ikke en testrigg godkjent av den internasjonale standarden for testing av hydrauliske turbiner, *IEC 60193* [1]. Denne masteroppgaven er en av de første stegene mot målet om å utvikle turbintestrigger i henhold til *IEC 60193* [1].

Formålet med denne oppgaven er å konstruere en Francismodell testrigg for TTL, ved å bruke Francis-testriggen på Vannkraftlaboratoriet på NTNU som utgangspunkt. Testriggen må oppfylle nøyaktighetskravene til *IEC 60193* [1], og den må være fleksibel for å utføre tester på forskjellige størrelser av turbiner.

Trykktanken og sugerørstanken er utformet med samme form som tankene på Vannkraftlaboratoriet, men med noen modifikasjoner på volumet. Hovedakslingen og lagerblokken vil inkludere systemer for å måle rotasjonshastighet, aksielle krefter, og generator- og friksjonsmoment uten at det er behov for hydraulikk. Ledeskovlsvinkelen er kontrollert med et servohjul koblet til en arm fra ledeskovlene.

Trykkforskjellen mellom innløp og utløp av turbinen måles med differensialtrykksensorer som kalibreres med et dødvekts manometer. Volumstrømmen måles med en elektromagnetisk volumstrømsmåler som kalibreres ved den volumetriske metoden. Ved utløpet av pumpene, måles temperatur, oksygennivå og trykk i vannet.

3D-CAD-tegninger av det endelige forslaget er laget i Autodesk Inventor Professional. Den mest praktiske og plassbesparende plasseringen av testriggen har blitt bestemt, og riggen er integrert i det eksisterende rørsystemet. Det er mulighet for å kjøre riggen i både åpen og lukket sløyfe. Prosedyrer for å utføre virkningsgradstest på turbinen har også blitt laget.

Utformingen som er utviklet i denne masteroppgaven er et bidrag til Norad-prosjektet *EnergizeNepal* om å konstruere en Francis testrigg på TTL.

Acknowledgements

This master's thesis is the result of work done at the Department of Energy and Process Engineering at NTNU, January - May 2014. The task of designing a Francis model test rig at Kathmandu University has been very educative and rewarding in many ways. It has been a great experience to visit Kathmandu University and to cooperate with the staff at TTL. My motivation for continuing working with such meaningful development projects has definitely increased. I am also thankful for the opportunity of working in the unique environment at the Waterpower Laboratory, with such an encouraging and helpful staff and professors.

A special thanks goes to my supervisor Prof. Ole Gunnar Dahlhaug, who has always been motivating and available for discussions. Also, a huge thanks to Bård Brandåstrø for time spent on explaining technical details of instrumentation and equipment of the laboratory. The Ph.D. candidates Biraj Singh Thapa, Peter Joachim Gogstad and Bjørn Winther Solemslie also deserve acknowledgements for their contributions to this work.

I also want to thank Ida Bordi Stene for a good cooperation during our master's thesis work and the fieldwork in Dhulikhel.

Lastly, a huge thanks to the staff at TTL, Ravi Koirala and Sailesh Chitrakar for ensuring a very rewarding stay in Nepal, and for all their valuable help during the whole working period of this thesis.

Inger Johanne Rasmussen
Trondhem, June 10, 2014

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Nomenclature

c	Velocity	m/s
D	Diameter	m
g	Gravity constant	m/s^2
H_e	Effective head	m
$H_{\mathrm{loss,hydraulic}}$	Hydraulic loss	m
I	Current	A
n	Rotational speed	rpm
n_{ED}	Speed factor	-
P	Power	W
p	Pressure	kPa
Q	Volumetric flow rate	m^3/s
Q_{ED}	Discharge factor	-
$Q_{\max}$	Maximum flow rate	-
T	Torque	Nm
$\Delta T_{\min}$	Minimum filling time	s
U	Voltage	V
$V_{\min}$	Minimum volume	m^3
z	Height	m
η_{h}	Hydraulic efficiency	-
ρ	Mass density of water	kg/m^3
σ	Thoma number, Cavitation factor	-
ω	Angular velocity	rad^{-1}

Abbreviations

NTNU	**N**orwegian **U**niversity of **S**cience and **T**echnology
KU	**K**athmandu **U**niversity
TTL	**T**urbine **T**esting **L**aboratory
Norad	**N**orwegian Agency for Development Cooperation
IEC	**I**nternational **E**lectrotechnical **C**ommission
EOT	**E**lectric **O**verhead **T**ravelling
rpm	**r**evolutions **p**er **m**inute
NPSH	**N**et **P**ositive **S**uction **H**ead
mwc	**m**eter **w**ater **c**olumn
BEP	**B**est **E**fficiency **P**oint
DC	**D**irect **C**urrent
AC	**A**lternating **C**urrent
DN	**D**iameter **N**ominal
CAD	**C**omputer-**A**ided **D**esign
NHE	**N**epal **H**ydro and **E**lectric
GE	**G**eneral **E**lectric Company

Chapter 1

Introduction

Nepal is situated between two of the world's fastest growing economies, China and India, but is still among the poorest countries in the world. With a growing population and an increase in development, Nepal is facing the challenge of a larger electricity demand than what its current infrastructure can supply. Although Nepal has about 42 000 MW of economically exploitable hydropower resources, about 63 % of the Nepalese households lack access to electricity. In 2010, the government of Nepal announced its intention to generate 38 000 MW of hydropower within the next 25 years. The development of local and reliable turbine manufacturers and research institutes is essential for an independent hydropower production in the country [2].

At Kathmandu University (KU), the Turbine Testing Laboratory (TTL) has been in operation since 2011. TTL's main activities are focused on education and research within the topics of sand erosion and turbine design. Some of the activities are funded by The Norwegian Agency for Development Cooperation (Norad). One such is the early-stage *EnergizeNepal* project which aims to develop turbine model test rigs for performance testing in compliance with the international standard *IEC 60193* [1]. The installation of such rigs will be a significant step for the hydropower industry in Nepal.

By making a suggestion for the design of a Francis model test rig at TTL, this master's thesis will be one of the first steps towards a laboratory that can handle complete performance tests according to the requirements of *IEC 60193* [1]. This work is a cooperation between the Waterpower Laboratory at the Norwegian University of Science and

Technology (NTNU), and TTL. Fellow master's student at the Waterpower Laboratory, Ida Bordi Stene, will work on the design of a model test rig for Pelton turbines.

1.1 Objective, Scope and Structure

The objective of this thesis is to suggest a design of the main parts in a new and fully equipped Francis model test rig at TTL, which also can be used to handle model tests according to the specifications of *IEC 60193* [1]. The Francis test rig at the Waterpower Laboratory will be used as the initial design. Modifications needed will be evaluated, designed and documented. The design is divided into three categories:

- components (Chapter 4.1)
- instrumentation (Chapter 4.2)
- power electrical system (Chapter 4.3)

The main focus is on the design of the pressure tanks, pressure, flow measurement, and total pipe system, in addition to ensuring a multifunctional and durable test rig. An overview of the power electrical system, measurement of temperature and oxygen level, instrument calibration methods, and the main shaft and bearing system is presented. The design of the turbine runner, spiral casing, draft tube cone and draft tube bend is not included in this thesis. An equipment list for each part is provided, and presented together with a rough estimation of equipment costs.

The thesis is structured by first presenting relevant previous work, together with an overview of the laboratories at NTNU and KU in Chapter 2. Chapter 3 presents the basic theory of model tests on Francis turbines, and a description of each component in a test rig. The description includes requirements from *IEC 60193* [1] and the equivalent design at NTNU. In Chapter 4, the design of the Francis model test rig for TTL is developed. The resulting design is presented and discussed in Chapters 5 and 6. Development of procedures for efficiency measurements of the Francis models is presented in Chapter 5.3. Suggestions of further work are summarized in Chapter 8.

Chapter 2

Background

2.1 Previous Work

The Turbine Testing Laboratory (TTL) at Kathmandu University (KU) is designed for performance testing of model turbines. The Waterpower Laboratory at the Norwegian University of Science and Technology (NTNU) has played an important role in the development of TTL. In cooperation with NTNU, several research projects have been carried out, both at NTNU and TTL, such as designing turbine test rigs with the required accuracy as stated in the international standard *IEC 60193* for *Model acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines* [1].

For his project thesis, Bidhan R. Halwai, designed a Francis turbine rig for TTL, and proposed options for the placement of the turbine, pipes and measurement instruments [3]. His suggestions were slightly modified by the employees of TTL, and the result was the simplified Francis turbine test rig which is now installed at TTL.

For her master's thesis, Johanne Seierstad made suggestions for the flow calibration method and design in relation to the existing Francis rig at TTL [4]. The choice of flowmeter, dimensions and calibration system in this thesis will be based on Seierstad's results and evaluation.

A pre-project by the author was done to perform tests on the Francis test rig at NTNU and to evaluate the Francis test rig at TTL for further improvement. In addition, fieldwork at Kathmandu University was performed in March 2014 to gain useful knowledge about the set-up of the laboratory. Chapters 2.2 and 2.3 give a description of the Waterpower Laboratory and TTL, based on the pre-project and the visit to TTL.

2.2 The Francis Model Test Rig at NTNU

The design of the Francis model test rig for TTL will be based on the design of the Francis model test rig at the Waterpower Laboratory at NTNU. The rig complies with the international standard *IEC 60193* [1].

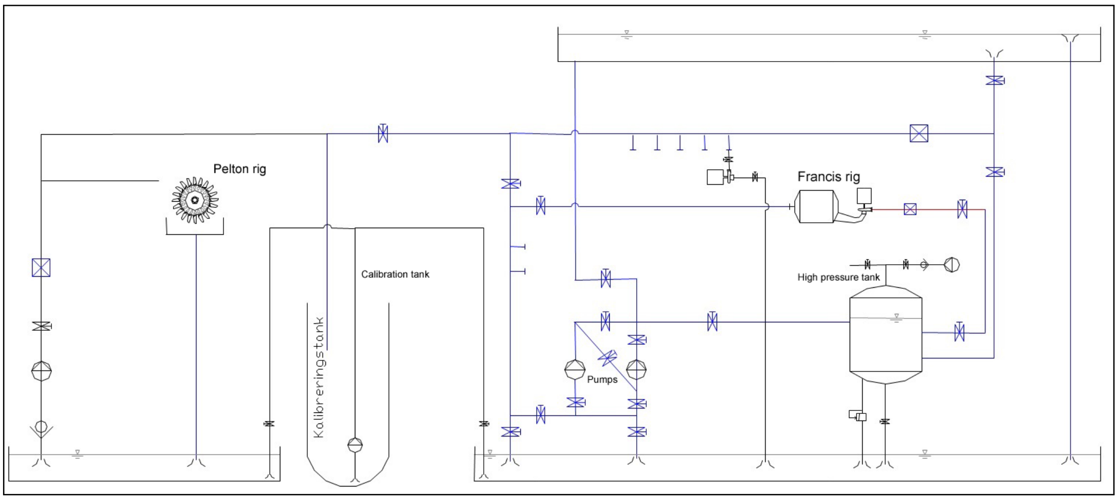

FIGURE 2.1: Overview of the test rigs at the Waterpower Laboratory at NTNU [5].

The pipe system mode for running the Francis test rig is shown in Figure 2.2. In this mode, the water from the rig goes back to the pump through pipes without forming any free surfaces, and it is therefore a closed loop. In the pipe between the pressure tank and the Francis turbine there is a flowmeter and transducers to measure pressure and temperature. From here, the water enters the spiral casing and guide vanes, and is led into the runner, where the hydraulic energy is transformed to mechanical energy. The water then flows through the draft tube and into the draft tube tank downstream the turbine. The pressure difference between the pressure tank (high pressure) and the draft tube tank (low pressure) gives the necessary driving forces to accelerate the flow through the turbine [6]. The maximum pressure of the system is 100 meter water column (mwc) at 0.5 m^3/s flow and the maximum flow is 1 m^3/s at 20 mwc [7].

The rig can also be operated in open loop mode. The water is then led from the pumps, up to the open channel upper reservoir, down to the pressure tank, through the turbine, to the draft tube, and back to the pumps.

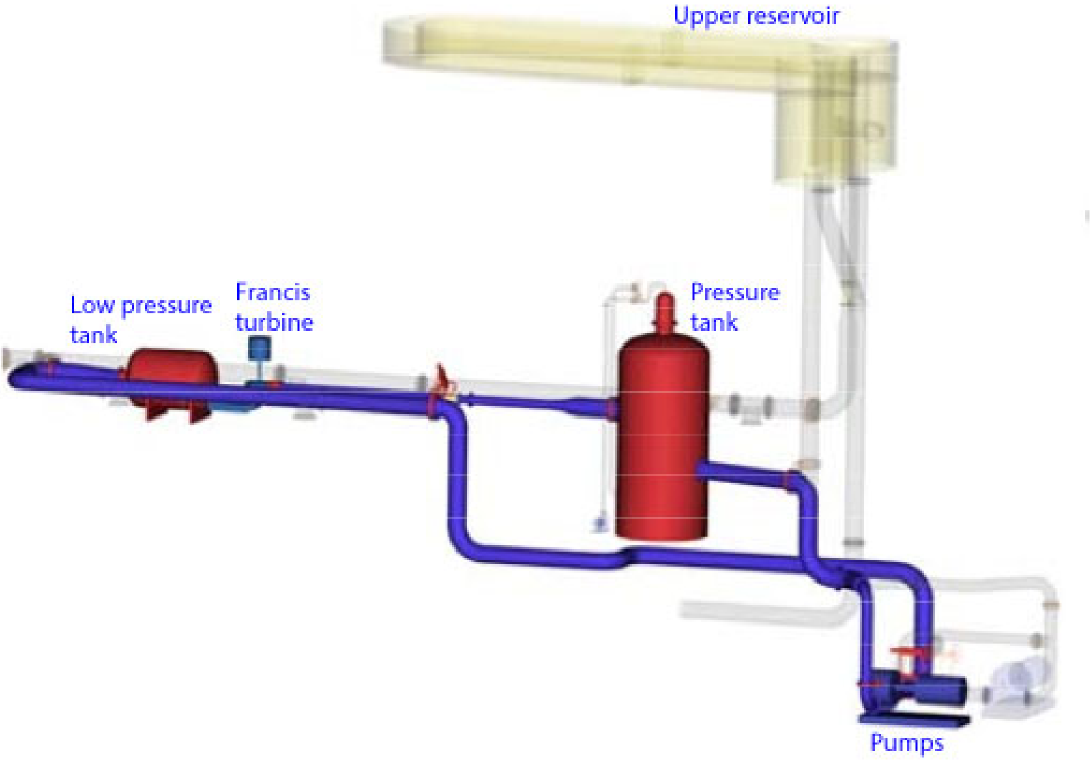

FIGURE 2.2: Pipe system mode for running the Francis turbine test rig at the Waterpower Laboratory in closed loop [7].

A more detailed description of the main components of the Francis rig at NTNU is found in Chapter 3.3.

2.3 The Turbine Testing Laboratory at KU

FIGURE 2.3: The Turbine Testing Laboratory plays an important role in the education, research and development of the hydro-power industry in Nepal [8].

The design of a turbine testing laboratory to be installed at the Dhulikhel campus of Kathmandu University - School of Engineering, started in 2000. In 2011 the construction phase was completed, and the first and only laboratory in Nepal with the purpose of research, teaching and training in the field of hydro-machinery opened.

The laboratory has one upper and one lower reservoir for storing and circulating water. The lower reservoir is the main reservoir and has a capacity of 300 m^3, while the upper reservoir has a capacity of 100 m^3 [3].

The topography of the laboratory location provides a 30 meter natural static head. The laboratory has two centrifugal pumps of 250 kW each. Each pump can produce a head of maximum 75 m and a maximum flow of 0.25 m^3/s. By connecting the pumps in series or parallel, they can produce a maximum head of 150 m or a maximum flow of 0.5 m^3/s respectively. Hence, the laboratory has the capacity to perform model tests on turbines up to 300 kW [8].

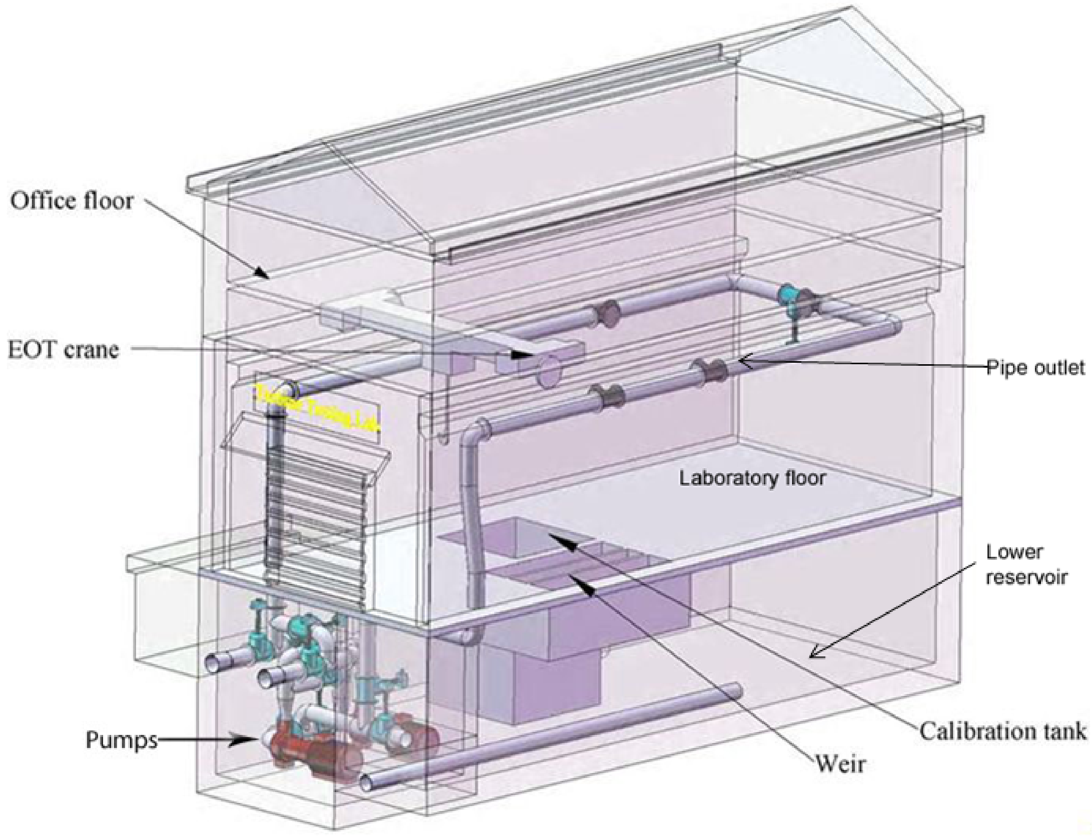

Figure 2.4: Transparent view of the Turbine Testing Laboratory [8]. The upper reservoir is situated on a hill top behind the laboratory.

The main pipe system at the laboratory consists of a loop from the two pumps in the basement up to the laboratory room, around and down to the pumps again. The pipes have a diameter of 400 mm and there are five possible outlets from the pipe (seen in Figure 2.4). The laboratory floor has several openings to the lower reservoir, which makes it possible to dissipate water when necessary.

In addition to the pump room and the lower reservoir in the basement, there are three weirs intended for flow measurement. These weirs have different shapes at the outlet, and the geometry is used to calculate the flow of the water. The weirs lead water to the lower reservoir.

Next to the pump room there is a calibration tank, which is a 2 m by 2.6 m, 5 m deep, with an opening to the laboratory floor. This is intended for calibrations of the flowmeter. Its use is further discussed in Seierestad's master's thesis [4].

The laboratory also has an electric overhead travelling crane (EOT) placed approximately five meters from the floor level. The crane can handle up to 500 kg.

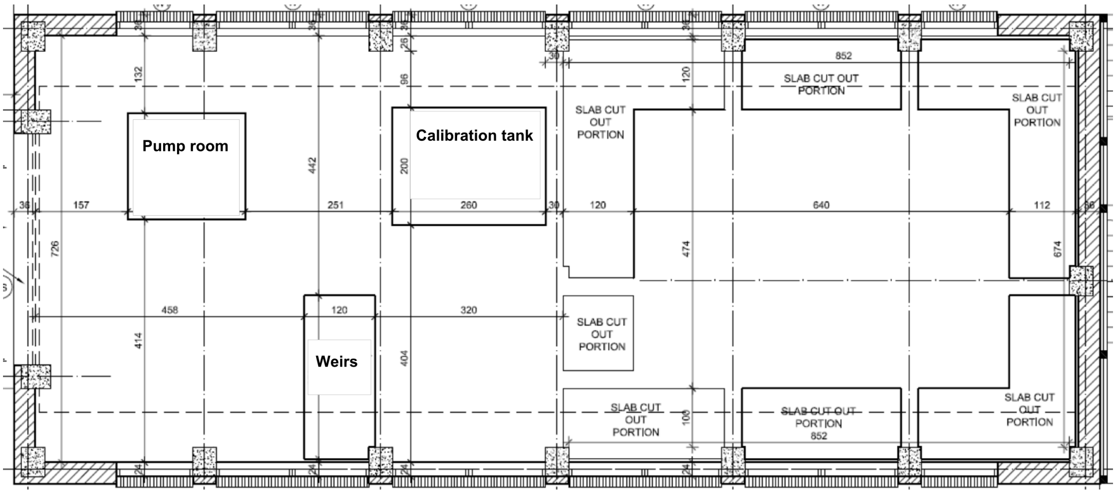

FIGURE 2.5: Technical drawing of the laboratory floor at TTL [9].

Currently, sand erosion and turbine design are the main areas of activity at TTL. In addition, TTL is working towards performing model tests in accordance to *IEC 60193* [1]. At this date, there is a simple Francis turbine test rig at TTL. This simplified test rig has been designed and manufactured by the students and staff at TTL, and is the first step towards a fully equipped Francis turbine test rig [10].

FIGURE 2.6: The simplified turbine test rig at TTL [10].

Limitations

As stated in the scope section in Chapter 1.1, the design of the model turbine test rig at the Waterpower Laboraty at NTNU will be used as the initial design for TTL. Some modifications must be done due to the differences between the two laboratories.

Firstly, TTL has less available laboratory space. The Waterpower Laboratory is five storeys high (including the basement) which all are used for the test rigs, reservoirs and pipe systems. TTL has two storeys available; the basement and the laboratory floor. On the other hand, TTL has the advantage of the natural head of 30 meter from the upper reservoir.

Secondly, TTL is 90 years younger than the Waterpower Laboratory and therefore has less experience on the many fields of hydropower turbines. It is a goal that a competent technical environment at TTL will be established through master's degrees, research programmes and the development of test rigs.

Thirdly, Nepal has for many years used load shedding to control the lack of energy production compared to the energy demand. This leads to limited operating hours at the laboratory at TTL and there is always a small risk of being unexpectedly disconnected from the grid.

Lastly, TTL has a lower budget and less resources available from local hydroelectric producers. With the development of the hydropower industry in the country this may change.

The mentioned limitations must be taken into account when designing the test rig for TTL. In addition, it is desired that the rig is flexible for multifunctional usage, durable and easily maintained.

Chapter 3

Model Testing of Francis Turbines

The first part of this chapter gives an overview of the basic theory of the Francis turbine and model tests of the turbine. The second part describes the function of the most important components of a Francis model test rig, and the requirements of the international standard for hydraulic turbine model tests, *IEC 60193* [1].

3.1 The Francis Turbine

Together with the Pelton and Kaplan turbines, the Francis turbine is the most used hydropower turbine. When in operation, the whole Francis turbine runner is filled with water, and it is therefore considered a full turbine, or a reaction turbine. A reaction turbine is defined as a turbine where approximately half of the specific energy at the inlet is pressure energy, caused by the pressure difference between the inlet and outlet of the runner. This is again converted to mechanical energy through the runner. The Francis turbines have a high efficiency and may be designed for a wide range of flows and hydraulic heads (up to 800 meters) [6].

The main parts of the Francis rig are labelled in Figures 3.1 and 3.2, followed by a description of each part.

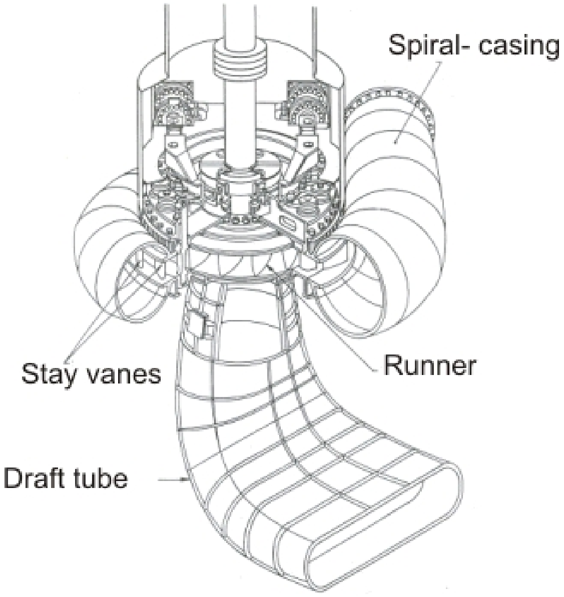

Figure 3.1: Cut out view of a Francis turbine [11].

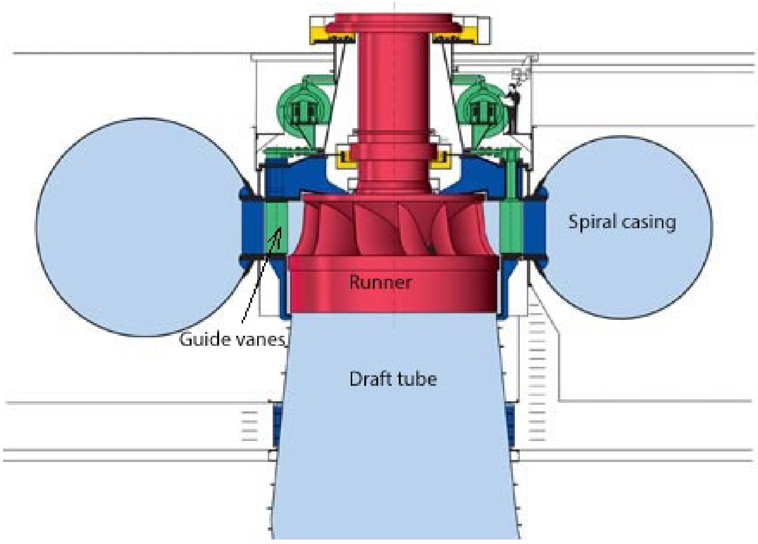

Figure 3.2: Cross section view of a Francis turbine [12].

Spiral casing The spiral casing distributes the water through the stay vanes (see Figure 3.1) onto the guide vanes to smoothen the flow conditions [6].

Guide vanes The guide vanes regulate the flow and give the right rotation to the water so that it hits the runner in the correct angle.

Runner The runner converts the specific energy in the water to mechanical energy.

Draft tube In the draft tube the flow rate of the water is reduced towards the outlet, and hence the pressure increases up to the pressure of the lower reservoir.

3.2 Model Testing

Most turbines used in hydropower stations are too big to be tested in a laboratory, and a performance test in the field is costly and difficult [13]. To compensate for this, a method for testing turbine models is used. This involves scaling down the prototype to a model, based on guidelines explained in the international standard for model testing of hydraulic turbines, *IEC 60193* [1]. According to this standard, the model must have both geometric and hydraulic similarity. Geometric similarity means that the model has to have the exact same shape as the prototype, with smaller dimensions.

Hydraulic similarity is achieved when the model and prototype are geometrically similar, and have identical ratios of forces acting between the fluid and the components of the turbine [13]. The ratios are defined by the reduced quantities discharge factor (Q_{ED}), speed factor (n_{ED}) and Thoma's cavitation factor (σ). When testing the performance of a Francis model, the results are commonly presented in a Hill diagram. To do this, the hydraulic efficiency (η_h) is plotted against the reduced values (Q_{ED} and n_{ED}). The Hill diagram is then applicable for the corresponding prototype.

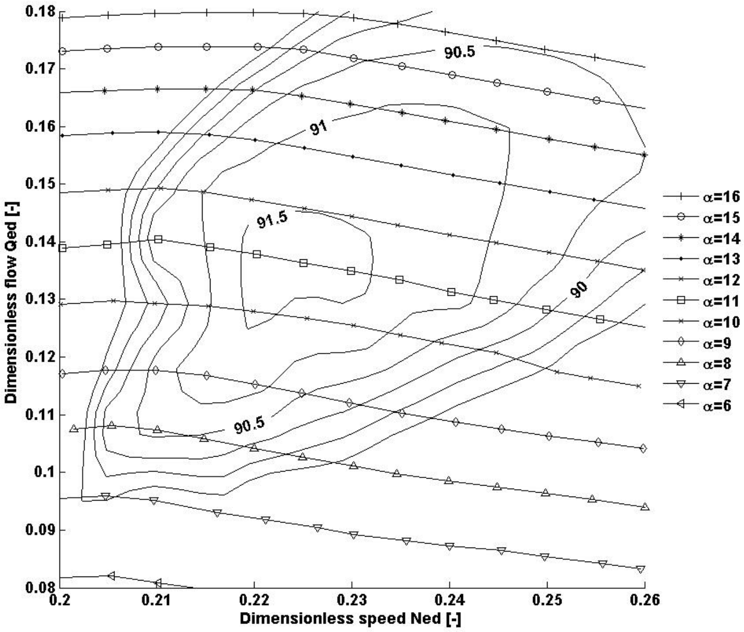

Figure 3.3: Example of a Hill diagram of a Francis turbine [14].

The equations for the discharge factor, the speed factor and cavitation factor are displayed below:

$$(Q_{ED})_{\text{prototype}} = (Q_{\text{ED}})_{\text{model}} = \frac{Q}{D^2\sqrt{g \cdot H}} \qquad [-] \tag{3.1}$$

$$(n_{\text{ED}})_{\text{prototype}} = (n_{\text{ED}})_{\text{model}} = \frac{n \cdot D}{\sqrt{g \cdot H}} \qquad [-] \tag{3.2}$$

$$\sigma_{\text{prototype}} = \sigma_{\text{model}} = \frac{\text{NPSH}}{H} \qquad [-] \tag{3.3}$$

In the equations, Q is the discharge, D is the diameter at the outlet of the turbine, g is the acceleration of gravity, H is the turbine head, NPSH is the Net Positive Suction Head[1] and n is the rotational speed.

Ideally, the prototype and the model should have identical ratio of forces acting between the fluid and the components of each machine. The ratios of forces are Reynolds ($Re = \frac{\text{inertia}}{\text{viscosity}}$), Euler ($Eu = \frac{\text{pressure}}{\text{inertia}}$), Froude ($Fr = \frac{\text{inertia}}{\text{gravity}}$) and Weber ($We = \frac{\text{inertia}}{\text{surface tension}}$). Achieving similitude of these ratios in the same test is normally impossible. Therefore, corrections have to be applied to the model results when they are transformed to prototype conditions [1].

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[1] A further description of *NPSH* may be found in Chapter 3.3 in *Pumper og turbiner*, Prof. H. Brekke [15].

3.3 Components in a Francis Model Test Rig

Chapters 3.3.1 to 3.3.3 describe the main components a Francis model test rig consists of. As explained in the scope of this thesis, the Francis turbine test rig at the Waterpower Laboratory at NTNU is to be used as the initial design for the development of a new test rig at TTL. The design and use of the components at the Waterpower Laboratory is therefore outlined. When applicable, the requirements of *IEC 60193* [1] for each component are also described.

3.3.1 Pressure Tanks

According to *IEC 60193* [1], the system should, as much as possible, be free from air and gas bubbles. In order to have control of the air content, the efficiency test of a Francis turbine should be done in a closed loop. At the Waterpower Laboratory, the closed loop contains a high pressure tank at the inlet of the turbine and a low pressure tank at the outlet.

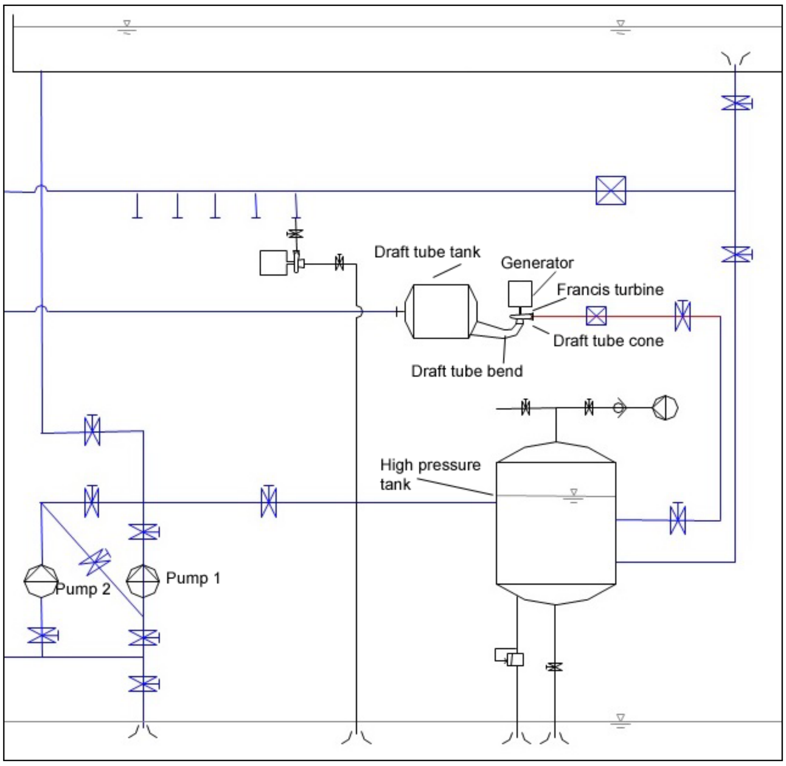

Figure 3.4: Positions of pressure tanks and Francis turbine at the Waterpower Laboratory [5].

The requirements of *IEC 60193* [1] regarding the pressure tanks are mainly concerning the flow conditions. For the inlet, the requirements are that ”installation shall ensure favourable hydraulic conditions free from vortices, undue turbulence and unsteadiness”. For the outlet it is stated that ”flow pattern shall not be influenced on the layout or construction of the test facility” [1, Chapter 2.1.2.4].

Inlet

The inlet of the test rig consists of a high pressure tank were the water is pressurized depending on the required head of the flow. The water is then led through pipes to the spiral casing and turbine runner through pipes.

The high pressure tank at the Waterpower Laboratory is approximately 5.2 m tall and has a diameter of approximately 2.25 m. The volume is 18 m^3 and the maximum working pressure is 10 bar [7]. There are systems for air ventilation, pressure measurement and safety valve. The tank is placed upstream the turbine, as can be seen from Figure 3.4.

Outlet

The outlet at the rig consists of a draft tube cone, draft tube bend and a low pressure tank (referred to as draft tube tank in this thesis). The draft tube cone has a see-through material which allows observing behaviour such as cavitation. This is a requirement of *IEC 60193* [1].

FIGURE 3.5: The draft tube of the Francis test rig at the Waterpower Laboratory. The draft tube cone has transparent casing so that the behaviour of the water can be monitored. The water is led from the draft tube to the draft tube tank (at the left, in the back).

The draft tube tank at the Waterpower Laboratory has a length of 4.4 m and a diameter of 2.5 m. The volume is approximately 20 m^3 [7]. It has systems for venting the tank, and to measure the pressure in the tank. The tank wall at the inlet (seen at the far back in Figure 3.5) is removable, and gives the possibility of attaching draft tubes of different shapes and sizes.

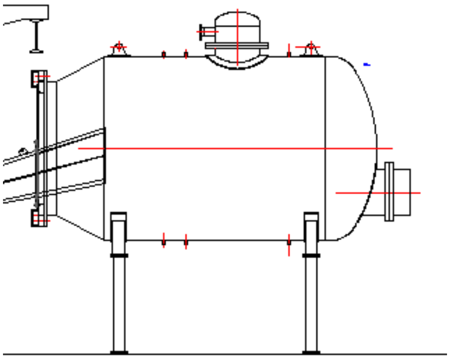

FIGURE 3.6: The draft tube tank of the Francis test rig at the Waterpower Laboratory.

3.3.2 Guide Vane Control System

The guide vanes control the degree of load and discharge on the turbine runner.

The main requirement from *IEC 60193* [1] is that ”elements used to vary machine geometry (runner/impeller blades, guide vanes, nozzles) shall be capable of repeating and maintaining a set position” [1, Chapter 2.1.3.2].

For the rig at the Waterpower Laboratory, all guide vanes are connected to a ring such that one movement of the ring will change the position of all guide vanes to the same angle. The ring is connected to an arm which again is connected to a wheel to manually regulate the guide vane angle. The arm is also connected to an electrical motor which makes it possible to remote control the guide vane angle.

3.3.3 Main Shaft and Bearing Block

The purpose of a bearing block is to connect the rotating shaft with the stationary parts of the rig, and to absorb the radial and axial forces in the turbine. The bearing block at the Waterpower Laboratory is placed on the shaft, just above the upper cover of the rig. The upper bearing is a double ball bearing and the lower bearing is a double roller bearing. The bearings are lubricated with oil from a hydraulic system, controlled by a pump. The system is connected to a cooling water supply.

The main shaft at the Waterpower Laboratory is vertical and 786 mm long with a diameter varying from 90 mm to 65 mm. There are no specific requirements regarding the shaft and bearing block stated in *IEC 60193* [1]. It is however crucial to ensure that the connections between the stationary and rotational components are free from friction. The bearings must be able to withstand the radial and axial force on the shaft. It is also important to install suitable seals to avoid unwanted water leakage.

3.4 Instrumentation

The parameters to be measured during a test in a Francis turbine test rig are inlet and outlet pressure, flow rate, speed of rotation, generator torque, friction torque, axial load, temperature and oxygen level in the water. In Chapter 2 of *IEC 60193* [1] it is stated that all measuring instruments should provide direct reading, independable of the data acquisition system [1, Chapter 2.1.2.5].

IEC 60193 [1] describes two types of measuring methods: primary and secondary. Primary methods are those measuring the fundamental quantities only: length, mass and time. Other methods based on other principles are called secondary methods. Instruments using secondary methods must be calibrated against primary methods [1, Chapter 3.2.1.1.2].

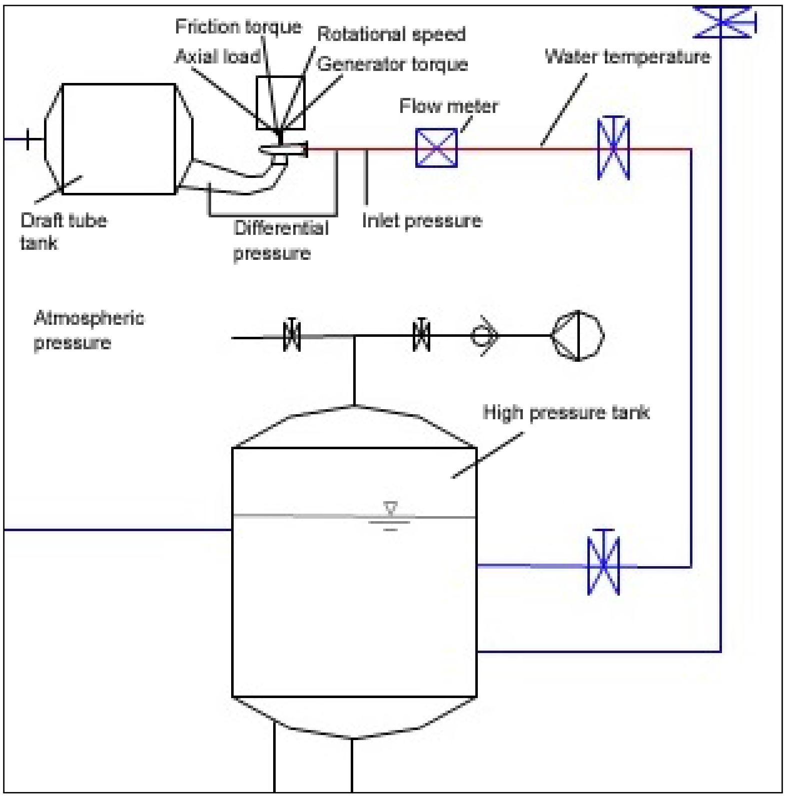

FIGURE 3.7: Positions of measuring instruments for the Francis turbine test rig at the Waterpower Laboratory [5].

3.4.1 Pressure

There are both primary methods and secondary methods to measure the pressure. Primary methods mentioned in *IEC 60193* [1] are liquid column manometers, dead weight manometers and pressure weighbeams. Secondary methods are pressure transducers or other apparatus such as spring gauges [1, 3.3.4.1].

At the Waterpower Laboratory, the pressure is measured by the use of pressure transducers. Pressure transducers are electromechanical devices that converts pressure into electrical signals [1, Chapter 3.3.4.5]. Procedures for measuring the pressure by the use of pressure transducers can be found in Appendix A.3 of this thesis. The appropriate range for the pressure transducer is dependent on the pressure to be measured.

According to *IEC 60193* [1], advantages of pressure transducers include the ease in which they are integrated into electronic data acquisition systems and that they provide rapid and accurate response. In addition, average values of fluctuating pressure or pressure differences are easily obtained.

The pressure transducers should have the following characteristics:

- sufficient calibration stability
- high repeatability
- low zero shift and low temperature sensitivity
- no influence by bias effect when charged by pressure

It is recommended that two similar transducers are installed in parallel to take simultaneous readings during the test, as a control for the uncertainty.

The pressure transducers are calibrated against a primary method. At the Waterpower Laboratory, a dead weight manometer is used for calibration. This method is described in Appendix A.2 in this thesis, and in Chapter 3.3.4.3 in *IEC 60193* [1].

At the Waterpower Laboratory, the pressure is measured at the inlet section of the turbine. The differential pressure between inlet and outlet section is measured at the draft tube. In addition, the atmospheric pressure is measured in the laboratory room.

The set-up consist of pressure taps that are installed on the water pipe. These are connected to a manifold leading into the transducer, where the average pressure of the pipe is obtained (illustrated in Figure 3.8). At least two pairs of opposed pressure taps shall be used at right angles to each other. The taps should neither be located at or near the highest point of the measuring section (to avoid air bubbles), nor the lowest point due to risk of dirt. Each tap should be separately valved and installed even with the pipe wall [1, Chapter 3.3.3.3].

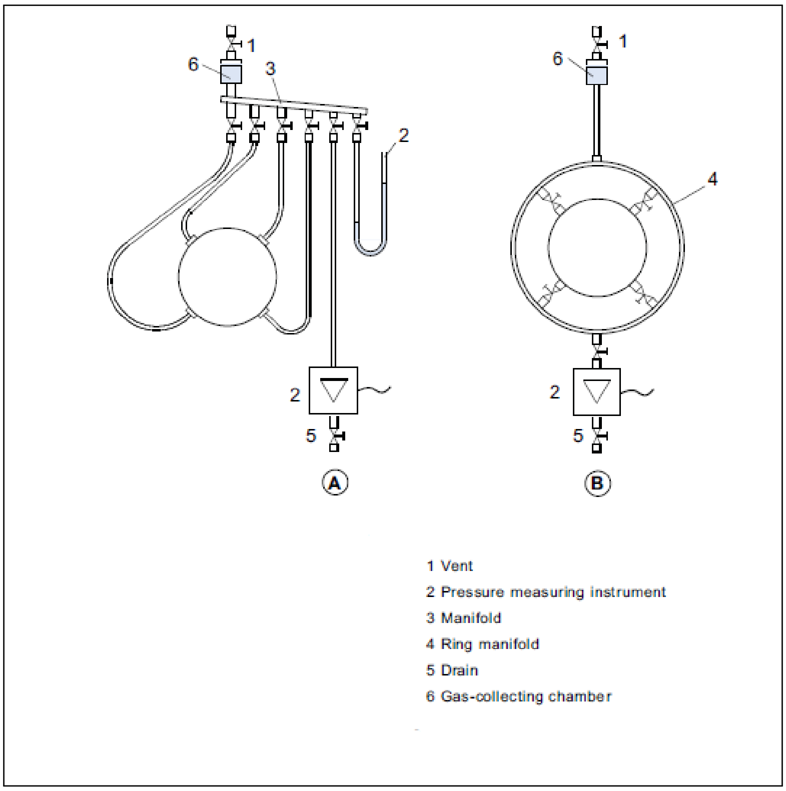

Figure 3.8: Illustration of two types of manifold: separate pipe manifold and ring manifold [1, Chapter 3.3.3.3].

The piping of the taps is recommended to be transparent plastic pipes for high pressure so that air bubbles may be detected. They must be installed so that there is a way to avoid trapping of air. Naturally, no leaks are permitted in the pressure taps and pipes. Further details are described in Chapter 3 of *IEC 60193* [1, Chapter 3.3.3.2].

When planning the instrument set-up, it is important to have equipment for pressure fluctuations tests in addition to standard efficiency tests.

3.4.2 Flow Rate

When it comes to flow rate, *IEC 60193* [1, Chapter 3.2] advises to have one primary and one secondary method. The primary method will be used to calibrate the secondary method. Primary methods described are the weighing method, the volumetric method, and the moving screen method.

A few different secondary methods are suggested in *IEC 60193* [1]. Some of them are using thin-plate weirs, differential pressure devices and various types of flowmeters, such as turbine, electromagnetic, acoustic and vortex flowmeters. These flowmeters allow quick measurements, generate little disturbance in the flow system and are easily integrated to a data acquisition system. Since they are secondary methods, they require regularly *in situ* calibration against one of the primary methods. *IEC 60193* [1] states that "Whatever method is used, a discharge measurement for a model acceptance test is valid only if the flow is steady or nearly steady during each point" [1, Chapter 3.2].

The flowmeter used at the laboratory at NTNU is of the electromagnetic type, manufactured by Krohne. In an electromagnetic flow meter, a magnetic field is generated and channelled into the water flowing through the pipe. Following the *Faraday's Law of Electromagnetic Induction*[2], a voltage will be generated when the conductive water flows through the magnetic field. Electrodes located on the inside of the pipe wall sense this voltage. The voltage generated increases proportionally to the flow rate. According to *IEC 60193* [1], the electromagnetic flow meters do not generate disturbance in the flow, there is no pressure loss, and they are not very sensitive to wear [1, Chapter 3.2.3.5]. The procedure for measuring the flow rate at the Waterpower Laboratory is attached in Appendix A.3.

As can be seen in Figure 3.7, the flow meter at the Waterpower Laboratory is installed on the pipe just before the inlet of the turbine runner. The calibration method used is the weighing method, which is further described in Appendix A.2 and in *IEC 60193* [1, Chapter 3.2.2.1].

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[2] *Faraday's Law of Electromagnetic Induction* is the law that predicts how a magnetic field will interact with an electrical circuit producing a voltage. Voltage is generated with any change in the magnetic environment [16].

3.4.3 Speed of Rotation

The speed of rotation of the turbine runner is needed in order to find the speed factor explained in Chapter 3.2. *IEC 60193* [1] recommends one of the following methods for the rotational speed measurement [1, Chapter 3.7.2]:

- counting of pulses generated by the turbine shaft using an electronic counter and timebase
- electrical frequency meter connected with a generator directly driven by the model shaft
- electrical high-precision tachometer comprising a stable permanent magnet directly driven by the model shaft

At the Waterpower Laboratory, the first method is used. The rotational speed is measured at the shaft, just above the upper sealing labyrinth of the turbine. The arrangement consists of a slotted disc mounted on the shaft. The disc may have many slots, but it is advantageous to have only one, as it allows control of the position of the shaft. When the disc rotates with the shaft, it passes through an optical sensor that registers the time between each passing of the slot. This frequency is converted into the rotational speed. This is a primary measuring method, and does not need calibration [17]. The procedure for measuring the speed of rotation at the Waterpower Laboratory is attached in Appendix A.3.

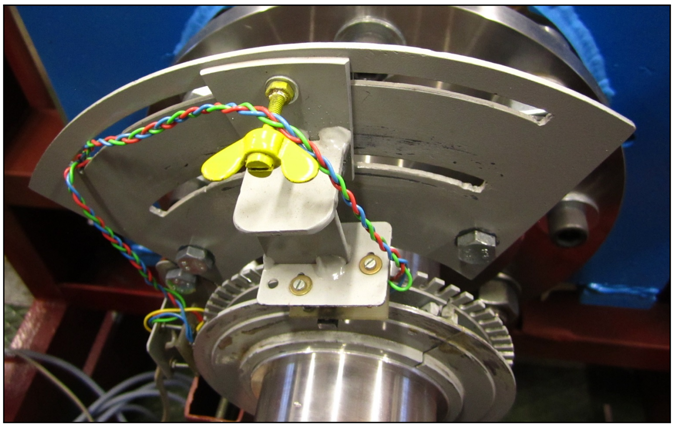

Figure 3.9: Example of speed of rotation measurement with a slotted disc and an optical sensor.

3.4.4 Generator Torque

There are several methods described in Chapter 3.6 in *IEC 60193* [1] to measure the generator torque. At the Waterpower Laboratory, it is done by a hydraulic bearing, a load cell, and an arm mounted on the generator. The torque is equal to the force measured on the load cell multiplied by the length of the arm. The procedure for measuring the torque at the Waterpower Laboratory is attached in Appendix A.3. This is a secondary method and must therefore be calibrated against a primary method [7].

Calibration methods are described in Appendix A.2 in this thesis, and in *IEC 60193* [1, Chapter 3.6.2.1]. *IEC 60193* also describes checks to verify operation of the torque measuring arrangement [1, Chapter 3.6.5].

3.4.5 Friction Torque

In a Francis turbine there may be friction torque in the guide bearings, thrust bearings, and shaft seals. This friction is mechanical loss in the hydraulic machine, and is therefore important to monitor [1].

The system for measuring the friction torque at the Waterpower Laboratory is similar to the one measuring the generator torque. The apparatus is the same, but with smaller dimensions, as the friction torque is usually less than the generator torque. Hence, the calibration methods are also similar to the methods described in Chapter 3.6.2.1 in *IEC 60193* [1].

3.4.6 Axial thrust

While the Francis turbine is in operation, there may be forces upwards in the axial direction. Together with the weight of the turbine, these forces make up the axial thrust. According to *IEC 60193* [1], the axial thrust should be tested and monitored during performance tests [1, Chapter 4.5.2].

There are various methods of measuring axial thrust. One of the most used is also used at the Waterpower Laboratory. The axial thrust measuring system consists of a hydraulic thrust bearing and a differential pressure transducer. The transducer measures the difference in pressure of the hydraulic oil in the two sections of the bearing. This procedure is attached in Appendix A.3.

Another method suggested by *IEC 60193* [1] is by use of strain gauges to measure the deflection of connecting parts between axial bearing and the housing [1, Chapter 4.5.2.2.1]. Both these methods are secondary methods, and need to be calibrated regularly.

3.4.7 Temperature

As the efficiency of a turbine is calculated using the mass density of the water, the temperature of the water must be registered during tests[3]. *IEC 60193* [1] also requires that the water temperature does not exceed 35 °C and should not vary significantly during the tests. Also, "Large differences between the water temperature and the ambient temperature of instruments should be avoided, as they could influence the accuracy of the measurements" [1, Chapter 2.1.2.3].

At the Waterpower Laboratory, the temperature is measured downstream the high pressure tank. The thermometer is calibrated externally.

3.4.8 Oxygen Level

According to Chapter 2.1.2.3 in *IEC 60193* [1], free gas and air bubbles should be removed as much as possible before testing. This is controlled by measuring the oxygen level in the water during tests.

At the Waterpower Laboratory, the oxygen level is measured in the feed pipe to the main pumps. The sensor measures the amount of dissolved oxygen based on diffusion of oxygen through a polytetrafluorethylene membrane [7]. The sensor is calibrated externally [18].

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[3] The mass density is dependent on the temperature of the liquid

3.5 Power Electrical System

3.5.1 Generator and Frequency Transformer

The generator connected to the turbine shaft has the purpose of transmitting the rotational energy, dissipating energy, controlling the rotational speed and driving the turbine when in pump mode. There are no specific requirements regarding the generator for a Francis turbine test rig in *IEC 60193* [1].

The generator at the Waterpower Laboratory is a DC generator of 352 kW with a rated speed of 1560 rpm. The generator is connected to a DC converter which again is connected to the power grid. The converter supplies and receives power to and from the generator. The generator is resting on a bed of pressurized oil, so that it is free to rotate without friction [7].

Depending on the generator in the Francis rig, a frequency transformer or converter might be needed to transform the output of the generator to the standardised frequency of the national power grid.

The energy produced in a Francis model test rig may be fed to the main system or the national grid. At the Waterpower Laboratory, the power is delivered to the national grid.

3.6 Efficiency Test

The purpose of an efficiency test is to map the efficiency of the turbine at different operational points. The two variables are the reduced values Q_{ED} and n_{ED} (explained in Chapter 3.2). By varying these, the best efficiency point (BEP) of the turbine can be found. Other tests that are used in combination with efficiency test are cavitation test, runaway speed test, and pressure fluctuation test. These tests are not within the scope of this thesis, and will not be described in detail.

3.6.1 Energy Conversion

For the Francis turbine, the kinetic and potential energy in the water is converted into mechanical energy going through the runner, and then converted to electric energy by the use of the generator [15]. This is shown mathematically in Equation 3.4, where ρ is the water density, Q is the flow, g is the acceleration of gravity, T is the torque transmitted to the shaft, ω is the rotational speed of the runner, U is the voltage and I is the current in the generator.

$$\rho \cdot Q \cdot g \cdot H \;\rightarrow\; T \cdot \omega \;\rightarrow\; U \cdot I \qquad [-] \tag{3.4}$$

About half of the total specific energy is kinetic energy by the inlet of the Francis runner. After having been converted through the runner, the draft tube recovers the remaining energy as pressure energy [15].

The specific energy is the energy available between the turbine inlet and the outlet of the draft tube:

$$E = g \cdot H + \frac{c^2}{2} + g \cdot z \qquad [\mathrm{J/kg}]\,, \tag{3.5}$$

where g is the acceleration of gravity, H is the head, c is the velocity of the water and z is the height where the energy is measured.

Equation 3.5 is developet from Bernoulli's equation for incompressible and frictionless flow [6].

$$\frac{p}{\rho} + \frac{c^2}{2} + g \cdot z = \text{constant} \qquad \left[\mathrm{m}^2/\mathrm{s}^2\right], \tag{3.6a}$$

or, expressed with pressure as meter water column (mwc):

$$h + \frac{c^2}{2g} + z = \text{constant} \qquad [\mathrm{m}], \tag{3.6b}$$

where c is the velocity of the water, z is the height where the energy is measured and ρ is the mass density of water.

3.6.2 Power and Efficiency

The power of a turbine is defined as the specific energy (E) multiplied with the mass flow ($\dot{m}$). As the mass flow is the same as the mass density multiplied with the flow ($\rho \cdot Q$), the equation for power becomes:

$$P = E \cdot \rho \cdot Q = g \cdot H \cdot \rho \cdot Q \qquad [\mathrm{W}] \tag{3.7}$$

Here, E is the specific energy, ρ is the mass density of water, Q is the flow and H is the head.

The efficiency of a turbine is defined as the power output divided by the power input, or, the specific energy that is converted to mechanical energy, divided by the specific energy from the water [6]. The hydraulic efficiency can be expressed as

$$\eta_{\mathrm{h}} = \frac{E}{g \cdot H} = \frac{g \cdot (H - H_{\mathrm{loss,hydraulic}})}{g \cdot H} \qquad [-], \tag{3.8}$$

where $H_{\mathrm{loss,hydraulic}}$ is the hydraulic loss in the turbine.

To determine the total power output of the turbine, the efficiency must be included in the power equation:

$$P = \eta_\mathrm{h} \cdot g \cdot H \cdot \rho \cdot Q \qquad [\mathrm{W}] \tag{3.9}$$

It is the efficiency at different operational points that is the main result when doing an efficiency test on model turbines.

3.6.3 Method of Testing

This chapter explains some for the requirements of the execution of efficiency tests from *IEC 60193* [1], in addition to procedures at the Francis turbine test rig at the Waterpower Laboratory, which are in compliance with this standard.

Before a test is performed, there are certain criteria that should be taken into account. According to *IEC 60193* [1], free gas and air bubbles should be removed as much as possible before testing. The water temperature should not exceed 35 °C and should not vary significantly during the tests. An inspection of the test circuit should be done before and after the test. The inspection shall at least include the following [1, Chapter 2.3.3]:

- Checks for water leakage in the loop and pressure transducers.
- Ensure that the flow conditions are regular.
- Ensure that the regulating devices are working properly and that the water quality and temperature is stable.

The data acquiring system should also be checked before and after the testing. *IEC 60193* suggests the following [1, Chapter 2.3.3]:

- The instruments used for the testing should be identified; there should be done ”zero readings” for the instruments[4].
- System should be checked for repeated measurements in well defined operating conditions.

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[4] ”Zero readings” are readings in well defined conditions for the different instruments, to detect if any drifting effects occurred during the tests [1].

- The mechanical friction torque should be measured in the bearings and shaft seals that are not connected to the stator.

It is also necessary to calibrate all instruments before carrying out a test. To ensure the required accuracy, the calibrations may be performed more than once. If the difference between two calibrations is less than the systematic uncertainty evaluated for the test, the test data is valid. If not, the test should be repeated [1, Chapter 2.3.3]. Recalibration after the test should also be considered.

Procedure for efficiency measurement

When performing a model test there should be focus on making the test repeatable. It is recommended to find the best efficiency point (BEP) first. The performance test should be carried out at a constant speed or at constant test head.

At the Waterpower Laboratory, the common procedure is to keep the head constant, and vary the guide vane opening and speed factor (n_{ED}) gradually. Measuring points should be taken systematically over the desired operating area around BEP. A LabView program logs the data from the measurements. The data from the logging of efficiency is then post processed by creating a Hill diagram.

An efficiency test was done as preliminary work of this project, and may be found in the author's project thesis: *Evaluation of the Francis Test Rig at Kathmandu University* [14].

A detailed procedure for model testing at the Waterpower Laboratory can be found in A. Stranna's project thesis [18, Appendix B].

Chapter 4

Design of a Francis Model Test Rig at TTL

This master's thesis is done in cooperation with fellow master's student, Ida Bordi Stene. Her thesis proposes a design of a Pelton model test rig for the Turbine Testing Laboratory at Kathmandu University [19]. In consultation with Prof. Ole Gunnar Dahlhaug at the Waterpower Laboratory at NTNU, Biraj Singh Thapa, Ph.D. candidate at NTNU and staff at TTL, the placement of the two test rigs has been decided. The main focus in this chapter is to design a rig that is durable, reliable, not too complicated, flexible and multifunctional, and at the same time fulfils the requirements of *IEC 60193* [1].

This chapter will describe suggestions to the design of the components for a Francis model test rig to be installed at TTL. The suggestions are based on the requirements of *IEC 60193* [1], the design of the equivalent rig at the Waterpower Laboratory at NTNU, and discussions with staff at TTL and NTNU. The limitations mentioned in Chapter 2.3 are also taken into account.

Most of the designs are sketched in the computer-aided design (CAD) program Autodesk Inventor Professional [20] by the author. The drawing of the total design is made in cooperation with Ida Bordi Stene.

The estimated cost for each component designed in this chapter is stated in its respective sub-chapter, and the total budget may be found in Chapter 5.2. It is emphasized that the prices in the budget are rough estimates, and should be confirmed before developing a final budget.

As described in Chapter 1, the level of detail in the suggested design will vary. Chapter 4.1 proposes design of the inlet pressure tank, low pressure tank, guide vane control system, main shaft and bearing block. Chapter 4.2 suggests methods and instruments for the measurement of pressure, flow rate, speed, torque, temperature and oxygen level. Chapter 4.3 gives an overview of the power electrical system. Finally, the total design of the Francis model test rig at TTL is developed in Chapter 4.4.

4.1 Components

4.1.1 High Pressure Tank

The shape of the high pressure tank suggested for TTL will be the same as the pressure tank at the Waterpower Laboratory. The Waterpower Laboratory has good experience with this design, and changes are therefore not necessary [21].

The high pressure tank is suggested to have a volume of $15\,\mathrm{m}^3$, compared to the Water Laboratory's $18\,\mathrm{m}^3$ [21]. According Ole G. Dahlhaug, this size will ensure a stable system, fulfilling the requirements of *IEC 60193* of having "favorable hydraulic conditions" [1, Chapter 2.1.2.4] [21]. The height of the tank is set as 4.0 m which is 0.5 m less than the maximum height to make it moveable by the crane installed at TTL. The diameter is set to 2.4 m. The tank must be made to withstand the maximum pressure of 150 mwc.

The pressure tank has one flange at the inlet and two flanges at the outlet. This is to make the rig flexible for testing different sized turbines. There is also one flange at the bottom of the tank for draining, and one flange on the top. From this flange there is a pipe with a valve for venting the tank if reduction of pressure is necessary. This pipe has a diameter of 100 mm. It ends up in the reservoir in the basement for the cases when the tank is overfilled. The valve for venting is placed approximately 1.5 m above the floor for easy access. Just above the valve there is a pressure gauge for visual readings of the pressure. This gives an extra reliable monitoring of the pressure in the tank, compared to digital readings. There is also a plastic pipe placed outside the tank for monitoring the water level in the tank. In addition, there must be a safety valve placed on the pressure tank in order to ensure venting when the tank is unintentionally over the pressure limit of 15 bar. Blind pipe flanges are used to seal the draining hole and the outlets that are not in use. All pipes and valves have a diameter of 400 mm.

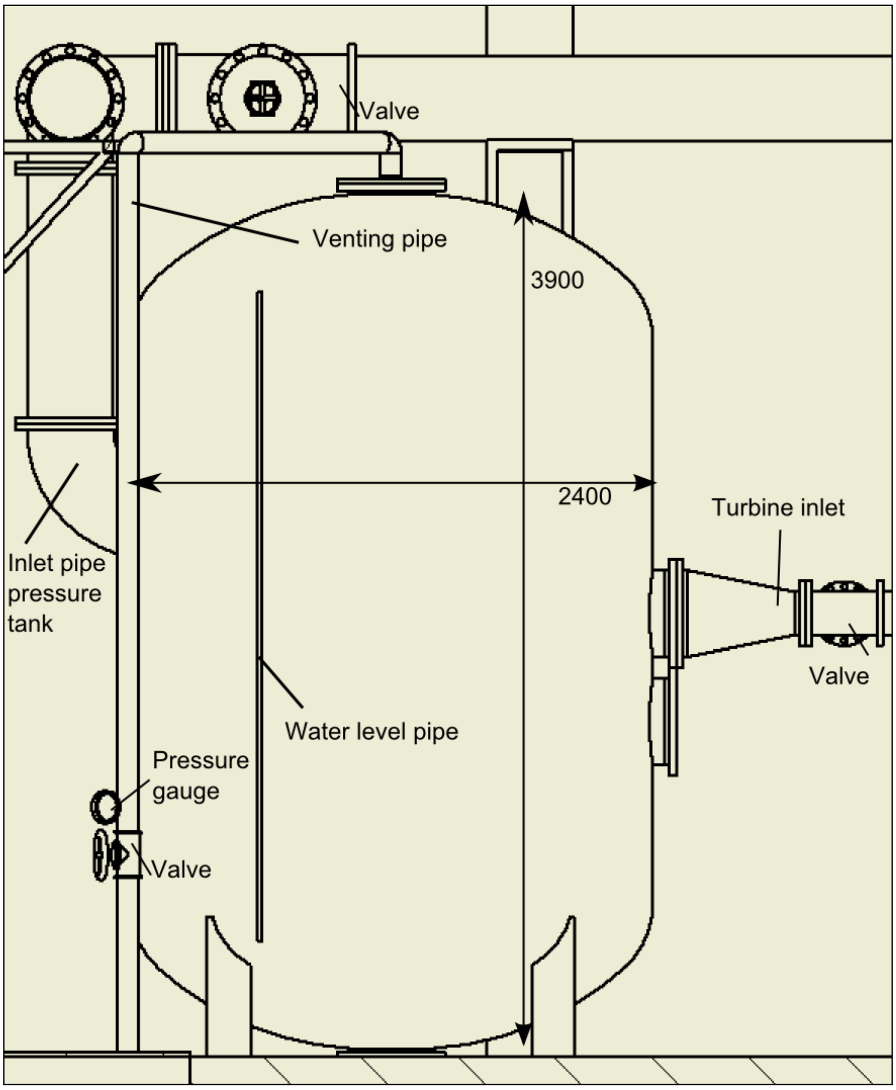


FIGURE 4.1: Drawing of the suggested pressure tank for TTL. All dimensions are in mm.

The high pressure tank must be placed upstream of the turbine. The space between the pressure tank and the turbine is dependent on where the flowmeter is placed. This is further discussed in Chapter 4.2.2.

The production of the pressure tank and connecting pipes can be done at Nepal Hydro and Electric Limited (NHE) in Butwal, Nepal. The suggested material is stainless steel as this is the most commonly used material for. It is important that the tank is produced with quality welding, and tested for the working conditions. NHE has estimated the price to be for the tank and outlet pipes [22].

An equipment list and cost estimate for both the high pressure tank and the draft tube tank is found in Chapter 4.1.2.

4.1.2 Draft Tube Tank

The outlet of the turbine will consist of a draft tube cone, a draft tube bend and a draft tube tank. The draft tube cone will have a transparent material in order to observe cavitation in the turbine. Further design of the draft tube cone is not within the scope of this thesis. Neither is the draft tube bend, which is specially designed depending on the turbine to be tested.

As with the high pressure tank, the draft tube tank has the same shape as the draft tube tank at the Waterpower Laboratory with a reduced size. It is suggested to have a volume of not less than $10\,\mathrm{m}^3$ as this will ensure a stable system [21]. The length of the tank is $3.6\,\mathrm{m}$ long and the diameter is $2\,\mathrm{m}$. The volume is approximately $10.2\,\mathrm{m}^3$. The tank must withstand a pressure of 150 mwc, but the working pressure will most often be close to atmospheric.

The wall of the inlet of the draft tube tank is flat in order to attach the draft tube bend. It is advantageous if the inlet of the tank is suitable for different shapes of the draft tube bend. The other flexibility of the tank are the adjustable legs the tank is resting on, which can be jacked up and down.

When testing a Francis turbine, it may be required to decrease the pressure in the draft tube tank. This is done by a vacuum pump on top of the tank. The vacuum pump is suggested to be of the same type as at the one used at the Waterpower Laboratory: *RVS 16/8* from Robuschi [23]. The possibility for other vacuum pumps available by local suppliers should be assessed.

The inlet of the pump is connected to a dome shaped part which should always be above water level of the tank. The water level of the tank may be read from the plastic pipe connected to the tank. There is also a venting pipe connected from the dome with a valve at a height reachable while standing on the floor. In addition, there is a pressure gauge before the valve, in order to read the pressure in the tank. A pressure tap for digital readings should also be installed if needed.

It should also be possible to ventilate the pipe after the valve in the main system, which is the highest point of the draft tube. This will help reducing the amount of air in the system.

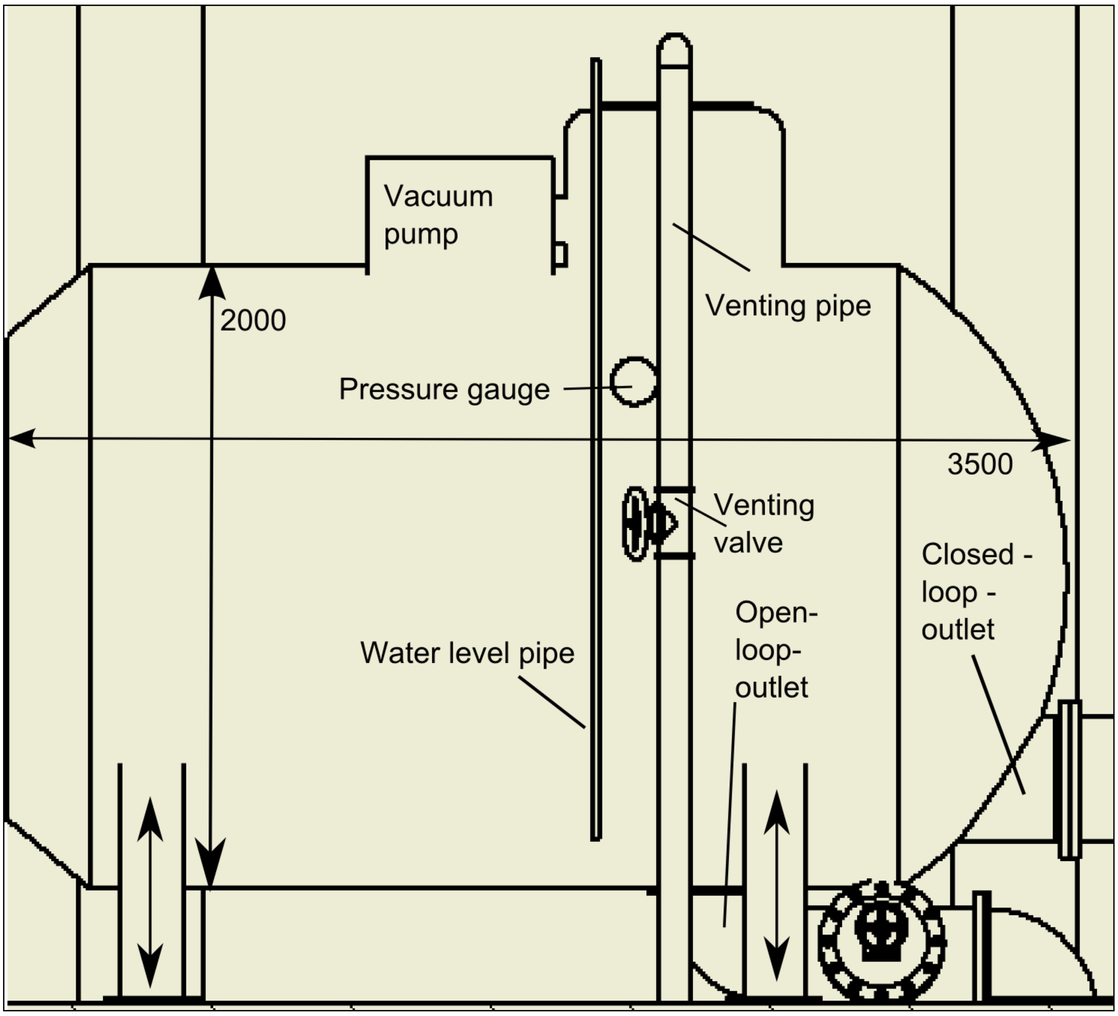


Figure 4.2: Drawing of the suggested draft tube tank for TTL. All dimensions are in mm.

Open and Closed Loop

There are two outlets from the draft tube; one for operating in closed loop and one for open loop. Having the possibility of doing tests in both open and closed loop is one of the requirements from *IEC 60193* [1]. The Francis model test rig should fulfil this requirement, and this will be controlled by the draft tube outlet. In closed loop mode, the water is led from the draft tube into a pipe connected to the main pipe going directly into the pumps.

In the open loop mode, the water is led to one of the openings in the floor to the lower reservoir. From the lower reservoir water is pumped to the upper reservoir and from there led down to the pipe going directly to the main system. The water in the lower reservoir may also be pumped directly into the main pipes, without passing the upper reservoir.

The outlets should be placed as far from the inlet as possible in order to have the possibility for placing a plate inside the tank which is necessary for some types of tests.

The draft tube tank and pipes should be of stainless steel and may be produced at Nepal Hydro and Electric (NHE) in Butwal, Nepal.

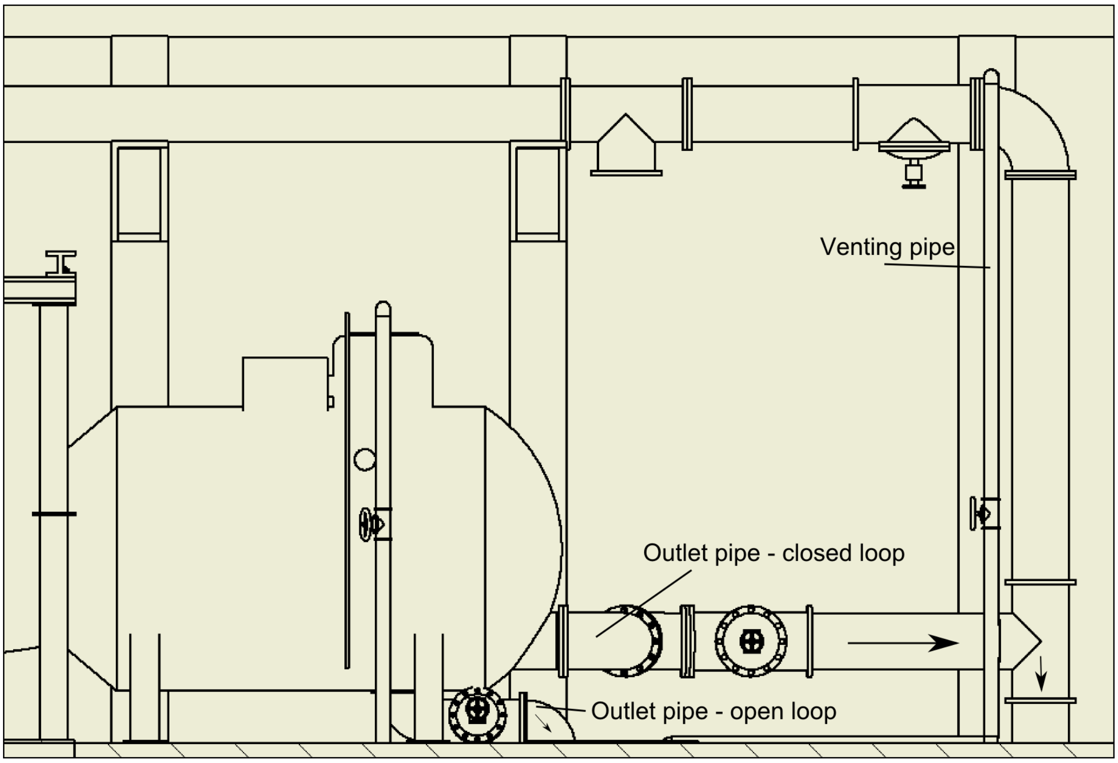


Figure 4.3: Drawing of the suggested outlets of the draft tube tank for TTL, showing the option for closed loop and open loop.

Table 4.1 gives an overview of the component list and cost estimate for the high pressure tank and the draft tube tank. The prices for the tanks, pipes, flanges and t-junctions are estimated by NHE [22]. The valves should be of the type butterfly valves, and the prices are estimated by Sales Engineer, Ken Hallstensen in KSB Norway [24].

Component	**Quantity**	**Cost [USD]**
High pressure tank 15 m^3	1	58 000
Draft tube tank 10 m^3	1	77 800
Tank frames	2	3 500
Venting pipe	3	1 500
Pressure gauge	2	1 000
Safety valve	1	2 000
Valves 100 mm	3	900
Valves 200 mm	1	700
Valves 300 mm	1	2 000
Valves 400 mm	3	8 000
T-junction 400 mm	1	400
Pipes inlet and outlet	8 m	3 500
Flanges 400 mm	18	4 200
Flanges 400/100 mm	2	400
Blind pipe flanges	2	500
Vacuum pump	1	7 000
Total		171 400

Table 4.1: Cost estimate of components related to the high pressure tank and draft tube tank set-up.

4.1.3 Guide Vane Control System

It is required that the guide vanes are adjustable from closed position to open position. The most reliable way to control the guide vane angle is to connect an arm to the guide vane ring and to a mechanical wheel which can adjust the position of the arm, as done at the Waterpower Laboratory [21]. The suggested angle measuring device is a rotary encoder from *Elfa* [21].

Table 4.2 shows the cost estimate for guide vane control system. The prices are estimated from the prices used at the Waterpower Laboratory [23].

Component	**Quantity**	**Cost [USD]**
Rotary encoder (Elfa)	1	900
Servo wheel	1	500
Total		1 400

Table 4.2: Cost estimate of components related to the guide vane control set-up.

4.1.4 Main Shaft and Bearing Block

The main shaft of the Francis rig is suggested to have the same dimensions as the shaft at the Waterpower Laboratory, with a connection piece at the lower end for the possibility of fitting it to different sized turbines. The turbine shaft will be connected to the generator and the bearing block through standard couplings.

The shaft should be connected to the stationary components through bearings. It is recommended that the diameter of the shaft is adjusted to suitable bearings available from the manufacturer. Through personal correspondence with Harry Opdal, Application Engineer in SKF Industrial Market, an upper and a lower bearing is suggested. For the upper bearing, a double row angular contact ball bearing (bearing number 3315 A 2Z/MT33) will give an expected lifetime of 13 100 hours (dimensions: inside diameter 75 mm, outside diameter 160 mm, width 68.3 mm). The upper bearing will support the axial load in both directions [25].

For the lower bearing, a single row deep groove ball bearing is suggested (bearing number 6217 C3 2RS1). As the load on this bearing will be low, the lifetime is not relevant (dimensions: inside diameter 85 mm, outside diameter 150 mm width 28 mm) [25]. These suggestions are made with the assumption of a maximum axial load of 20 kN and a maximal rotational speed of 1500 rpm. Both bearings should be lubricated and sealed. This avoids the necessity of installing a lubrication system attached to the bearings.

Table 4.3 shows the component list and cost estimation for the shaft and bearing block. The costs are estimated by staff at the Waterpower Laboratory and prices for the bearings are given from SKF-supplier *Abra-Kulelagersenteret* in Norway [26].

Component	**Quantity**	**Cost [USD]**
Double row ball bearing	1	2 000
Single row ball bearing	1	800
Couplings	2	2 500
Shaft, seals and bearing block cover	-	18 000
Total		23 300

Table 4.3: Cost estimate of components related to the shaft and bearing block set-up. The integration of axial thrust measurement is in a separate budget in Chapter 4.2.6.

4.2 Instrumentation

This chapter describes the chosen measurement instruments and methods for the Francis model test rig at TTL. Most of the instruments have been chosen in discussions together with Prof. Ole G. Dahlhaug and employee at the Waterpower Laboratory, Bård Brandåstrø. The requirements for the chosen instruments are ease of installation and maintenance, long service life and reasonably priced.

All instruments are produced externally, and an estimated price with the suggested manufacturer is specified for each case.

Some of the instruments require calibration. Detailed descriptions of calibration methods is not within the scope of this thesis. Hence, the calibration method will only be suggested and briefly described for each instrument. Detailed procedures are found in Appendix A.3 in this thesis.

4.2.1 Pressure

Both the inlet and the differential pressure should be measured. The atmospheric pressure should also be measured as a reference pressure, and there should be a pressure measurement at the main pipe system, just after the pump outlet.

As stated in Chapter 3.4.1, *IEC 60193* [1] describes a number of methods for measuring pressure. Because of the advantages of the pressure transducers, this will be a suitable method for the rig at TTL. The good experience with this method from the Waterpower Laboratory may be transferred to TTL.

The transducers are connected to tubes of plastic filled with pressurized water from the main system. The plastic tubes are connected to the measuring point by pressure taps. As explained in Chapter 3.4.1, there must be two pairs of taps at each measuring point. The tubes must be installed so that it is possible to remove trapped air bubbles in the pipes. The four tubes will meet in a manifold, which is connected to the transducer.

The two differential pressure transducers will be placed on floor level of the wall next to the turbine, as can be seen in Figure 4.4. The transducers are placed as low as possible to be able to get rid of all air in the plastic tubes. This is also to avoid a low pressure in the transducers and hence the risk of boiling. Three differential pressure transducers from the *FCX-series* from Fuji is suggested (one transducer in back-up). An atmospheric pressure sensor for reference pressure in the laboratory will be placed next to the pressure transducers. The suggested type is the *PTU300* from Vaisala, which also measures humidity and temperature in the air.

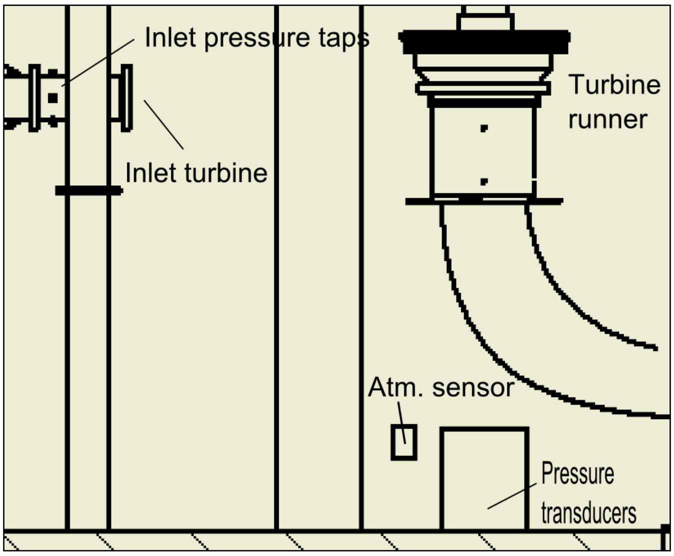


Figure 4.4: Drawing of the suggested placement of the pressure transducers.

It is suggested that the system installs four tubes at the inlet and four at the outlet of the turbine runner. In addition, the rig should be equipped with pressure transducers for pressure fluctuations measurements. Six transducers from the *PTX600*-series from *The General Electric Company* (GE) is recommended for this use [21]. The range of the transducers should correspond to the operational points used for the tests.

As additional equipment a pitot tube is necessary for measurements of the velocity in the pipes. The recommended pitot tubes are prison shaped from Nokval and have a diameter of 6 mm and three holes.

Calibration

The calibration of the pressure transducers will be done by a deadweight manometer. Model *P3000* from GE is suggested. The procedure is explained in Appendix A.2 in this thesis, and in Chapter 3.3.4.3 in *IEC 60193* [1]. The deadweight manometer may be stored away when not used, and set up close to the transducers when calibrating.

In addition, it is recommended to use a portable pressure calibrator for smaller checks and calibrations, as this is more convenient to use in some situations. The *Druck DPI 610* from GE is suggested for this use.

Table 4.4 shows the component list and cost estimate for the pressure measurements. The prices are based on the costs estimated at the Waterpower Laboratory.

Component	**Quantity**	**Cost [USD]**
Pressure transducers (*PTX600*)	6	10 000
Differential pressure transducers (*Fuji FCX*)	3	5 000
Atm. pressure sensor (*PTU300*)	1	4 000
Deadweight manometer (*P300*)	1	20 000
Pressure calibrator (*Druck DPI 610*)	1	5 000
Manifold, plastic pipes, taps and valves	-	300
Pitot tube (*United Sensors*)	1	3 500
Total		47 800

Table 4.4: Cost estimate of components related to the pressure measurement and calibration set-up.

4.2.2 Flow Rate

As mentioned in Chapter 2.1, Johanne Seierstad [4] did a thorough evaluation on the type of flowmeter to be used at the Francis rig at TTL. Her suggestion is the electromagnetic flowmeter *Optiflux2000* (DN250)[1] from Krohne with a converter type *IFC300.* Although this is a suggestion based on the simplified Francis test rig, this will also be a suitable flowmeter for the Francis model test rig design in this thesis. The only modification is that the diameter of the flowmeter should be reduced to ensure higher velocities and hence higher accuracy.

The diameter of the flowmeter is determined by using the following relation:

$$Q = A \cdot v \qquad [\mathrm{m^3/s}] \tag{4.1}$$

where Q is the flow rate, A is the cross sectional area and v is the velocity of the flow.

---

[1] DN=diameter of the pipe

The maximum flow at TTL is 0.5 $\mathrm{m^3/s}$. In the *Technical Datasheet* for *Optiflux2000*, the flow versus accuracy curve of the flowmeter is presented (see also Figure 4.5) [27]. If correctly installed, the suggested flowmeter has a deviation of 0.2 % of measured value if the velocity is above 5 m/s [27, Chapter 2.3]. The deviation increases rapidly when the velocity goes below 1 m/s.

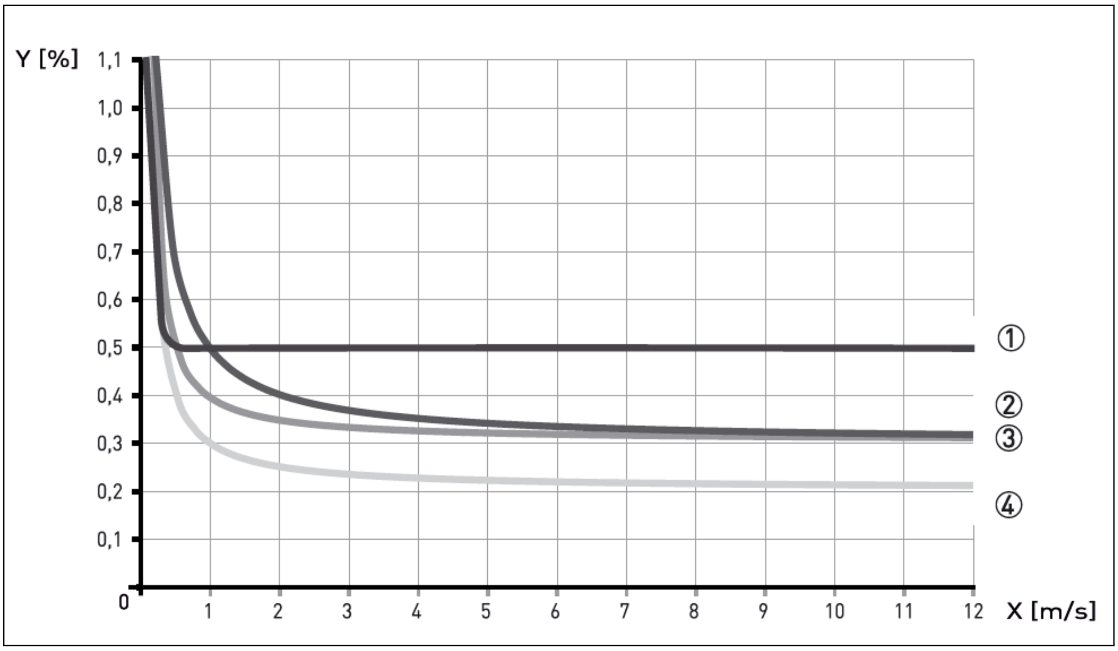


FIGURE 4.5: The curve shows the accuracy of the flowmeter depending on the velocity of the flow. The x-axis [m/s] is the flow velocity and the y-axis is the deviation from the actual measured value in %. The curve is from the Optiflux Technical Datasheet [27]. The chosen flowmeter (*Optiflux2000*) is of accuracy-class 4.

Using the relation in (4.1) with a flow rate up to 0.5 $\mathrm{m^3/s}$, the velocity will not be higher than 8.14 m/s for a diameter of 250 mm, and it will be lower than 5 m/s when the flow rate is below 0.25 $\mathrm{m^3/s}$. It is very likely that a flow rate less than 0.25 $\mathrm{m^3/s}$ will be used when testing turbines, and it is desired to increase the accuracy. A solution is to decrease the diameter of the flowmeter to 200 mm. With this diameter, a flow rate of down to 0.16 $\mathrm{m^3/s}$ may be used before the velocity is below 5 m/s, and hence the deviation is just above 0.2 %. The *Optiflux2000* (DN200) from Krohne with a converter type *IFC300* is therefore chosen for the Francis model test rig in this thesis.

Calibration

For calibration, the pipe with the flowmeter must be connected to a calibration facility. As mentioned in Chapter 3.4.2, the primary calibration methods recommended by *IEC 60193* [1] are the moving screen method, the volumetric method and the weighing method. Seierstad's master's [4] thesis suggests that the volumetric method is used as a primary method for calibration of the electromagnetic flow meter. According to her evaluation, this will be the most suitable for TTL when considering the space available, accuracy, economical aspects and available resources in the laboratory. This will also make use of the existing calibration tank in the laboratory [4, Chapter 4].

The calibration design made by Seierstad [4] consists of all the necessary components for the weighing method. This design may be used for flowmeters for different types of turbines and is therefore used in the final suggestion for the new model turbine test rig.

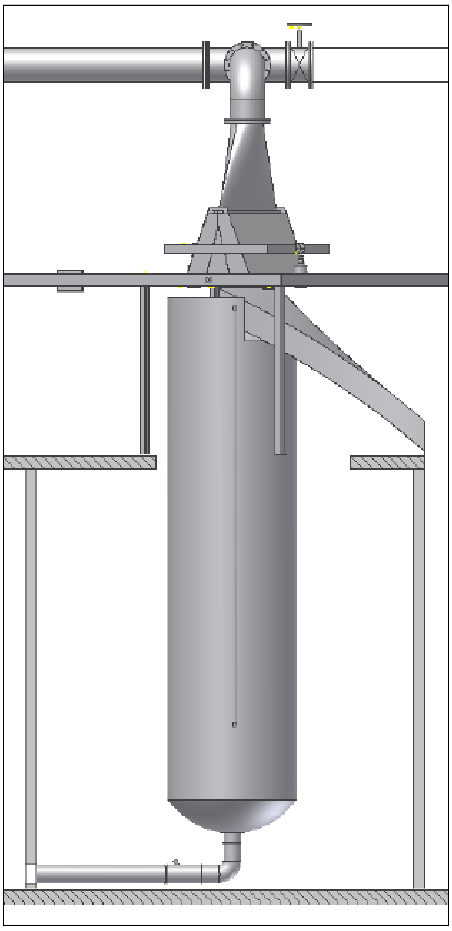


Figure 4.6: Flowmeter calibration facility, the volumetric method. Designed by Seierstad [4, Chapter 8.2].

The dimensions of the calibration facility are made based on the operational mode and flow range of the existing Francis runner at TTL [4]. It is desired to design the facility such that it may be used for the whole range of operational modes of the pumps. This means that the tank must be designed for a flow rate of $0.5\,\mathrm{m^3/s}$, in contrast to the $0.3\,\mathrm{m^3/s}$ [4, Chapter 4.3.3]. According to Seierstad [4], the minimum filling time is set by *ISO 8316* (*International Standard for measurement of liquid flow in closed conduits*) to be 30 seconds. The minimum volume of the calibration tank is the maximum flow rate multiplied by the minimum filling time:

$$V_{\mathrm{min}} = Q_{\mathrm{max}} \cdot \Delta T_{\mathrm{min}} = 30\,\mathrm{s} \cdot 0.5\,\mathrm{m^3/s} = 15\,\mathrm{m^3} \tag{4.2}$$

A modification of Seierstad's [4] design is therefore to increase the size of the tank to $20\,\mathrm{m^3}$, which includes a safety factor to the calculations.

Positioning of the flowmeter

There are several options for where to place the flowmeter. The two main factors to take into account are the installation requirements of the flowmeter, and the possibility for calibration. The technical datasheet of *Optiflux2000* describes the installation requirement for the flowmeter. The requirements are based on the necessity of having a steady flow through the flowmeter to get the best accuracy [27]. Based on Chapter 3.3 in the datasheet of *Optiflux2000*, the most relevant requirement for the installation at TTL will be to ensure that the pipe upstream the flowmeter is longer than 10 x DN and that the pipe downstream is longer than 2 x DN. The flowmeter should not be placed close to a discharge [27].

If the flowmeter is to be installed in a pipe which has a diameter larger than what makes it possible to fulfil the installation requirements, there are several methods of making the flow steady and fast enough. Methods used in this thesis are to narrow the pipe upstream and downstream the flowmeter, use cascade bends and flow straighteners. Cascade bends are pipe bends with several fins inside the bends and the flow straighteners are pipe sections consisting of smaller pipes inside the main pipe, as illustrated in Figure 4.7. According to the staff at TTL, all existing bends at TTL are cascade bends [28].

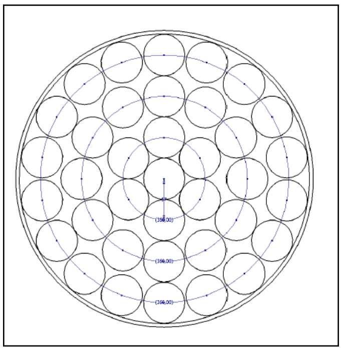


Figure 4.7: Cross-section of the flow straightener. Figure from Seierstad's master's thesis [4].

Based on the installation requirements and the possibility for calibration, three different options (1a, 1b and 2) of positioning the flowmeter have been made.

1a - Main pipe downstream pumps, vertical before bend

This positioning is based on the result of Seierstad's master thesis and is also the original plan of TTL [4]. In this option, the flowmeter is placed on the main pipe just downstream the pumps in the basement. The diameter will not give high enough velocity for the required accuracy of the measurement. Therefore, the pipe must be narrowed down upstream the flowmeter and expanded downstream the flowmeter (sections 2 and 3 in Figure 4.8). In addition, there is a section with a flow straightener before section 2, and a cascade bend after section 3. The sketch and dimensions of this option in Figure 4.8 is taken from Seierstad's master's thesis.

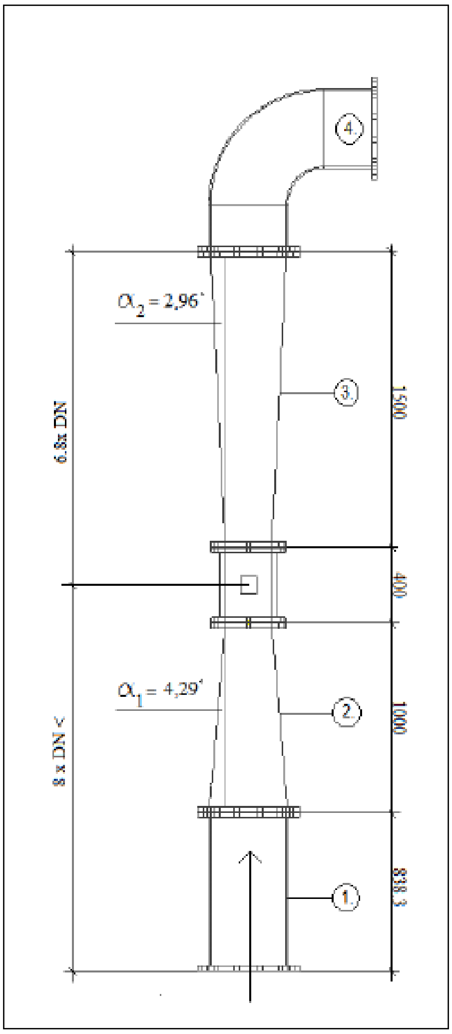


FIGURE 4.8: Option 1a for dimensions of the flowmeter with flow straightener (section 1), narrowing down of pipe (section 2 and 3) and cascade bend (section 4). Taken from Seierstad's master's thesis [4, Chapter 4.11.2].

The connection to the calibration facility has also been made by Seierstad [4]. As can be seen in Figure 4.11, the calibration facility is connected to the closest t-junction on the main pipe. The existing t-junction at TTL must be moved to be in line with the inlet of the calibration nozzle. Valves make it possible to lead the water into the calibration system or continue through the main system.

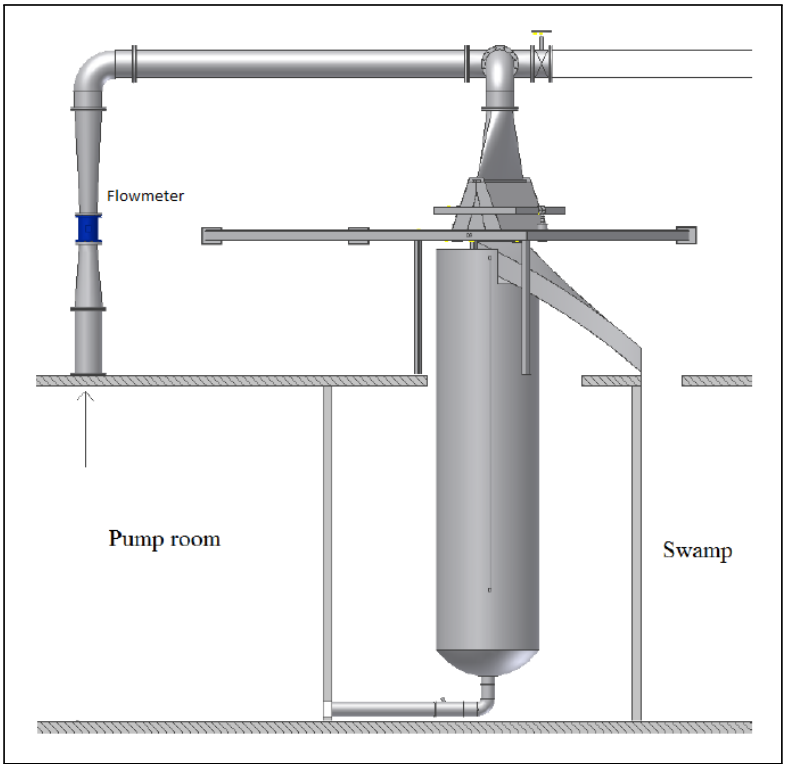


FIGURE 4.9: Option 1a for positioning of the flowmeter with the connection to the calibration facility. Taken from Seierstad's master's thesis [4, Chapter 8.2].

1b - Main pipe downstream pumps, horizontal after bend

This option is very similar to option 1a. The only difference is that the flowmeter is placed after the cascade bend instead of before the bend. The modification of the pipe to achieve the necessary hydraulic conditions will also be very similar. In this option, a decrease in diameter at the place of the flowmeter is also necessary. To improve the hydraulic conditions, there will be a section of a flow straightener after the bend and before the constrain of the pipe. The dimensions of the pipe of the flowmeter will be the same as in Figure 4.8. The connection of the flow calibration facility is similar to option 1a.

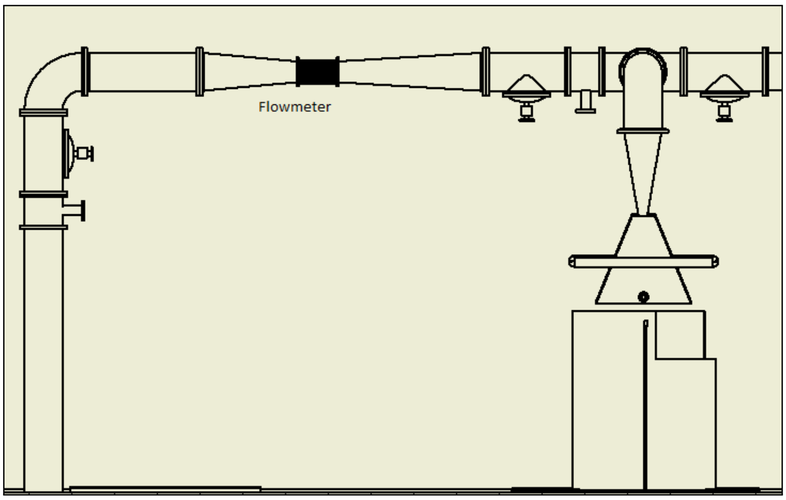


Figure 4.10: Option 1b for positioning of the flowmeter with the connection to the calibration facility.

2 - Inlet pipe to Francis turbine

In this option the flowmeter has the same positioning as in the Waterpower Laboratory: at the inlet pipe to the turbine runner. The inlet pipe is decided to have a diameter of 200 mm and this will give a good enough velocity of the flow. Hence, narrowing down of the pipe is not necessary, but the pipe still has to fulfil the requirements of a pipe length of 10 x DN upstream the flowmeter and 2 x DN downstream. For a DN of 200 mm, this means that the inlet pipe must be at least 3 m (including the length of the flowmeter).

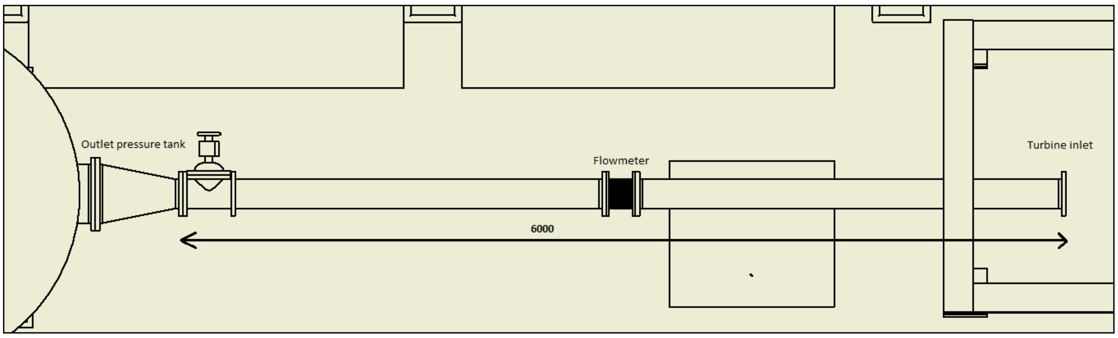


FIGURE 4.11: Option 2 for positioning of the flowmeter. All dimensions are in mm.

> The connection of the calibration system in this option is a challenge. The hydraulic condition is critical since it is close to the turbine runner. Any disturbance, such as valves and pipe connections after the flowmeter and before the turbine should be avoided. It is therefore not recommended to connect a pipe from the inlet pipe leading to the calibration facility.
>
> A solution to this challenge is to have an extra pipe from the main pipe at the outlet of the pumps. This pipe will lead to the calibration facility. When calibrating, the flowmeter must be removed from its original place and be fastened to the extra pipe. The pipe should have the possibility of attachment of different sized flowmeters, and this is done by designing pipes that are narrowed down to the size needed.

The advantage of option 1a is that the flowmeter will be placed at a height that will make it possible to stand at the laboratory floor and read from the flowmeter display manually. According to the *Technichal Datasheet* of *Optiflux2000*, placing the flowmeter vertically before a bend is also an advantage for the accuracy of the flowmeter [27]. On the contrary, the pipe after the bend (option 1b) is one meter longer than the pipe before the bend (option 1a). This increases the stability of the flow through the flowmeter. An other advantage with option 1b is that it takes up less space of the laboratory floor, as everything is 4 meters above the floor.

As TTL is meant to consist of several types of test rigs, it is desirable to have a flowmeter set-up that may be used for all rigs. A description of how the flowmeter of a Pelton model test rig should be positioned is described in Ida B. Stene's master thesis [19]. As the Pelton turbine operates at less flow, the flowmeter will have a smaller diameter. To adjust for this it will be possible to add a pipe parallel to the flowmeter for the Francis rig. This is visualized in Figure 4.12.

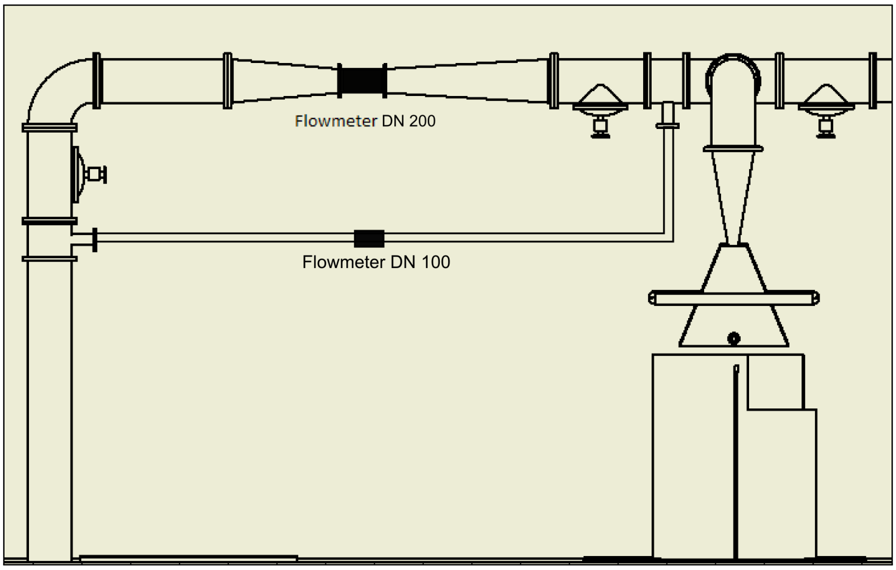


FIGURE 4.12: Pipe set-up for the possibility of calibrating two different flowmeters.

The set-up in Figure 4.12 is only possible if option 1b is chosen, as there must be space in the pipe for the necessary valves to control the flow through the desired flowmeter. For option 1a, the flow is less likely to regain the desired stability after the pumps.

The flexibility of calibrating more than one type of flowmeter is also possible in option 2, but it is slightly more complicated as the flowmeter must be detached from its original place and attached to the extra pipe to the calibration facility. Option 2 also gives restrictions to the length of the inlet pipe, which may be a challenge because of the limited space at TTL.

In this thesis, option 1b will be the basis of the total design, based on the desire to have a flexible and multifunctional rig. In this way the flowmeters may measure the flow of all rigs and will still be concentrated to one location in the laboratory connected to the same calibration facility.

Table 4.5 presents the component list and cost estimate for the flow measurements. The prices are based on the budget made by Seierstad in her master's thesis [4]. The valves necessary for a smaller flowmeter in parallel are included in the budget. The price of the valves is estimated by KSB Norway [24].

Component	**Quantity**	**Cost [USD]**
Flowmeter (*Optiflux2000*)	1	8 400
Converter (*IFC300*)	1	5 000
Valves 400 mm	3	8 000
Valves 100 mm	2	600
T-junction 400 mm	1	400
T-junction 400/100 *mm*	2	400
Calibration tank (NHE)	1	20 000
Drain system for calibration tank (*Ahlsell*)	1	2 000
Temperature measurement (*PT 100*)	1	400
Level measuring device	1	2 500
Diverter	1	2 000
Pneumatic parts for diverter	1	5 000
Nozzle, pipe, valve	1	6 000
Total		60 700

Table 4.5: Cost estimate of components related to the flow measurement and calibration facility set-up. The prices are based on Seierstad's master's thesis [4] and on the experience from the Waterpower Laboratory [23].

4.2.3 Speed of Rotation

For measuring the speed of rotation of the turbine it is suggested that the same method as the one at the Waterpower Laboratory is used, described in Chapter 3.4.3. This is a reliable primary method, and does not need calibration. It is recommended that the disc has only one slot due to the advantage of controlling the shaft's position. The slotted disc should mounted on the shaft together with the optical sensor.

The estimated cost for the speed of rotation measurement is presented in Table 4.8. The slotted disc is easily manufactured and the optical sensor can be bought locally.

Component	**Quantity**	**Cost [USD]**
Slotted disc	1	100
Optical sensor	1	300
Total		400

Table 4.6: Cost estimate of components related to the speed of rotation measurement.

4.2.4 Generator Torque

For measuring generator torque, it is recommended to use the same system as at the Waterpower Laboratory, described in Chapter 3.4.4. This method requires a load cell connected to an arm mounted on the generator. To ensure accurate measurements, the load cell must be of high quality.

The load cell is calibrated using deadweights. The set of deadweights may be bought locally and must be calibrated at a certified calibration institute. The calibration procedures may be found in Appendix A.2 in this thesis, and in Chapter 2.6.6 in *IEC 60193* [1].

Table 4.7 presents the estimated cost of the generator torque measurement device.

Component	**Quantity**	**Cost [USD]**
Torque meter including flex piece (HBM)	1	23 400
Coupling and flanges	2	2 000
Calibration equipment	1	4 200
Total		29 600

Table 4.7: Cost estimate of components related to the generator torque measurement.

4.2.5 Friction Torque

As the method used for measuring the friction torque at the Waterpower Laboratory is very costly, it is recommended that TTL measures the friction torque by running the generator and turbine without load. The torque meter will then measure the generator torque and the friction torque in the same measurement. There might be some deviance when the turbine is run with load, but this is still a good enough method to use in the first phase of tests at TTL. There are no extra costs related to this method.

4.2.6 Axial Thrust

General Electric Canada Inc. in Montreal has made a design for the axial thrust measurement and calibration [21]. This design is seemingly suitable for the conditions of the rig at TTL. The concept is to use strain gauges to measure the deflection of connecting parts between the axial bearing and the housing. As mentioned in Chapter 3.4.6 this method is suggested in *IEC 60193* [1]. The strain gauges must be calibrated by applying an external force, e.g. calibrated weights [1, Chapter 4.5.2.3]. It is recommended that the same set of calibrated deadweights for calibrating the torque meter is used to calibrate the axial thrust.

The budget for the axial thrust measuring system is a very rough estimate as the design is not detailed in this thesis.

Component	**Quantity**	**Cost [USD]**
Axial thrust measurement	1	3 500
Total		3 500

Table 4.8: Cost estimate of components related to the axial thrust measurement.

4.2.7 Temperature and Oxygen Level

Both air and water temperature should be monitored. The water temperature is suggested to be measured by a temperature sensor at the outlet of the pumps. A temperature sensor should also be installed in the laboratory room to measure the air temperature. The suggested temperature sensors are the *311* from Nokeval. The atmospheric pressure sensor mentioned in Chapter 4.2.1 also has functions to measure the temperature and humidity of the air.

The oxygen level should be measured by a sensor placed at the main pipe system by the outlet of the pumps, together with the temperature sensor and a pressure gauge. This is a place with an easy access to monitor and where water will always pass when performing tests in the laboratory. It is suggested that the type *TriOxmatic 700SW* sensor is used [21].

The budget for temperature and oxygen level measurements is presented in Table 4.9.

Component	**Quantity**	**Cost [USD]**
Temperature sensor (Nokeval)	2	3 400
Oxygen sensor (TriOxmatic 700SW)	1	4 200
Total		7 600

Table 4.9: Cost estimate of components related to the speed of rotation measurement.

4.3 Power Electrical System

4.3.1 Generator and Frequency Transformer

The type of generator that has been suggested for the rig at TTL is a 110 kW AC generator from Siemens, based on discussions with the staff at the Waterpower Laboratory. The AC generators are less expensive than the DC generators. If the quality of the AC generator is high, it will function just as good as a DC generator [23].

As the capacity of TTL is 300 kW, the possibility of increasing the generator size should be assessed. It must then be taken into account that the power capacity of the generator is dependent on the speed of rotation of the turbine.

The AC generator must be connected to a frequency transformer. This is suggested to be a *Sinamics S150 Cabinet Unit* from Siemens. The transformer should be placed as close to the generator as possible, to minimize power losses. However, because of the electrical noise, solutions for placing it in a separate room should be assessed. It is highly recommended that all components of the generator system is of high quality and installed by qualified technicians. An important factor to take into account when choosing a generator and transformer for TTL is the risk of an unexpected disconnection from the national grid.

The generator also needs an *IGSS control system*, and this is suggested to be a *PLC Driver* from Siemens [21].

Investing in a generator and a frequency transformer that will work for both the Francis and the Pelton rig should be considered. It will then be advantageous to have the torque meter and speed sensor attached to the generator to be used for both rigs. Another possibility is to convert one of the existing frequency transformers of the pumps into a frequency transformer for the generator. The advantage of this solution is that some major expenses will be saved, but comes with the disadvantage of reducing pump capacity to a single pump.

The generator is resting on a steel plate attached to a steel support structure. The legs of the support stand are adjustable up and down, and the steel plate is flexible in both directions, as illustrated in Figure 4.13. This allows for installing different sized turbines.

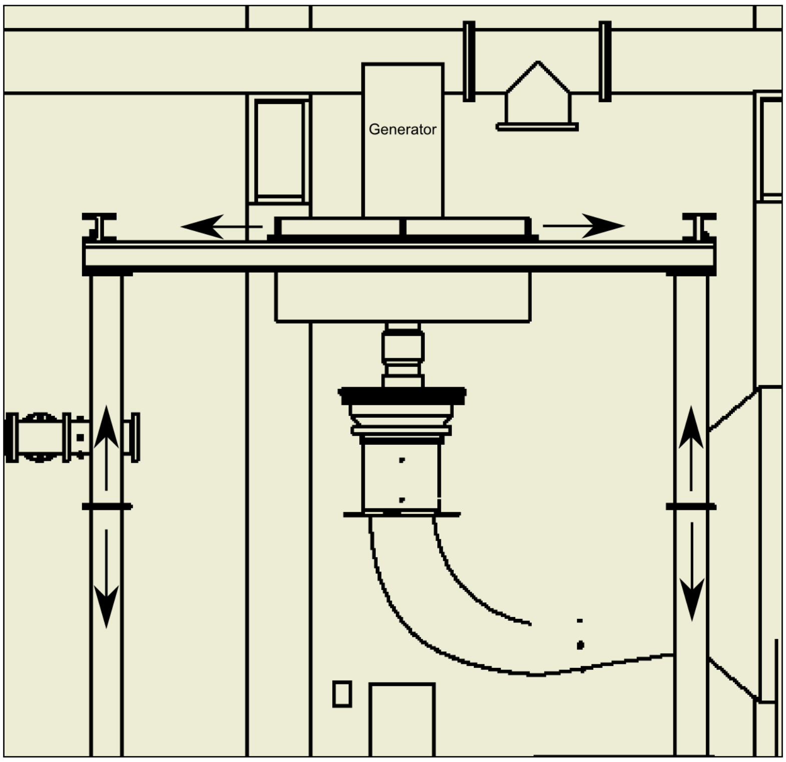


Figure 4.13: The support structure of the turbine and the generator is flexible to move in the direction of the arrows.

The budget for the generator and its frequency transformer is presented in Table 4.10.

Component	**Quantity**	**Cost [USD]**
Generator (110 kW, AC)	1	20 000
Frequency transformer (*Sinamics S150*)	1	42 000
Cables and electrical couplings	-	2 500
Steel structure support (including machining)	1	10 000
IGSS control system for generator	1	22 000
Total		95 500

Table 4.10: Cost estimate of components related to the generator and frequency transformer.

The power produced by the Francis turbine rig must be dissipated from the generator. One way is to feed the power to the national grid. The national regulations for connecting to the grid must then be taken into account. Other solutions should be assessed by qualified engineers in the field of power electronics.

4.4 Total Design

In addition to designing and choosing each component and instrument in Chapters 4.1, 4.2 and 4.3, it is important that all items are assembled to function together as a Francis model test rig. Because of the two pressure tanks, a Francis rig takes up relatively much space compared to other turbine rigs. It is therefore important that the space in the laboratory is used as optimally as possible. During the visit at TTL, the best options for placing the rig were discussed. The plan of installing a Pelton rig has been taken into account and there must also be space for other rigs, such as cross-flow turbines, which is a big part of the research at TTL. The flow calibration facility is also a space demanding instalment, which must be taken into account. Other factors, such as the existing pipe system and t-sections, openings to the lower reservoir on the floor, openings to the weirs, crane capacity, doorways and port door, must be regarded.

After several alternatives, Figures 4.14 and 4.15 show the best placement of the pressure tanks and turbine. This turned out to be the most functional option. The placement of the Pelton rig was decided together with Ida B. Stene, and Seierstad's design of the calibration facility is used [4]. With this solution, two of the existing t-junctions at the main pipe must be moved or adjusted. Firstly, the t-junction leading the water to the inlet of the calibration facility needs to be rotated from having the opening down, to vertical opening. Secondly, the opening of the t-junction by the inlet of the pressure tank must be turned from facing out to be facing down, and must be moved approximately two meters. For the outlet of the draft tube tank, a new t-bend must also be installed on the inlet pipe to the pumps.

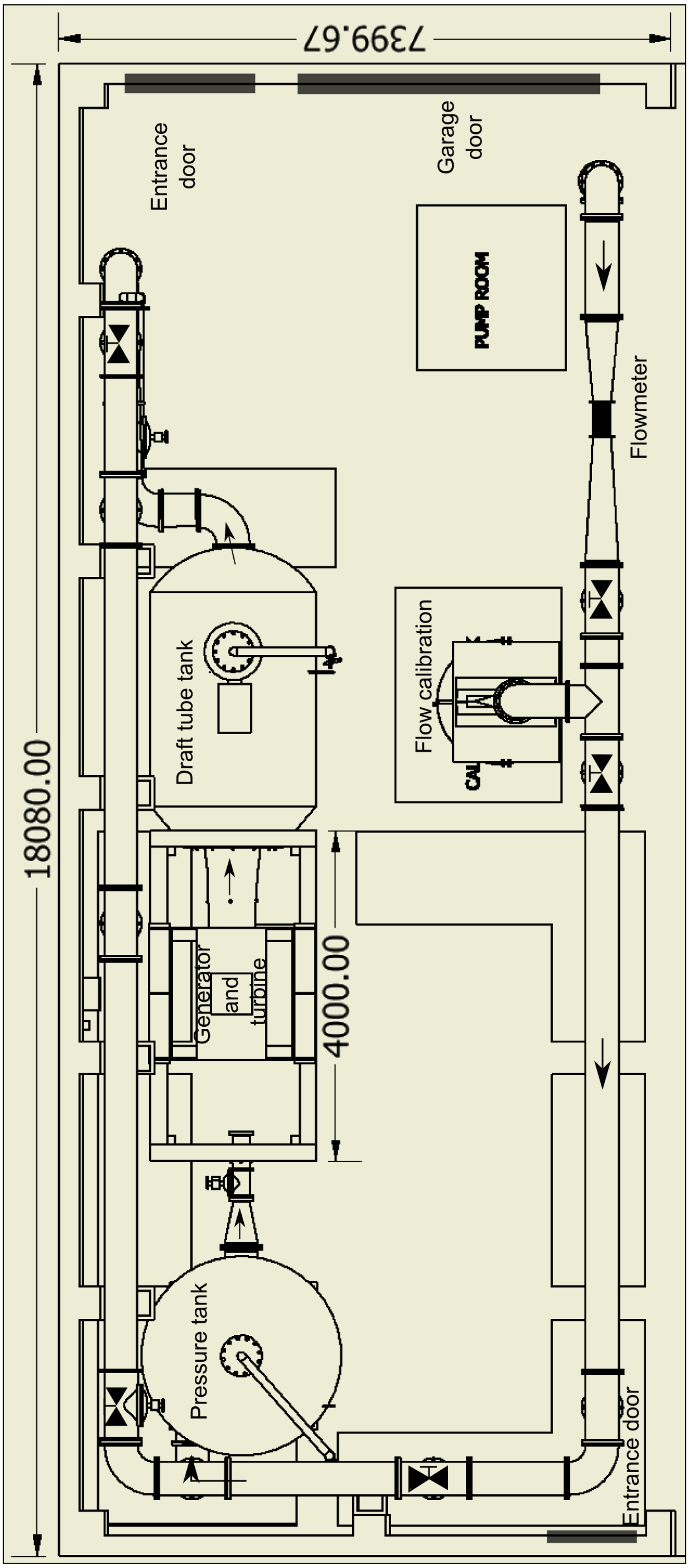


FIGURE 4.14: Placement of Francis rig seen from above.

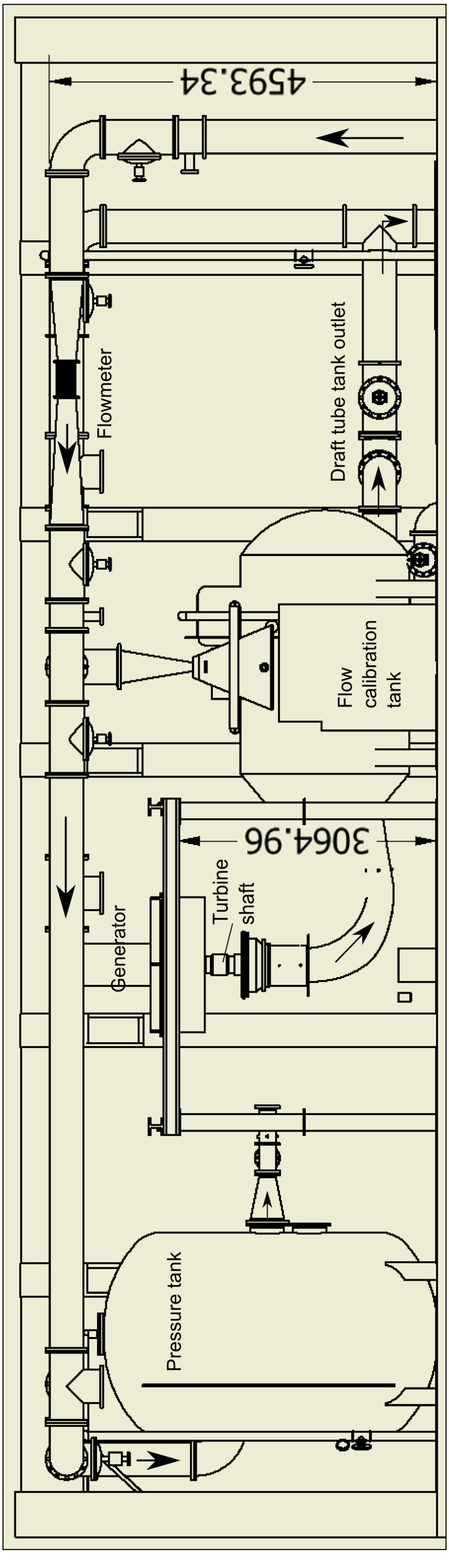


FIGURE 4.15: Placement of Francis rig with a side view.

In addition to the t-junctions, several valves must be installed at the main pipe system in order to guide the water in the right direction. A valve downstream the inlet of the pressure pipe is needed to lead the water to the Francis rig. Two 400 mm valves are needed to control the flow meter system, and another two to control the outlets of the draft tube tank. A further three valves of 100 mm must be installed at the venting pipes of the tanks (see Chapters 4.2.1 and 4.1.2). All valves should be of the same type, and butterfly valves are recommended. The placement of valves for the Pelton inlet are included in Ida B. Stene's thesis [19].

Flanges of diameter 400 mm, 300 mm, 200 mm and 100 mm are used to connect all pipes and components together. All flanges should be of the welded type. The welding should be done at a local manufacturer. All pipes, tanks, valves and flanges must tolerate a pressure of 15 bar.

The diagram in Figure 4.16 illustrates the new design of the test rig set-up at TTL, including instrumentation, pipe system, tanks, t-outlets, valves, and test rigs.

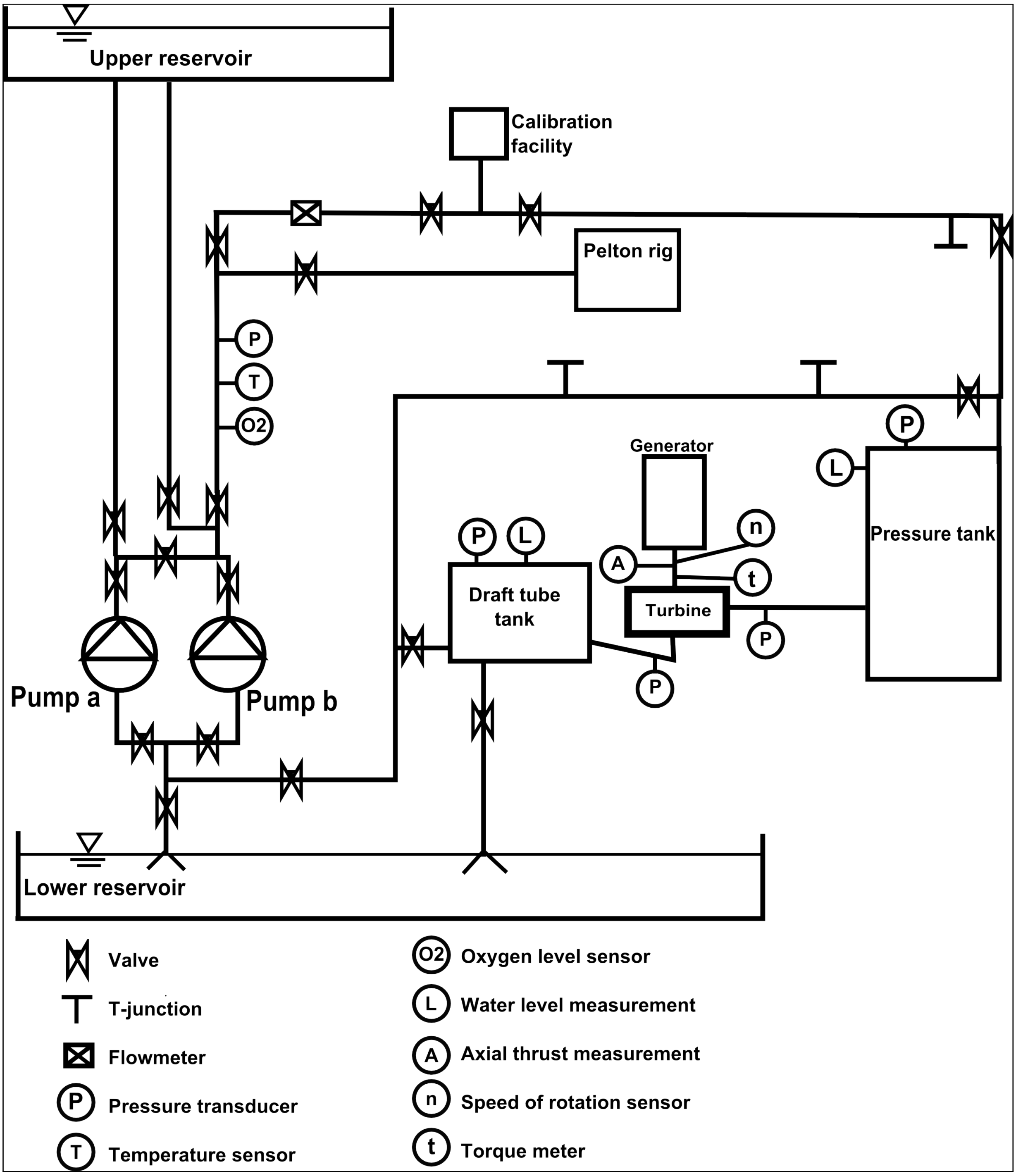


Figure 4.16: Diagram of the new design for TTL, including instrumentation, pipes, tanks, t-outlets, valves, and test rigs.

To make the Francis model test rig function for performing turbine tests, a data acquisition program, computers and various software is needed. Choice and design of these components are not within the scope of this thesis.

Component	**Cost [USD]**	
Lab computer	1	20 000
Software and educational license	1	5 000
Various equipment	1	6 000
Total		31 000

Table 4.11: Cost estimate of components related to the data acquisition and processing for the Francis model test rig.

Chapter 5

Results

5.1 Design of a Francis Model Test Rig at TTL

In this chapter, the final design of components and choice of instruments are presented. Where applicable, 3D CAD drawings are added as an illustration of the design. Every component should be produced with quality welding and tested to withstand a pressure of 15 bar. All instruments must be certified in order to ensure that the required accuracy of *IEC 60193* [1] is achieved.

5.1.1 Components

Pressure Tank

The pressure tank is determined to have the same shape as the pressure tank at the Waterpower Laboratory. It is 4 m high with a diameter of 2.4 m. The volume is approximately 15 m^3. The inlet is placed 2.5 m up from the bottom of the tank. The two outlets are placed 2 m and 1.5 m from the bottom. All pipes and flanges are of 400 mm diameter, except for the outlet pipe because of the constriction to the 200 mm inlet pipe of the turbine runner. Connected to the pressure tank is a venting valve, safety valve, pressure gauge, and a water level pipe.

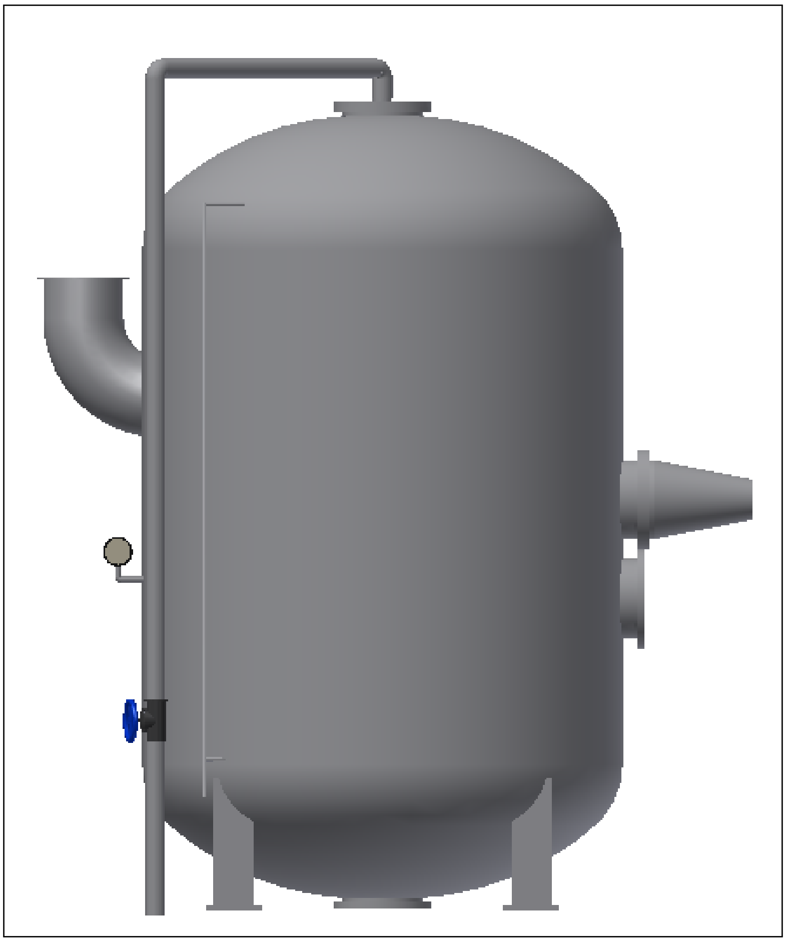


Figure 5.1: 3D CAD drawing of the suggested design of the pressure tank with inlet, two outlets, water level pipe, pressure gauge, and venting pipe. The safety valve is not in the figure.

Draft Tube Tank

The draft tube tank is decided to have the same shape as the draft tube tank at the Waterpower Laboratory. It is 3.6 m long with a diameter of 2 m. The volume is approximately 10.2 m^3. The inlet is at the outlet of the draft tube bend, and the two outlets are at the downstream end of the tank. One outlet leads to the pump room (closed loop mode) and the other one to the lower reservoir (open loop mode). All pipes and flanges are of 400 mm diameter, except from the outlet pipe going to the lower reservoir, which is 300 mm. On the top of the tank there is a dome where a vacuum pump for reducing the pressure is connected. There is also a venting valve and a water level pipe with a pressure gauge.

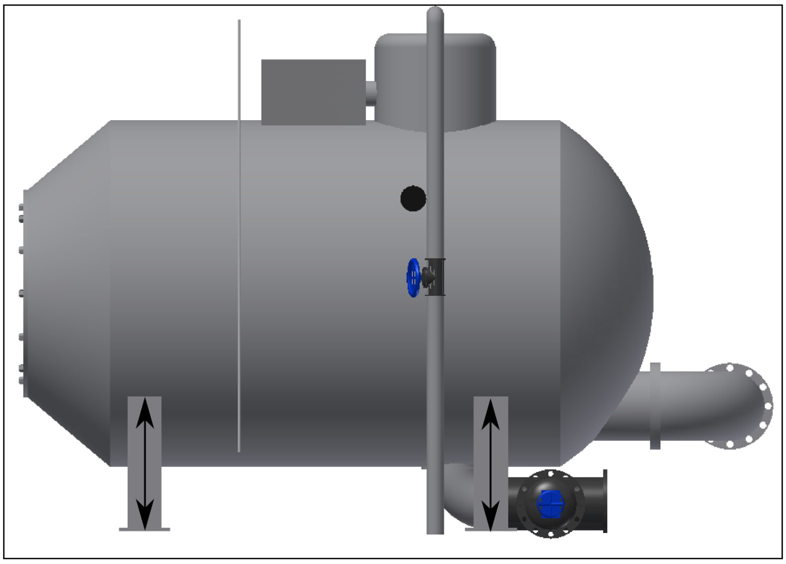


Figure 5.2: 3D CAD drawing of the suggested design of the draft tube tank with inlet, outlets, vacuum pump, water level pipe and venting pipe.

Guide Vane Control System

The suggested set-up for guide vane control is to use a wheel connected to an arm which again is connected to the guide vanes. A rotary encoder from Elfa will measure the angle of the guide vanes.

Main Shaft and Bearing Block

The main shaft of the turbine should have approximately the same shape and dimensions as the one at the Waterpower Laboratory. Suitable bearings for the shaft are a double row angular contact ball bearing (number 3315 A 2Z/MT33) for the upper part and a single row deep groove ball bearing (number 6217 C3 2RS1) for the lower part. The bearings should be of high quality, properly sealed and pre-lubricated. The bearing block will include a measurement system for the axial load.

5.1.2 Instrumentation

Pressure

The pressure is to be measured by differential pressure transducers at the inlet and outlet. The set-up consists of pressure taps in the water pipe, connected to plastic tubes gathered in a manifold and led to the differential transducers. Pressure is also measured by the outlet of the pumps. The atmospheric pressure in the laboratory room is measured by a sensor of the type *PTU300* from Vaisala. The differential transducers are recommended to be from the *FCX-series* of Fuji.

The rig should also be equipped with pressure transducers from the *PTX600-series* from GE and pitot tubes from Nokval.

The suggested calibration system is the deadweight manometer *P3000* and the portable pressure calibrator *Druck DPI 610*, both from GE.

Flow Rate

The flowmeter suggested for the Francis rig is the *Optiflux 2000* (DN200) from Krohne with the converter *IFC300*. This will give a good accuracy to the measurement. The flowmeter should be placed just after the first bend downstream the pumps, as shown in Figure 5.3. Upstream the flowmeter there will first be a cascade bend and flow straightener before the 400 mm pipe is narrowed down to 200 mm for the flowmeter. The diameter is increased to 400 mm again downstream the flowmeter.

The pipe downstream the flowmeter is connected to the calibration facility through a t-junction and a valve. The calibration method was decided and designed by Johanne Seierstad [4], to be the weighing method using the existing calibration tank at TTL.

For the integration of several different rigs, it is suggested to install a smaller pipe in parallel with the main pipe, as illustrated in Figure 4.12 in Chapter 4.2.2.

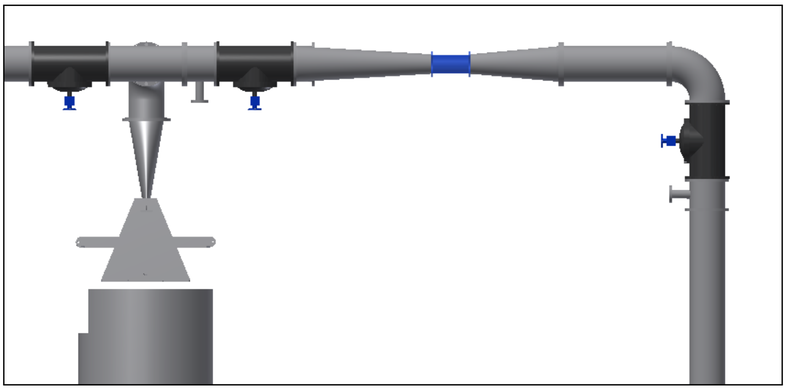


Figure 5.3: 3D CAD drawing of the suggested design of the flow measuring system with the connection to the flow calibration facility.

Speed of Rotation

For the measurement of speed of rotation it is suggested to use a slotted disc with an optical sensor to monitor the time between each passing of the slot. This should be set up on the shaft of the turbine. The disc may be produced locally and the sensor is easily bought.

Generator and Friction Torque

A torque meter is used to measure the generator torque and the friction torque. The torque meter should be of the best quality from HBM for the required accuracy. The meter may be calibrated using certified calibrated deadweights.

Axial Thrust

A design from *General Electric Canada Inc.*, using strain gauges is suggested for the measurement of the axial load in the Francis test rig. The system should be designed in more detail in the next step of this project.

Temperature and Oxygen Level

The water temperature should be measured by *311* sensors from Nokeval, and the oxygen sensor should be of the type *TriOxmatic 700SW*. It is suggested that both sensors are placed on the pipe coming up from the pump room.

5.1.3 Power Electrical System

Generator and Frequency Transformer

The generator suggested for the TTL rig is a 110 kW AC generator from Siemens. By using this generator as a motor, model tests may also be done in pump-mode. The generator should be resting on a support structure with flexible legs and ability to move in the vertical direction. This is illustrated in Figure 5.5.

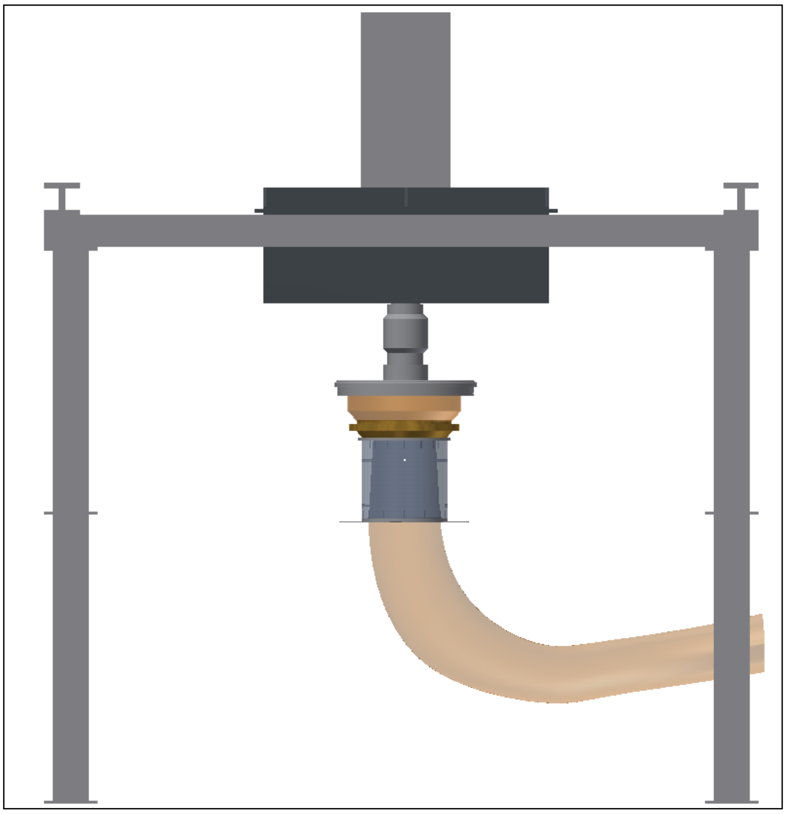


FIGURE 5.4: 3D CAD drawing of the suggested design of the structure supporting the generator and the turbine. View from the side.

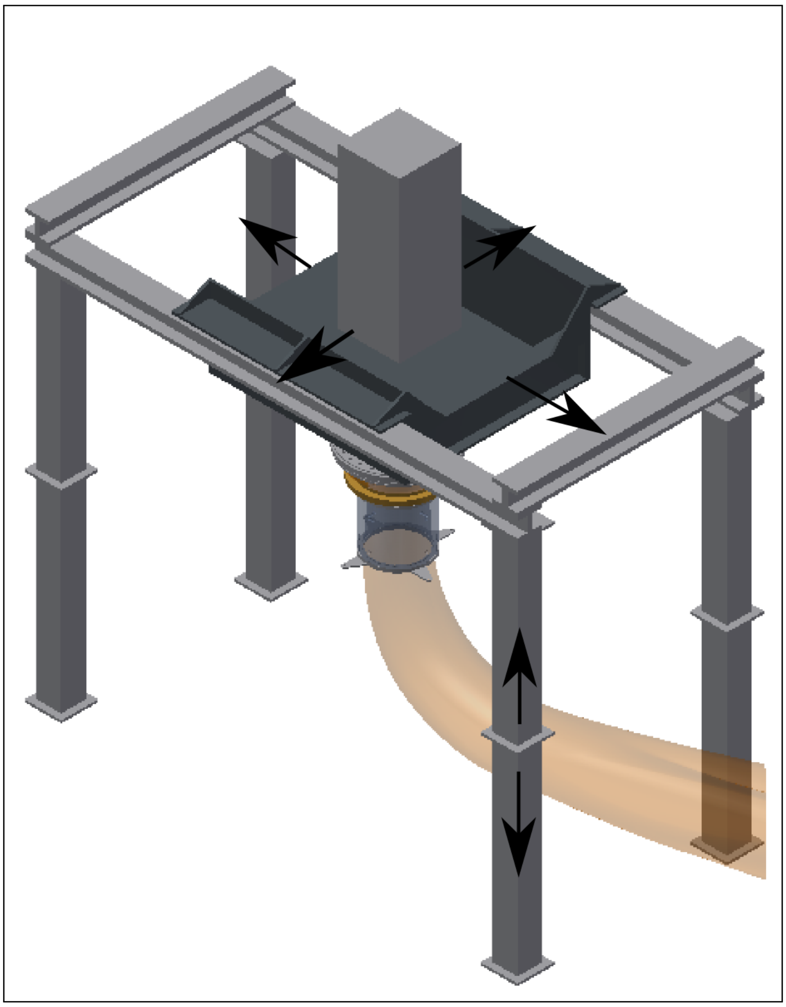


Figure 5.5: 3D CAD drawing of the suggested design of the structure supporting the generator and the turbine.

The generator should be connected to a frequency transformer of the type *Sinamics S150 Cabinet Unit* from Siemens and an IGSS control system of the type *PLC Driver* from Simens.

As a future extension to this design, a system for feeding the produced energy back to the main grid should be assessed.

5.1.4 Total Design

The complete design of the Francis model test rig, and the placement in the laboratory is presented in Figures 5.6 to 5.9.

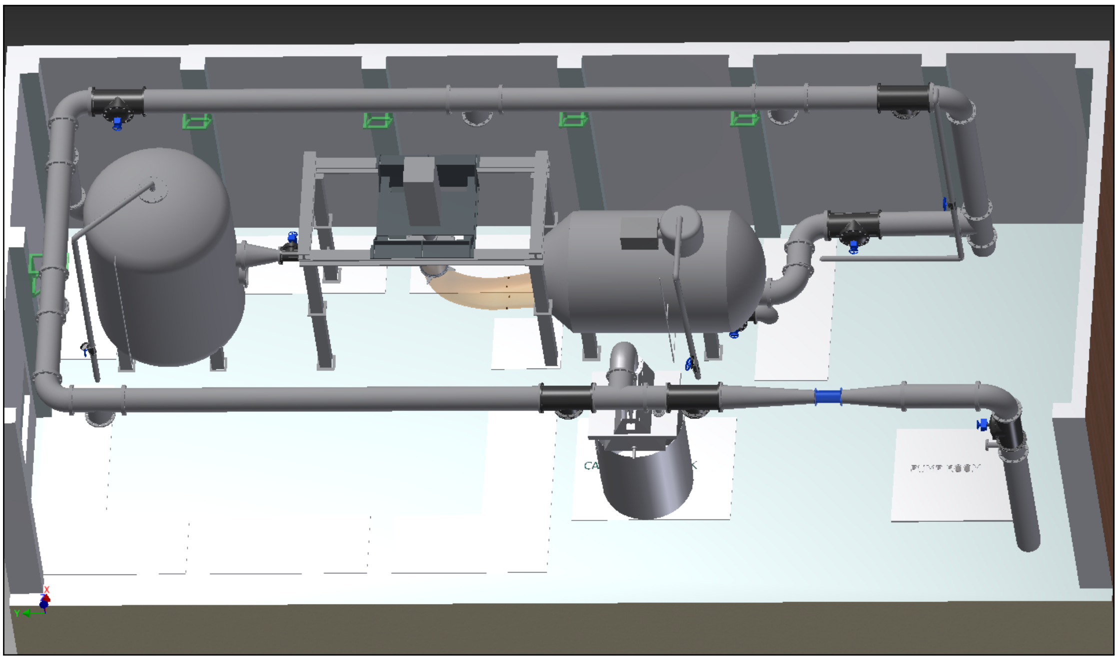


FIGURE 5.6: The suggested design of the Francis model test rig at TTL.

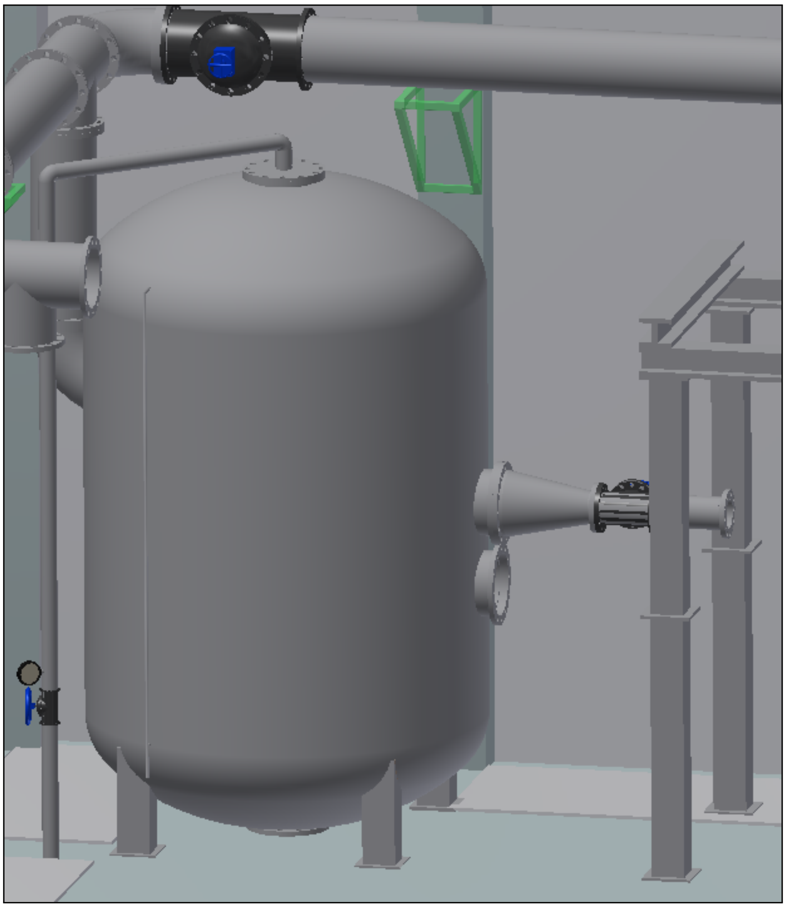


FIGURE 5.7: Close-up view of the pressure tank.

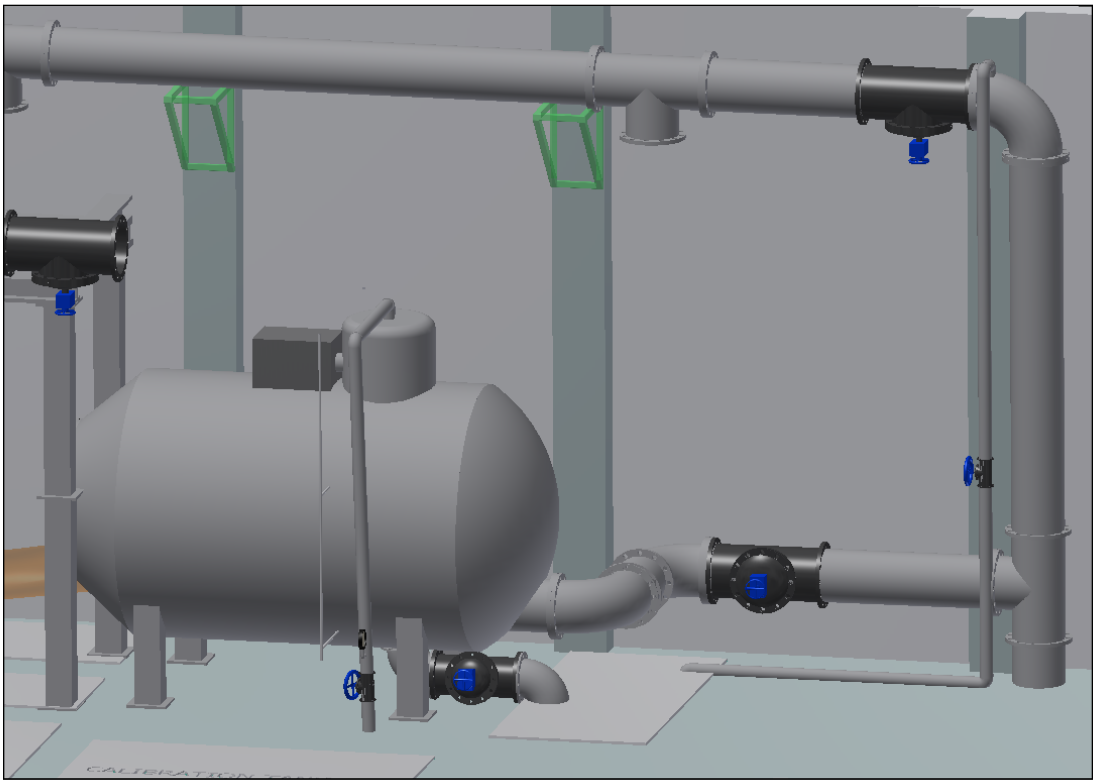


FIGURE 5.8: Close-up view of the draft tube tank.

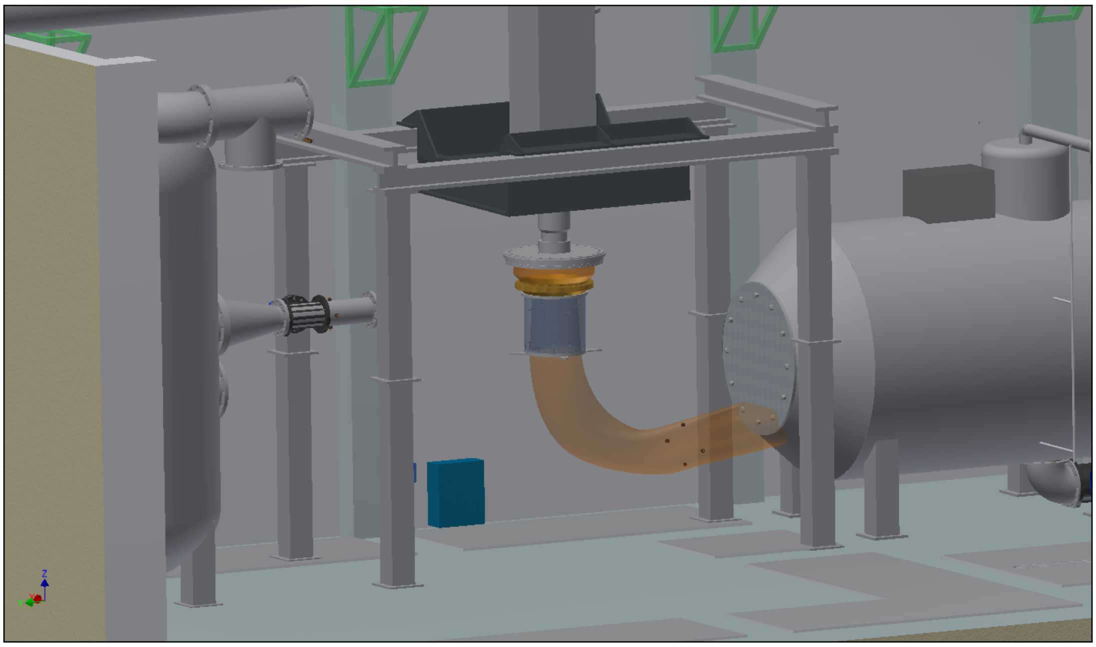


FIGURE 5.9: Close-up view of the support structure with turbine and generator.

The design of a Pelton model test rig was designed by Ida Bordi Stene [19]. Figures 5.10 and 5.11 illustrate the arrangement of the laboratory with both the Francis rig and the Pelton rig.

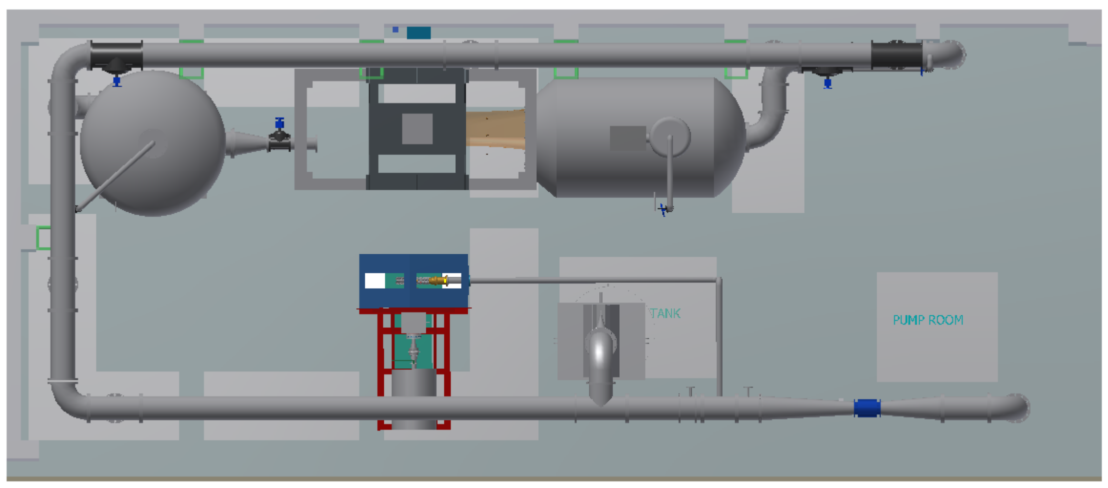


FIGURE 5.10: TTL with both the Francis and Pelton model test rigs. View from above.

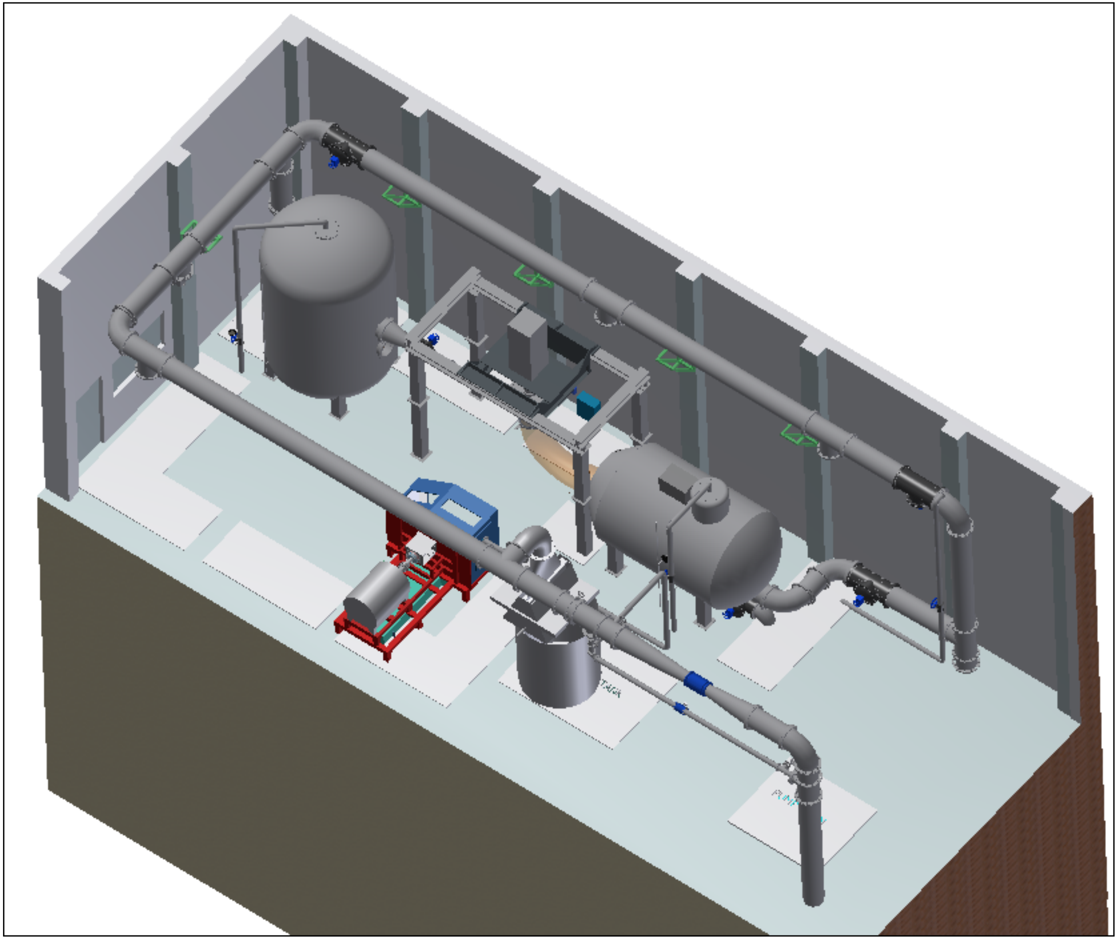


FIGURE 5.11: TTL with both the Francis and Pelton model test rigs.

5.2 Estimated Total Budget

Table 5.1 gives an overview of the necessary installations and related estimated costs of the new design of the Francis model test rig for TTL. The budget is gathered from Chapters 4.1 to 4.4, and is a very rough estimate of what the total cost of the rig may be expected to be. The cost for the installation of the planned Pelton model test rig is presented in Ida B. Stene's master's thesis [19].

Component	**Cost [USD]**
Pressure tanks	171 400
Guide vane control system	400
Main shaft and bearing block	23 300
Pressure measurement	47 800
Flow measurement	60 700
Speed of rotation	400
Generator torque measurement	29 600
Friction torque measurement	-
Axial thrust measurement	3 500
Temperature and oxygen level measurement	7 600
Generator and transformer	95 500
Lab computer and software	25 000
Various equipment	6 000
Total	471 200

Table 5.1: Equipment list and cost estimate of components related to the suggested total design of the Francis model test rig.

5.3 Procedures for Efficiency Measurements

The following chapter gives a suggestion of procedures for running and doing efficiency measurements of the planned Francis turbine test rig designed in this thesis for TTL. The procedures are based on the experience from running the Francis turbine test rig at the Waterpower Laboratory, and on the procedures developed in Stranna's master's thesis [18, Appendix B]. The procedures are adjusted to the conditions at TTL.

The theory and method of an efficiency test is described in Chapter 3.6.3. The procedures are described for tests in both open and closed loop modes.

For the procedures, it is assumed that a logging program exists to register data from the measuring instruments.

Open Loop

The first set of procedures are for running the Francis rig in open loop, as shown in Figure 5.12.

Start up

1. **Turn on the power of the pumps**
2. **Make and inspection around the laboratory**
    - Make sure that all drain tubes are closed
    - Check for water leakage on the turbine
    - Check that the venting valve on the pressure tank is open
3. **Set the pipe loop**

    Open and close the necessary valves in order to guide the water through the open loop as in Figure 5.12.
4. **Start the pump**

    Start the pump at a 100 rpm and increase the speed slowly to pump the water to the upper reservoir. Water will start to flow down through the pipe system and the turbine will start spinning.

5. **Start the generator**

   Start the generator at a 100 rpm when the turbine has accelerated to around 90 rpm.

6. **Increase pump speed and increase generator speed**

   Increase the speed of the pump gradually to stabilize the head. The speed must be such that there is an overflow in the upper reservoir.

7. **Close pressure tank venting valve**

   When the desired level is reached, close the pressure tank venting valve.

8. **Make an inspection in the laboratory**

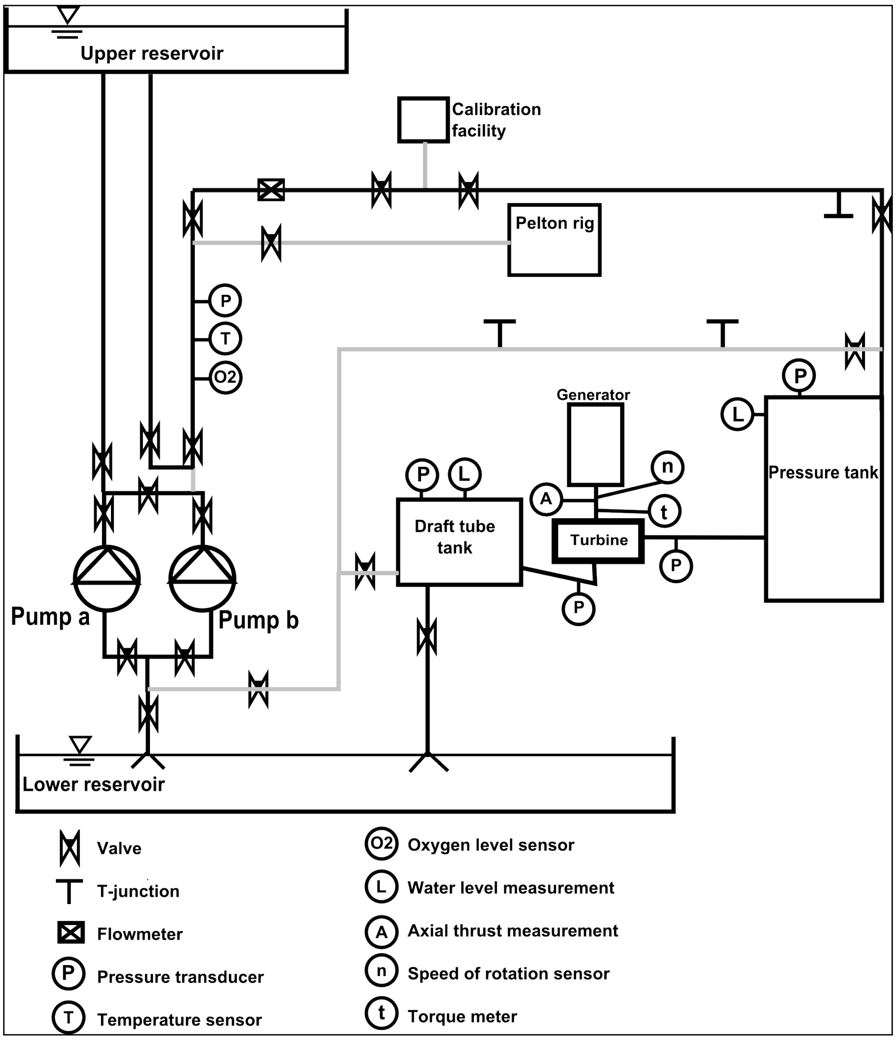


Figure 5.12: Diagram of the open loop mode when running the Francis model test rig at TTL.

Efficiency test

The following procedure explains running the rig for the purpose of taking measurements for a Hill diagram. The procedure mainly consists of varying the guide vane opening and the speed of the generator at a constant head. In an open loop, the head will stay constant as long as there is an overflow of water in the upper reservoir.

1. **Prepare a running sequence**

   Take measurements for one guide vane opening at the time, incrementing the speed of the generator gradually. The same speed increments should be used for all guide vane openings.

2. **Set recording time and directory in the data acquisition program**

   The recording time should be 30 seconds. The data should be saved in an external document automatically.

3. **Set guide vane angle**

   Use the wheel by the spiral casing to adjust the guide vane angle to the starting point of the first measurement series.

4. **Set generator speed**

   Adjust the generator speed to the first measurement point.

5. **Record measurement point**

   Make sure the operation point is stable before recording the measurement in the data acquisition program.

6. **Set generator speed**

   Increase the generator speed to the value of the next measuring point.

7. **Record measurement point**

8. **Complete the first measurement series**

   Continue by repeating step 6 and 7 until the final measurement point of the first guide vane angle series is recorded.

9. **Set new guide vane angle**

   Use the guide vane wheel again to increase the guide vane angle to the next measurement series.

10. **Set generator speed**

    Set the generator speed to the same value as the start of the previous series.

11. **Record measurement point**

12. **Complete measurement series**

    Repeat steps 10 and 11 until the measurement series is completed.

13. **Carry out remaining measurement series**

    Complete the series by repeating steps 9 to 12.

Shut down

1. **Stop the pump**

   Run down the pump and then stop it.

2. **Stop the generator**

   Run down the generator as the head and volume decrease. Stop the generator when the flow through the turbine is close to standstill.

3. **Turn off the power for the pumps**

Closed Loop

The following set of procedures are for running the Francis rig in closed loop. As described in Chapter 4.1.2 and shown in Figure 5.13, the water goes from the pump through the main pipe system to the pressure tank. The water is then led through the turbine to the draft tube and back to the pumps. It is important to note that the loop needs to be filled before starting to run the rig.

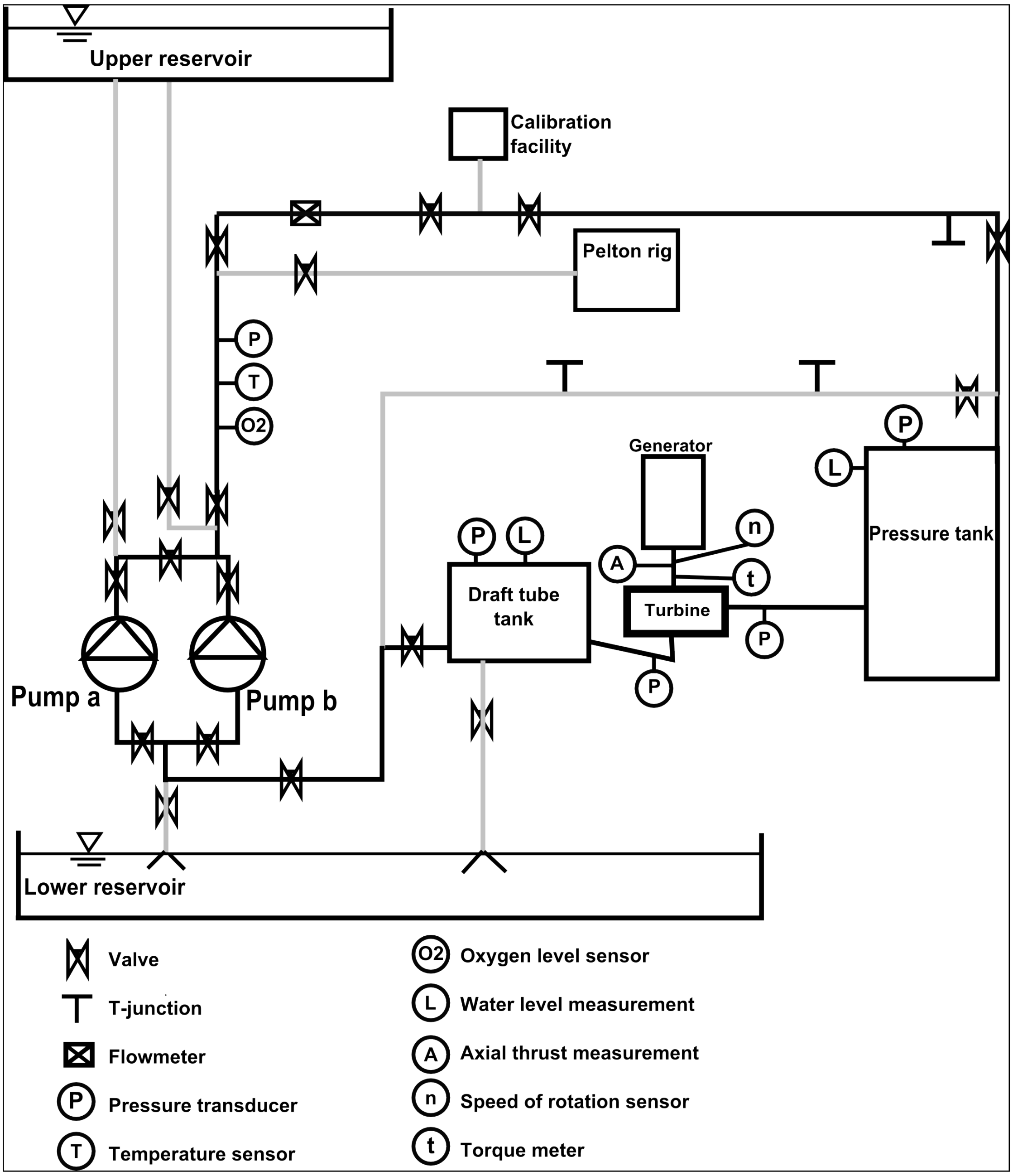


Figure 5.13: Diagram of the closed loop mode when running the Francis model test rig at TTL.

Start up

1. **Turn on the power of the pumps**
2. **Make and inspection around the laboratory**
    - Make sure that all drain tubes are closed
    - Check for water leakage on the turbine
    - Check that the venting valve on the pressure tank is closed
3. **Set the pipe loop**

   Open and close the necessary valves in order to guide the water through the open loop as in Figure 5.13.
4. **Prepare vacuum pump**

   Make sure the valves to the vacuum pump are in the correct positions and that the priming water for the pump is on.
5. **Start the pump**

   Start the pump at a 100 rpm.
6. **Start the generator**

   Start the generator at a 100 rpm when the turbine has accelerated to around 90 rpm.
7. **Increase pump speed and increase generator speed**

   Increase the speed of the pump gradually to stabilize to the desired the head.
8. **Close pressure tank venting valve**
9. **Make an inspection in the laboratory**

Efficiency test

The following procedure explains running the rig for the purpose of taking measurements for a Hill diagram. The procedure mainly consists of varying the guide vane opening and the speed of the generator at a constant head. In a closed loop, the head will drop slightly as the discharge increases. The pump speed should then be increased to maintain a stable head.

1. **Prepare a running sequence**

   Take measurements for one guide vane opening at the time, incrementing the speed of the generator gradually. The same speed increment should be used for all guide vane openings.

2. **Set recording time and directory in the data acquisition program**

   The recording time should be 30 seconds. The data should be saved in an external document automatically.

3. **Set guide vane angle**

   Use the wheel by the spiral casing to adjust the guide vane angle to the starting point of the first measurement series.

4. **Set generator speed**

   Adjust the generator speed to the first measurement point.

5. **Record measurement point**

   Make sure the operation point is stable before recording the measurement in the data acquisition program.

6. **Set generator speed**

   Increase the generator speed to the value of the next measuring point.

7. **Record measurement point**

8. **Complete the first measurement series**

   Continue by repeating step 6 and 7 until the final measurement point of the first guide vane angle series is recorded.

9. **Set new guide vane angle**

   Use the guide vane wheel again to increase the guide vane angle to the next measurement series.

10. **Set generator speed**

    Set the generator speed to the same value as the start of the previous series.

11. **Record measurement point**

12. **Complete measurement series**

    Repeat steps 10 and 11 until the measurement series is completed.

13. **Carry out remaining measurement series**

    Complete the series by repeating steps 9 to 12.

Shut down

1. **Slow down generator and pump**

   Alternate between gradually decreasing the speed of the generator and the pump.

2. **Stop the generator**

   Stop the generator when both the pump and the generator are at 100 rpm.

3. **Stop the pump**

4. **Turn off the priming water for the vacuum pump**

5. **Turn off the power for the pumps**

Chapter 6

Discussion

6.1 Design of the Francis Model Test Rig

The focus of this thesis has been to design a well-functioning Francis model test rig, where the whole system facilitates performance tests in compliance with *IEC 60193* [1]. The components, instrumentation and power electrical system have been designed at different levels of detail depending on the relevancy at this stage of the project. Suggested continued work towards the completion of this project is presented in Chapter 8.

6.1.1 Components

High Pressure Tank and Draft Tube Tank

The tanks for TTL have been designed on the basis of the shape of the tanks at the Waterpower Laboratory. It is not guaranteed that the dimensions in Figures 4.1 and 4.2 are the most optimal, as the detailed dimensioning has not been the main focus in this thesis. The size of the tanks are set based on advice from the technical staff at the Waterpower Laboratory, and are from experience a suitable size in order to ensure stable operating conditions. This could be evaluated further, as the tanks are a relatively large investment. It must be taken into account that the weight of the tank must be within the capacity of the EOT crane of 500 kg.

As mentioned in Chapter 4.1.1, the pressure tank must have a system for ventilation of air, in addition to a safety valve for pressures above 15 bar. This system has not been designed in detail, and the safety valve is not on the drawings. The installation of the safety valve will vary depending on the manufacturer and supplier. Increasing the diameter of the venting pipe from the suggested 100 mm may also be considered.

Main shaft and bearing block

Due to the risk of friction between the rotating and stationary parts in the turbine, it is crucial that the bearings are of high quality and properly lubricated. This will eliminate a potential source of error in the measurements. The bearings suggested in this thesis are therefore high quality bearings from a reliable supplier.

As mentioned in Chapter 4, the bearing block must be designed in more detail for the completion of a total design.

6.1.2 Instrumentation

The instruments chosen for the Francis model test rig are in most cases of the same quality as the instruments at the Waterpower Laboratory. This will ensure the required accuracy of the measurements and a long lifetime of the instruments. The consequence of choosing high-end instrumentation is the increase of costs. However, if the necessary funding is achieved, the instruments will be a well worth investment.

Pressure

The pressure measuring system is chosen to be similar to the system at the Waterpower Laboratory. This is due to the experience of a well functioning and accurate system. If other methods are to be assessed, it is important to take into account the requirements of an automatic data acquisition system.

Flow rate

The choices made for the flow measurement system are strongly based on Seierstad's master's thesis [4]. A modification is made to the diameter and the position of the flowmeter. The reduction from 250 mm to 200 mm of the diameter is to increase the accuracy of the flow rate measurements. With this diameter, the deviation will be just above 0.2 % with a flow rate of more than $0.16\,\mathrm{m^3/s}$. Three different placements of the flowmeter were discussed in Chapter 4.2.2. The flexibility and assurance of a steady flow through the flowmeter were the main factors for placing the flowmeter upstream the pumps, after the first bend.

Using the volumetric method for calibrating the flowmeter was a result from Seierstad's master's thesis [4]. This method is evaluated based on the accuracy, economical aspects, and available space and resources in the laboratory. An alternative to installing a new calibration tank is to use the existing concrete tank. This will be a less costly solution, but complicates the drainage and increases the chances of impurity in the water.

Generator and Friction Torque

Measuring the friction torque together with the generator torque may be a source of error when performing tests on the turbine model. As described in Chapter 4.2.5, the friction torque will be measured without load on the turbine. There is a possibility of a deviation in the friction torque when running the turbine with load. This will be a relatively small error, but should be accounted for. It will be possible to install a separate measuring system for the friction torque at a later stage if necessary.

6.1.3 Power Electrical System

The choice of generator and frequency transformer has been discussed with the staff at the Waterpower Laboratory [23]. The focus on the power electrical system has been less than for the other components, and the suggestions in this thesis has therefore not been evaluated thoroughly.

A placement of the frequency transformer has not been suggested in this thesis. To ensure no unnecessary losses from the generator to the frequency transformer, the two should be placed near each other. However, the noise of the transformer must be taken into account, and it may be reasonable to place the transformer in a separate room outside of the laboratory. The existing transformers for the pumps are placed in a room in the yard outside, on the opposite side of the placement of the Francis turbine. It might be possible to place the transformer of the generator in the same room.

The support structure for the generator and turbine has not been tested for durability and strength. This should be done before the design is finalized. The system for extending and contracting the legs of the structure, moving it up and down, has not been designed. This system should be discussed with the manufacturer, and the same system should also be used for the legs of the draft tube tank.

6.1.4 Total Design

The placement of the rig has been of importance regarding the facilitation of other rigs in the laboratory. The openings in the laboratory floor and the existing pipe system must also be taken into account. From evaluations during the work of this thesis, the placement shown in Figure 4.14 is proven to be the most adequate.

One disadvantage with this placement is that the closed loop outlet of draft tube tank is placed just above the opening to the weirs under the laboratory floor. The pipes are raised about 0.4 m above the floor, so it will still be possible to use the weirs, but the access might be difficult. Better access to the entrance door and the garage port weighs up for the small blockade of the weir opening. This placement also leaves sufficient space for the Pelton model test rig, the flow calibration facility and other smaller test rigs such as cross flow turbine rigs.

In the suggested arrangement in Figure 5.10, the smallest space between the Pelton rig and the Francis rig is just above one meter. At normal operation of the rig, this should be enough. If there are situations where the width is not sufficient, the Pelton rig is installed in a way that makes it moveable using the crane.

At the Waterpower Laboratory the whole Francis rig is raised approximately 6 m from the pumps. This is because of the risk of cavitation in the pumps. Because of the limited space capacity at TTL, it has been decided to keep the rig at the laboratory floor. It should be assessed if this position will be a disadvantage for the pump system.

The 3D CAD drawings have been made based on constructional drawings and measurements done during the visit at TTL. The best achievable accuracy in the dimensions at

TTL has been attempted, but there might be some deviations from reality. The drawings are mainly made for illustrative purposes, and proper technical drawings should be produced for a more detailed design of the test rig.

Detailed design of bends, flanges and pipes have not been made, and this should be discussed with the manufacturer in order to find the best suitable dimensions. As also mentioned in Chapter 4, it is important that the tanks, pipes and flanges are produced with quality welding, and tested for the working conditions, which has a maximum pressure of 15 bar.

When it comes to the budget, the degree of estimate is varied. Mostly, Norwegian suppliers have estimated the costs for the instruments. It is assumed that the instruments have universal prices, and that the cost will not vary much from country to country. However, it might be better to purchase instruments from a local supplier if it is possible to achieve the same quality. All tanks, pipes, bends, t-junctions and flanges should be produced locally. The prices for this are estimated by the local manufacturer, NHE [22]. The remaining cost of components and parts is very roughly estimated, and should be assessed further before a final budget is made. Most emphasis was made on developing an equipment list for the Francis model test rig, rather than obtaining the correct prices.

Developing a fully equipped turbine testing laboratory at Kathmandu University is a major improvement over the existing laboratory. The Francis turbine test rig designed in this thesis is hoped to be an important contribution.

6.2 Development of Procedures for Efficiency Measurement

The procedures for start-up, shut-down and efficiency test in open and closed loop of the Francis model test rig were developed based on the procedures from the Waterpower Laboratory. The procedures should be completed with more detail when the design of the test rig has come to a further stage.

Chapter 7

Conclusion

The Turbine Testing Laboratory (TTL) at Kathmandu University (KU) has been developed with the purpose of increasing the research capacity and turbine testing ability within the field of hydropower in Nepal. A major step towards this goal is to develop a test rig which can handle performance testing of Francis turbines in accordance with the international standard *IEC 60193* [1].

Based on the requirements from *IEC 60193* [1] and the Francis model test rig at the Waterpower Laboratory at NTNU, a suggestion for the design of a Francis model test rig for TTL has been developed. The components have been made using 3D CAD drawings, and assembled into a total design, presented in Figure 5.6. The necessary instrumentation has been chosen based on methods suggested in *IEC 60193* [1], and the equipment at the Waterpower Laboratory. Space and resource limitation has been taken into account when designing the rig, as well as the desire to have a multifunctional and durable test rig. The power electrical system is briefly described.

Procedures for efficiency measurement using the Francis model test rig have been developed. The procedures are only tentative, as they are dependent on the final set-up of the Francis test rig.

The work done in this thesis is an input to the *EnergizeNepal* project of developing a Francis test rig at TTL. It is therefore emphasized that this work is only a suggestion, and there might exist better solutions for the rig at TTL. An overview of suggested further work of this project is presented in Chapter 8.

Chapter 8

Further Work

This chapter suggests further work for the next stage towards fulfilling the design of a Francis model test rig at TTL.

Detailed design of components

Every component, such as pipes, bends, valves, flanges, and tanks, should be designed in detail according to what is available by the manufacturer. The grade and type of stainless steel must be decided.

Detailed design of the bearing block

Suggestions for further work of the bearing block is mentioned in Chapter 6. A detailed design of the shaft and bearing block including couplings, bearings, seals, axial thrust measurement, friction measurement, and speed of rotation measurement should be done to complete the work started in this thesis.

Design of the ventilation system of the pressure tank

A safety valve must be integrated in the design of the ventilation system of the pressure tank. The dimension of the venting pipe should also be evaluated.

Leakage valves

The pipe system should contain leakage valves in order to monitor water leakages in the system. Quantity, type, and placement must be decided and included in the total budget.

Generator and frequency transformer

A generator and frequency transformer has been suggested in this thesis. It should be evaluated if the generator should have a larger capacity than 110 kW. The placement and integration of the frequency transformer must also be decided.

Strain test of the support structure

The support structure must be designed in order to withstand the forces it is exposed to. The system for adjustable legs must also be designed.

Develop a system for improving the conditions of the water

The untreated concrete floor and tanks at TTL are sources of impurities. With a proper coating and routines for cleaning, the water will have better conditions for carrying out tests without the risk of damage to equipment.

Connection to the main power electrical system

The integration of the rig into the power electrical system is an important task, and must be worked on further.

Development of technical drawings

The drawings produced in this thesis are sketches with the purpose of illustration. For a more detailed design of the rig, proper technical drawings are needed.

Development of a detailed budget

As stated in Chapter 5, the budget for the test rig is made on the basis of estimated prices. A new and updated budget should be developed when the final design of the rig is decided. The possibility of using local suppliers should also be surveyed.

Development of procedures for running the Francis model test rig

In addition to the efficiency procedures made in this thesis, procedures should be developed for filling the closed loop, runaway speed tests, pressure pulsations tests and cavitation tests, together with procedures for calibrating the flowmeter, pressure transducers, torque meter, and strain gauges.

System for data acquisition

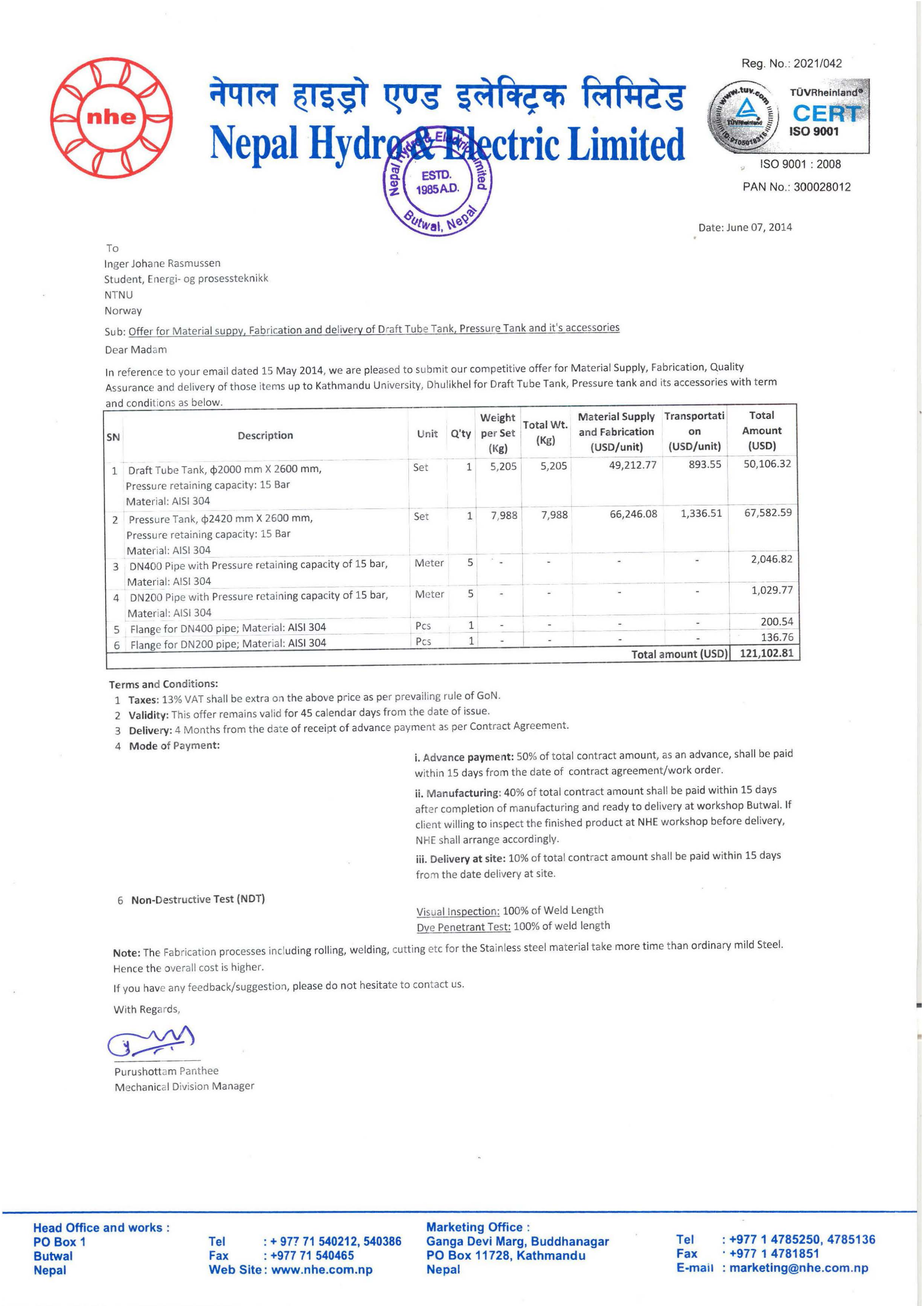
A system for gathering and processing data from the measuring instruments must be designed and installed.

Appendix A

Appendices

A.1 Cost Estimation from Nepal Hydro & Electric

Nepal Hydro and Electric Limited has done an estimation of the costs related to pressure tank and the draft tube tank designed in this thesis.



नेपाल हाइड्रो एण्ड इलेक्ट्रिक लिमिटेड
Nepal Hydro & Electric Limited

Reg. No.: 2021/042
TÜVRheinland® CERT ISO 9001
ISO 9001 : 2008
PAN No.: 300028012

ESTD. 1985 A.D.

Date: June 07, 2014

To
Inger Johane Rasmussen
Student, Energi- og prosessteknikk
NTNU
Norway

Sub: Offer for Material suppy, Fabrication and delivery of Draft Tube Tank, Pressure Tank and it's accessories

Dear Madam

In reference to your email dated 15 May 2014, we are pleased to submit our competitive offer for Material Supply, Fabrication, Quality Assurance and delivery of those items up to Kathmandu University, Dhulikhel for Draft Tube Tank, Pressure tank and its accessories with term and conditions as below.

SN	Description	Unit	Q'ty	Weight per Set (Kg)	Total Wt. (Kg)	Material Supply and Fabrication (USD/unit)	Transportati on (USD/unit)	Total Amount (USD)
1	Draft Tube Tank, ϕ2000 mm X 2600 mm, Pressure retaining capacity: 15 Bar Material: AISI 304	Set	1	5,205	5,205	49,212.77	893.55	50,106.32
2	Pressure Tank, ϕ2420 mm X 2600 mm, Pressure retaining capacity: 15 Bar Material: AISI 304	Set	1	7,988	7,988	66,246.08	1,336.51	67,582.59
3	DN400 Pipe with Pressure retaining capacity of 15 bar, Material: AISI 304	Meter	5	-	-	-	-	2,046.82
4	DN200 Pipe with Pressure retaining capacity of 15 bar, Material: AISI 304	Meter	5	-	-	-	-	1,029.77
5	Flange for DN400 pipe; Material: AISI 304	Pcs	1	-	-	-	-	200.54
6	Flange for DN200 pipe; Material: AISI 304	Pcs	1	-	-	-	-	136.76
							Total amount (USD)	**121,102.81**

Terms and Conditions:

1 **Taxes:** 13% VAT shall be extra on the above price as per prevailing rule of GoN.
2 **Validity:** This offer remains valid for 45 calendar days from the date of issue.
3 **Delivery:** 4 Months from the date of receipt of advance payment as per Contract Agreement.
4 **Mode of Payment:**

i. Advance payment: 50% of total contract amount, as an advance, shall be paid within 15 days from the date of contract agreement/work order.

ii. Manufacturing: 40% of total contract amount shall be paid within 15 days after completion of manufacturing and ready to delivery at workshop Butwal. If client willing to inspect the finished product at NHE workshop before delivery, NHE shall arrange accordingly.

iii. Delivery at site: 10% of total contract amount shall be paid within 15 days from the date delivery at site.

6 **Non-Destructive Test (NDT)**

Visual Inspection: 100% of Weld Length
Dye Penetrant Test: 100% of weld length

Note: The Fabrication processes including rolling, welding, cutting etc for the Stainless steel material take more time than ordinary mild Steel. Hence the overall cost is higher.

If you have any feedback/suggestion, please do not hesitate to contact us.

With Regards,

Purushottam Panthee
Mechanical Division Manager

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Tel : +977 1 4785250, 4785136
Fax : +977 1 4781851
E-mail : marketing@nhe.com.np

A.2 Calibration Procedures for the Francis Rig at NTNU

The procedures for doing calibration for the at the Francis model test rig at the Waterpower Laboratory, NTNU, are attached digitally as Appendix A.2.

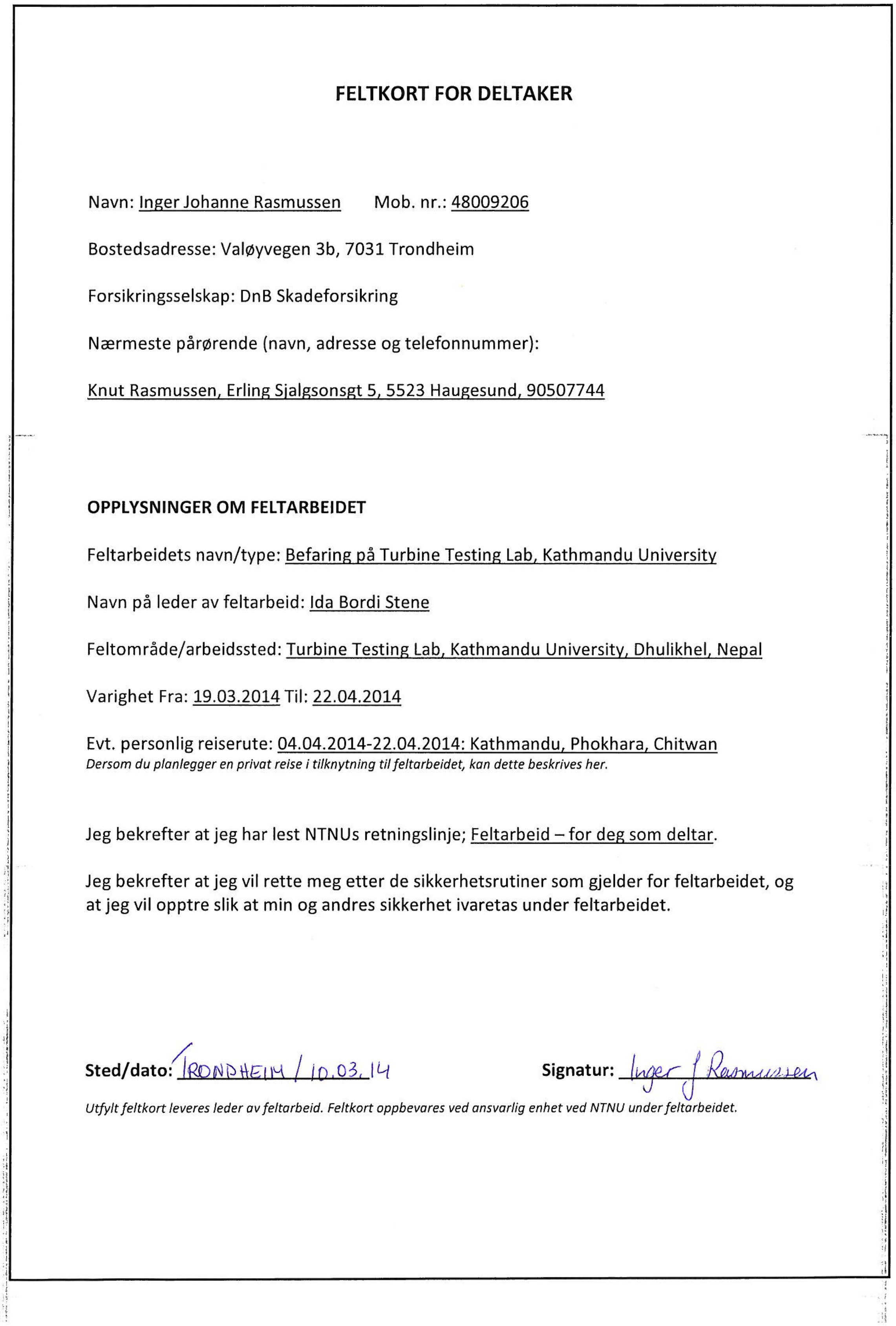
A.3 Measurement Procedures for the Francis Rig at NTNU

The procedures for doing measurements for the Francis model test rig at the Waterpower Laboratory, NTNU, are attached digitally as Appendix A.3.

A.4 3D CAD Drawings of the Francis Model Test Rig at TTL

All 3D CAD drawings made for the design for this thesis are attached digitally as Appendix A.4.

A.5 Field Card for Fieldwork at TTL



FELTKORT FOR DELTAKER

Navn: Inger Johanne Rasmussen Mob. nr.: 48009206

Bostedsadresse: Valøyvegen 3b, 7031 Trondheim

Forsikringsselskap: DnB Skadeforsikring

Nærmeste pårørende (navn, adresse og telefonnummer):

Knut Rasmussen, Erling Sjalgsonsgt 5, 5523 Haugesund, 90507744

OPPLYSNINGER OM FELTARBEIDET

Feltarbeidets navn/type: Befaring på Turbine Testing Lab, Kathmandu University

Navn på leder av feltarbeid: Ida Bordi Stene

Feltområde/arbeidssted: Turbine Testing Lab, Kathmandu University, Dhulikhel, Nepal

Varighet Fra: 19.03.2014 Til: 22.04.2014

Evt. personlig reiserute: 04.04.2014-22.04.2014: Kathmandu, Phokhara, Chitwan
Dersom du planlegger en privat reise i tilknytning til feltarbeidet, kan dette beskrives her.

Jeg bekrefter at jeg har lest NTNUs retningslinje; Feltarbeid – for deg som deltar.

Jeg bekrefter at jeg vil rette meg etter de sikkerhetsrutiner som gjelder for feltarbeidet, og at jeg vil opptre slik at min og andres sikkerhet ivaretas under feltarbeidet.

Sted/dato: TRONDHEIM / 10.03.14 **Signatur:** Inger J Rasmussen

Utfylt feltkort leveres leder av feltarbeid. Feltkort oppbevares ved ansvarlig enhet ved NTNU under feltarbeidet.

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