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Design system for primary calibration of flow

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MASTER THESIS

For
Johanne Seierstad

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Design system for primary calibration of flow

Design system for primærkalibrering av vannføring

Background

The Turbine Testing Lab 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 calibration facility for flow measurements. There are several methods which could be considered.

Objective:

Develop primary method for flow calibration for the Turbine Testing Lab at Kathmandu University

The following tasks are to be considered

1. Survey alternative methods for primary calibration of flow
2. Choose a method that could realistically be implemented at TTL Kathmandu University
3. Design the calibration facility
4. Evaluate the accuracy of selected method
5. Establish software for logging measured data

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.

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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 lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☒ Field work

Department of Energy and Process Engineering, 24.April 2013

Olav Boll

Olav Bolland
Department Head

Torbjørn K. Nielsen
Academic Supervisor

Academic co-supervisor: Ole Gunnar Dahlhaug

Preface

This thesis is written at the Department of Energy and Process Engineering, at the Norwegian University of Science and Technology, in 2013.

The aim of this work has been to develop a primary method for flow calibration at the Turbine Testing Lab in Nepal. I am grateful for having the opportunity to work with such a meaningful and important project. This work has been educative both professionally and personally. Therefore, a special thanks goes to Ole Gunnar Dahlhaug for letting me participate in the development of the laboratory in Nepal.

I would also like to thank Biraj Singh Tapa, Sudip Adhikari, and Bhidan Rajkarnikar Halwai for a close co- operation, and taking good care of me during my stay in Nepal this spring.

A big thanks goes to Halvor Haukvik and the technicians in the lab for being patient answering all my questions, and for educational discussions when turning theory into practice. Finally a special thanks goes to my supervisor Torbjørn Nielsen, for being an important support in many ways this year.

Johanne Seierstad,
Trondheim 26.09.2013

Sammendrag

Parallellt med et økende energibehov i Nepal og nærliggende områder, investeres det stadig i nye vannkraft- prosjekter både av lokale og multinasjonale selskaper. Utviklingen har blant annet ført til etableringen av Turbine Testing Lab ved Kathmandu University i Nepal, innviet i 2011. Laboratoriet er i løpende utvikling, og jobber nå med installering av en Francis- rigg for testing av modellturbiner. Målet for laboratoriet er å kunne gjennomføre modelltester i henhold til IEC 60193, som er gjeldene standard for testing av løpehjul.

En svært viktig parameter ved måling av hydraulisk virkningsgrad, er volumstrømsmålingen. I henhold til IEC skal det sekundære instrumentet benyttet til måling av volumstrøm, kalibreres på stedet med en av følgende primære metoder: veiemetode, volumetrisk metode eller bevegelig lerret- metode.

Oppgaven omhandler utvikling og design av en primær metode for kalibrering av volumstrøms- måleren i laboratoriet. På bakgrunn av en studie av nevnte metoder, samt økonomi, nøyaktighet, og rådføring med teknisk personell, er det utarbeidet et design basert på en volumetrisk metode.

En volumetrisk metode går ut på å fylle vann i en tank med en kjent geometri, og ved måling av nivå og tid kunne beregne volumstrømmen. Kalibreringsriggen inneholder strømningsmåler, innløpsdyse, vippeskjerm, nødoverløp, kalibreringstank, nivåmåling, tidsmåling, avløpsrenne, dreneringssystem, samt et oppgradert rørstrekk ved måleseksjon til strømningsmåleren.

Det er utarbeidet et LabView- program, for logging og behandling av utgangsignalet fra strømningsmåleren. Resterende måledata registreres manuelt i separat kalibreringssjema.

Det er og gjennomført en evaluering av usikkerheten i kalibreringsmetoden, som kan benyttes til å beregne usikkerheten når riggen er installert. Forutsatt at installeringen og utstyret som benyttes er i henhold til ISO 8316, ligger oppnåelig nøyaktighet i metoden på mellom± 0,1-0,2 %. Den største usikkerheten i metoden ligger i bestemmelse av kalibreringsvolumet og tilhørende tank- kalibrering.

Det er foreslått å redusere diameter på strømningsmåler fra opprinnelig størrelse på 400 mm til 250 mm. Reduksjon i diameter samt et oppgradert rørstrekk ved måleseksjonen, vil øke nøyaktigheten i målingene som et resultat av forbedret strømningsmønster ved måleseksjonen.

Når kalibreringsriggen er installert i laboratoriet, er dette et stort og betydelig steg i retning av et IEC- godkjent laboratorium i Nepal, som åpner dører til et internasjonalt marked.

Abstract

Whilst growing demand for energy in Nepal and neighbouring- countries, investments in hydro- power projects appears continuously, both by local and multinational companies. As a consequence of this, Turbine Testing Lab was founded in 2011 at Kathmandu University in Nepal. The laboratory is rapidly developing, and is currently implementing a Francis turbine test rig. A long- term goal for the laboratory, is to execute model tests according to IEC 60193, which is the standard used in model tests of hydraulic runners.

When determining the hydraulic efficiency of a runner, a central parameter is the discharge measurement. According to IEC, any secondary device used to measure the discharge shall be calibrated *in sitù* against one of the following primary methods: the weighing method, volumetric method or the moving- screen method.

The aim of this work has been to develop and design a primary method for calibration of the flowmeter at TTL. Based on an evaluation of the mentioned primary methods, as well as economy, accuracy and correspondence with technical staff, a volumetric method is chosen as calibration principle. The principle of the method is based on collecting water into a tank with a known geometry, and by execution of level- and time measurements calculating the discharge.

The calibration rig consists of a flowmeter, inlet nozzle, deflector mechanism, emergency weir, calibration tank, level measurement, time measurement, drainage system, emergency weir, and an upgraded pipe run at the measuring section of the flowmeter.

It is developed a LabView program, for logging and processing the voltage output from the flowmeter. The other measurements executed is registered manually in a separate calibration sheet for data processing.

An evaluation of the accuracy in the calibration method is conducted, which may be used to determine the total uncertainty when the calibration facility is installed. Provided design and installation according to ISO 8316, the accuracy in discharge measurement with the volumetric method lies within ± 0,1- 0,2 %. The major uncertainty contribution in the method lies in the determination of the volume collected, and the corresponding tank calibration.

It is proposed to reduce the diameter of the flowmeter from original size of 400 mm to 250 mm. Reduction in diameter and upgraded pipe run will increase accuracy of the flow measurement, a result of improved flow pattern at the measuring section.

When the primary calibration rig is installed at TTL, this will be a large step towards an IEC- approved laboratory in Nepal, which open doors against an international market.

Contents

List of Figures

Nomenclature

β	Thermal expansion coefficient, $[1/K]$
Δ	Delta
η	Hydraulic efficiency
ω	Angular velocity, $[s^{-1}]$
π	Pi
ρ	Density, $[kg/m^3]$
θ	Temperature, $[^\circ C]$
H_e	Effective head, $[m]$
$P_{hydraulic}$	Hydraulic power, $[W]$
$P_{mechanical}$	Mechanical power, $[W]$
Q_{max}	Maximum discharge, $[m^3/s]$
T_{fric}	Friction torque, $[Nm]$
T_{gen}	Generator torque, $[Nm]$
V_{avr}	Average voltage, $[V]$
A	Area, $[m^2]$
B	Magnetic field strength, $[A/m]$
b	Width, $[m]$
D	Diameter, $[m]$
d	Depth, $[m]$
DN	Nominal diameter, $[mm]$
e	Absolute error

f	Relative error
g	Acceleration of gravity, $[m/s^2]$
k	Geometry factor
l	Length, $[m]$
m	Mass, $[kg]$
n	Rotational speed, *[rpm]*
p	Pressure, $[Pa]$
Q	Discharge, $[m^3/s]$
r	Correcton coefficient
S	Standard deviation
t	Time, $[s]$
U	Voltage, $[V]$
V	Volume, $[m^s]$
v	Velocity, $[m/s]$
z	Level, $[m]$

Abbreviation

DN	Nominal diameter
IEC	International electrotechnical Commission
IP	Enclosure rating
ISO	International Organization for Standardization
KU	Kathmandu University
NTNU	Norwegian University of Science and Technology
RSS	Root-sum-square
TOF	Time of flight
TTL	Turbine Testing Lab

Chapter 1

Introduction

1.1 Motivation

The raise in both globalisation and economical growth in large parts of the world, have led to an increased demand in power and energy also in developing countries. Nepal is regarded as one of the poorest countries in the world, and only about 40 % of the population have access to electricity [14].

Access to energy and electicity is essential when it comes to development and growth, and in 2008, the government of Nepal declared an energy crisis in the country [11].

Despite a huge hydro- power potential readily available, only a fraction of this is utilized. In 1992, the Nepalese government approved development policies for hydropower which in turn led to increased investments, both from local and international operations.In 2010, the nepalese government presented a goal of developing 38.000 MW in the next 25 years [13]. This development has led to a demand in knowledge within the hydro- power field.

As a result of the preceding arguments, the Turbine Testing Lab (TTL) at Kathmandu University in Nepal, was inaugurated in November 2011. In addition to the high activity within sand erosion and turbine design, TTL is currently working with a development and implementation of a Francis turbine test rig. A long- term goal for the Turbine Testing Lab, is to be able to conduct model tests according to IEC 60193 - "Hydraulic turbines, storage pumps and pump- turbines Model acceptance test". In order to achieve the required accuracy, one of the most important tasks is to establish a proper flow calibration facility.

1.2 Structure

According to IEC, any secondary instrument used during a model test, should be calibrated against a primary method [6]. The main object of this work, has been to design a primary calibration facility for flow measurements at Turbine Testing Lab.

The thesis is structured as follows:

Chapter 2 is an outline of previous work, technical set up and current situation at TTL, to look at limitations and factors that can affect the chosen method and design. Then a study of the theoretical basis for the work is given in chapter 3, with focus on flow calibration and uncertainty evaluation. A survey of the alternative primary methods required by IEC, is given in the same chapter.

The design chapter (Chapter 4) opens with an argumentation of chosen calibration principle, followed by a step by step evaluation of the design phase of the calibration facility.

An uncertainty evaluation of the chosen method is given in chapter 5, which can be used as a basis in the uncertainty calculation when the calibration rig is installed.

Required data acquisition, calibration procedure and software for the calibration can be found in chapter 6. Finally, results and the calibration facility design is presented, followed by a discussion of the chosen method and design.

Installation of a primary calibration facility for discharge measurements, is a central step in the direction of an IEC- approved laboratory at TTL. Until now, such model tests for Nepalese companies has been accomplished abroad. Establishment of an IEC- approved laboratory at TTL is of major significance for the hydro- power development in Nepal, and the academic knowledge within hydraulic runners in the country.

Chapter 2

Background

2.1 Preliminary work

The design of the Francis turbine test rig, was done by master student Bidhan Rajkarnikar Halwai in June, 2012 [16]. In retrospect, some configurations are done by the employees at TTL. The Francis rig is based on the Jimhruk/Kulekhani-model runner, and the runner specifications is given later in this chapter.

The purpose of my project thesis in 2012, was an evaluation of the planned Francis rig setup, and comparing it to the specificantions set by IEC 60193. As a result of this evaluation, it showed that one of the main factors to approach an IEC-approved testing facility at TTL lies in a proper flow calibration facility.

An outline of the current situation and technical set up at TTL, based on my project thesis and a fieldwork/visit at TTL this spring, is given in the next section.

2.2 Turbine Testing Lab, Kathmandu University

Turbine Testing Lab (TTL) was inagurated in 2011, and is located at Kathmandu University - School of Engineering, in Dhulikhel in Nepal. Turbine Testing Lab is a co- operation between KU, Norad, NTNU and local investors, and an important contributor to the hydro- power development in the country. In addition to high activity within sand erosion and turbine design, TTL is currently working with implementation of a Francis turbine test rig. The design and implementation of the simplified Francis rig is an ongoing process, and parts of the instrumentation are still not decided. When the Francis test rig is installed at TTL, the first object is to accomplish efficiency tests of the Kulekhani III- model [21].

Figure 2.2.1: Turbine Testing Lab

2.2.1 Technical set up

Loop system

There are two options for setting the loop system, either an open loop or by use of the pump head. The corresponding head is 30 m natural head for the open loop, or 75 m by using the pump head. The main pipe system in the laboratory consists of pipes with a nominal diameter of 400 mm. During the calibration, the rpm of the pumps is used to decide the flowrate for the closed loop system.

Pump system

The pumps available in the laboratory (2 x 150 kW) are installed in the basement. Both are varied frequency driven. The pumps can be connected in series to increase the head, or in parallel to increase the flow. Maximum head and flow is respectively 150 m head when running in series, and 0,5 m^3 when running in parallel.

Reservoirs

The laboratory consists of two reservoirs. The upper reservoir has a capacity of 100 m^3, while the lower (swamp) has a capacity of 300 m^3. With a closed loop, the laboratory will be able to run model tests of prototypes up to 300 MW. There is also a crane available in the laboratory, with a range up to 500 kg EOT.

The generator is still not decided for the Francis rig, but must be able to handle approxiamately 100 kW and 1000 rpm. The shaft, bearing and cooling system are not specified for the system.

Specifications of model runner

Instrumentation and advices regarding measuring of the test rig are based on the model turbine made for Jhimruk Hydroelectric. The design of the simplified Francis test rig was done by master student Bidhan Rajkarnikar Halwai, during his thesis spring 2012 [16]. The Kulekhani III/ Jimhruk- model, is used as a basis for the flow calibration facility, and the design parameters for the runner are given under:

Design parameters	**Model turbine**
Head (H)	43 m
Discharge (Q^*)	0.2277 m3/s
Max discharge (Q_{max})	0.3026 m3/s
Power (P)	92 kw
Speed of the runner (n)	1000 rpm
Speed number	0.32

Flowmeter

TTL has proposed installation of an electromagnetic flowmeter, a *Magmaster 2500* delivered by ISOIL, for their test rig. The nominal diameter is 400 mm. The flowmeter will be installed at the vertical pipe above the pump room, as illustrated in figure 2.2.3. The location is according to the specifications given by the manufacturer, which requires an inlet length of 3 x DN, and an outlet length of 2 x DN [2]. Specifications of the flowmeter can be found in the technical datasheet delivered with the flowmeter.

Floor plan

The outlet of the Francis test rig is placed above the main sump. The pump room border to the main sump on the west side, and the existing calibration tank to the south. An overview of the floor plan and set up of the laboratory is shown in figure 2.2.2 and 2.2.3.

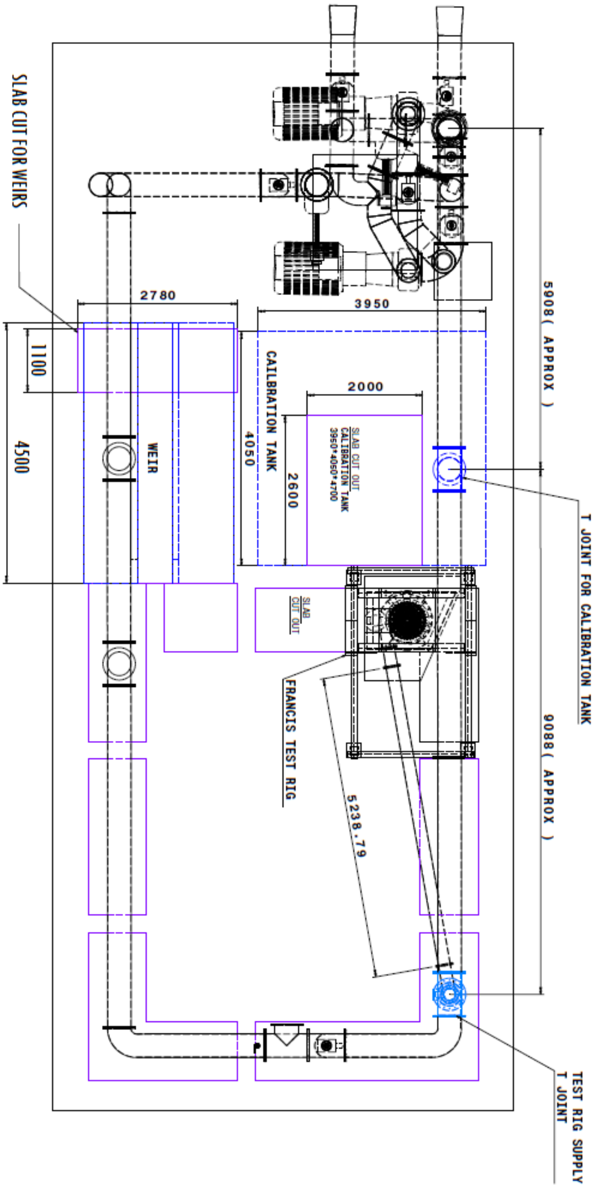

Figure 2.2.2: Floor plan at TTL

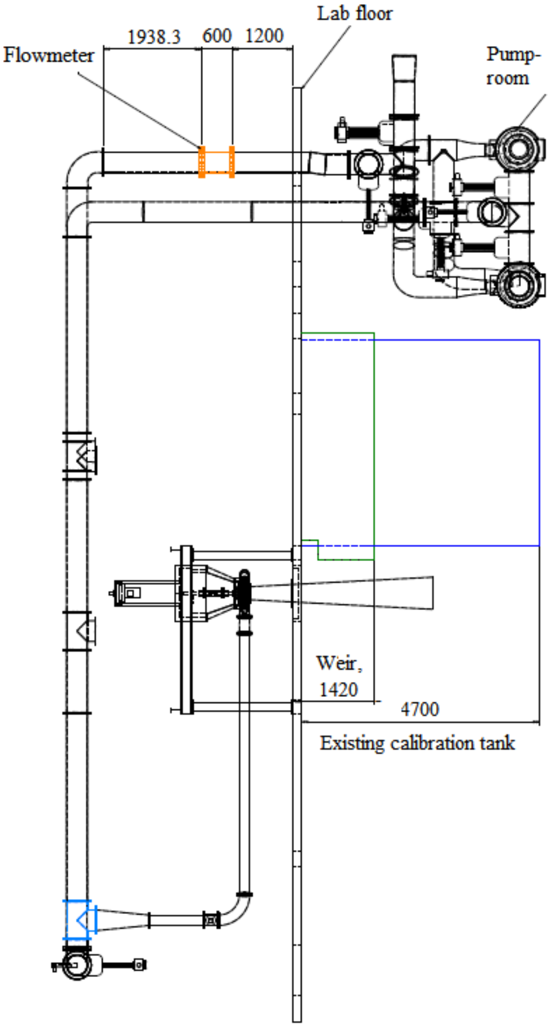

Figure 2.2.3: Side view of TTL

Chapter 3

Theory

3.1 General

3.1.1 Model testing

Model testing of turbines is done due to different purposes; To investigate the turbine mode of operation, to reach maximum efficiency for a new runner design, to look at improvements to increase the efficiency of an existing runner or as a part of the guarantee of a new runner [23].

A main objective in model testing is to determine the efficiency of the runner. The hydraulic efficiency η_h, is defined by IEC [6] as:

$$\eta_h = \frac{P_{mechanical}}{P_{hydraulic}} = \frac{(T_{gen} + T_{fric})\omega}{\rho g Q H_e} \tag{3.1.1}$$

where T_{gen} and T_{fric} is the generator- and friction torque, ω is the rotational speed, ρ is the density of the water, g is the gravity and Q is the discharge. The effective head over the turbine, H_e is defined in equation (3.1.2) [23]:

$$H_e = \frac{\Delta p}{\rho g} + \frac{v_1^2 - v_2^2}{2g} + \Delta z \tag{3.1.2}$$

To ensure an accurate determination of the hydraulic efficiency, the instrumentation used during the model test have to be calibrated.

3.1.2 Discharge measurement

Equation (3.1.1) shows that the discharge measurement is essential in a model test, and affects the hydraulic efficiency directly.

The discharge measurement at TTL will be executed by an electromagnetic flowmeter. This measuring technology is based on Faraday‘s law of induction, as explained under:

The flowmeter consists of two coils which are mounted on an electrical insulated pipe, and generate a magnetic field. The field is perpendicular to the flow direction. When the water flows through the magnetic field B, with a velocity v, a voltage U is induced in the water. As the voltage signal is proportional to the water velocity, the discharge through the flowmeter with pipe diameter D can be determined by equation 3.1.3 [18]:

$$U = v \cdot k \cdot B \cdot D \tag{3.1.3}$$

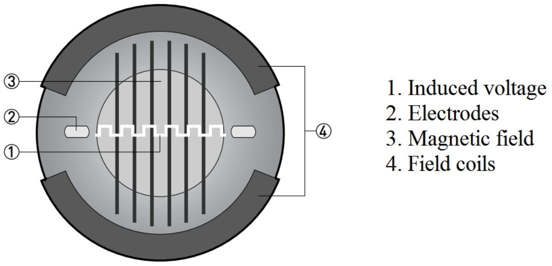

Figure 3.1.1: Electromagnetic flowmeter

To ensure a measuring section completely filled with water, the flowmeter should be installed in a vertical pipe with ascending flow.

For the inlet- and outlet conditions of the flowmeter, the various manufacturers operates with several requirements. According to ”‘*Flow measurement handbook*”’, the following is specified: [1, p. 299]:

Spacing such as 3D to 5D upstream, with 3D downstream, should be treated with caution.

For a model testing purpose, prof. Ole Gunnar Dahlhaug recommended a 10xDN upstream straight pipe run before the installation [9].

When purchasing a flowmeter the meters are usually calibrated in advance by the manufacturer, and delivered with a corresponding calibration curve. For a model test, IEC requires that the secondary device used for flow measurements shall be calibrated *in situ*, against one of the primary methods evaluated in section 3.2 [6, p. 197].

3.1.3 Calibration

In a model test of a runner, there are several parameters which have to be measured by different instruments and measuring devices. In order to obtain a measured value as close as possible to the real value, the instrument have to be calibrated.

A calibration is based on comparing the output signal of the instrument against a primary measurement, and establishing a known linear relation between the output of the instrument and the primary measurement. For a flow measurement, this means to compare the voltage output from the flowmeter, with a calculated flow rate obtained through a primary calibration method.

A primary quantity is a size that is measurable and traceable back to fundamental SI standard units, such as mass, length and time. For a discharge calibration, this means a measurement of either mass and time, or mass and volume (length).

Each instrument is delivered with a corresponding calibration sheet, with technical data, accuracy and repeatability. Since an instrument can drift over time due to variations in the environment and electronic, the instrument has to be calibrated regularly to ensure a reliable measured value.

For a model test accomplished according to international standards, IEC operates with strict requirements for calibration and traceability.

3.1.4 IEC Requirements

As stated in IEC, any secondary device used to measure the discharge shall be calibrated against a primary method. The primary methods required by IEC are described in section 3.2. The calibration shall be carried out without dismantling the flowmeter from the system, with the same operating conditions for the calibration and model test. The discharge measurement is only valid if the flow is steady or close to steady in the whole operating area. Any loss or addition of water between the runner and flowmeter should be avoided, or measured and corrected for. The calibration of the secondary device shall be carried out *in situ* [6, p. 197-213].

For the procedure and design of the calibration facility, IEC refers to the corresponding ISO standard for each primary methods recommended.

The result from the calibration should be treated with a regression method to establish a linear relationship between the discharge and corresponding voltage value from the flowmeter. To ensure accurate test results, the calibration of the electromagnetic flowmeter should be carried out both before and after a model test [6, p. 213-215].

3.2 Methods for primary calibration of flow

Primary methods are those methods which are based on measuring fundamental quantities/SI-units, such as mass, length or time. For a secondary instrument used to measure discharge in a model test, IEC requires calibration against one of the following primary methods;

- Weighing method
- Volumetric method
- Moving screen method

3.2.1 Volumetric method

The volumetric method is mainly based on time and level measurements, and derives the average discharge over the measured filling time period. All requirements for the procedure, design, and installation of the volumetric method are given in ISO 8316 - "'Measurement of liquid flow in closed conduits. Method by collection of the liquid in a volumetric tank"' [26].

The principle of the method, is to direct the water flowing through the flowmeter, into a tank with a known geometry. The collected volume ΔV can then be determined through level measurements carried out before and after the filling period. By measuring the filling time Δt, the corresponding discharge can be calculated from:

$$Q = \frac{\Delta V}{\Delta t}[m^3/s] \tag{3.2.4}$$

The volumetric method can be divided into *static* and *dynamic gauging*, depending on how the time and level measurement is executed in the calibration [26, p. 7]:

For a *static gauging*- method, the level measurement is carried out when the tank filling is finished, and the system has come to rest. An electrical timer triggered by the deflector motion measures the filling time.

With a *dynamic gauging*- method, measurement of the collected volume is carried out while the water is flowing into the tank, and measured between two fixed levels. The filling time measurement starts when the water reaches the first level, and stopped when the water reaches the final level.

For a calibration according to IEC, only the static method is required [6, p. 201].

For the total accuracy of the method, the calibration of the volumetric tank is central. The tank calibration should be executed by one of the methods described in section 5.5, in ISO 8316 . For the tank calibration, a level-volume relationship should be established through a linear regression [26].

The tank calibration should be checked regularly, to ensure leakage or variations in the geometry [26]. A steel tank should be calibrated every 3.rd year, and a concrete tank every 5.th year [6, p. 201].

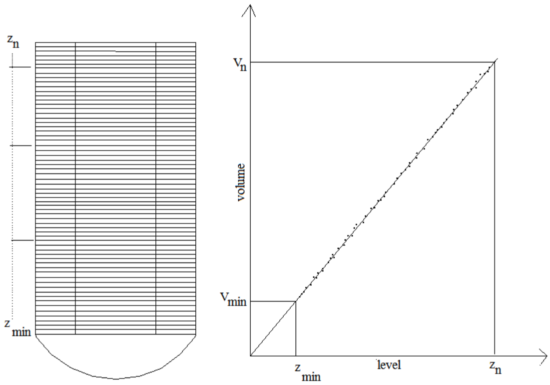

Figure 3.2.2: Volumetric tank calibration

The systematic errors due to the volumetric method arises in the volumetric tank and its calibration, the filling time measurement, deflector mechanism, and level measurement. If any significant temperature deviation occur during the calibration, this shall be corrected for in the collected volume determination. [26, p. 3]. If the construction, installation, and procedure is done according to ISO 8316, an uncertainty between ± 0,1 - 0,2 % is attainable for the method [6].

3.2.2 Weighing method

The flow calibration at the Waterpower Laboratory at NTNU, is based on the weighing method.

The principle of this method is based on weight cells mounted under the tank, that measures the total amount of water. Measurements are done for water temperature, ambient- temperature, and ambient- pressure, and the water density can be calculated through the density equation given in appendix A.2.1. Through measurements of mass, calculation of density, and a correction for the buoancy, the corresponding flowrate is calculated by equation (3.2.5):

$$Q = \frac{\Delta m}{\rho_m \cdot \Delta t(1 - \frac{\rho_a}{\rho_m})} [m^3/s] \tag{3.2.5}$$

where

ρ_a = Density of the air and ρ_m = Density of the water

The water density is calculated by the equation given in appendix A.2.

Before the calibration can be carried out, a substitution calibration for the weighing tank system must be conducted. The output from this calibration is a calibration curve and correction equation. The equation is used during the main weighing method calibration, to correct for the systematic errors in the weighing cells.

Similar to the volumetric method, the calibration can be carried out both static and dynamic. IEC only require the static method [6].

The weighing method is defined as one of the most accurate calibration methods. The systematic errors from the method arise in the weighing tank and the substitution calibration, the time measurement, deflector mechanism, and the determination of water density [6, p. 527]. The accuracy in the weighing cells depends on the load, with increased accuracy with higher load [17].

If the calibration set up and procedure is done according to ISO 4185, it is possible to reach an accuracy between ± 0,1 - 0,2 % [6] for the weighing method.

3.2.3 Moving screen method

The moving screen method is based on the same principle as the volumetric method, by determing a volume through level and time measurements. The method mode of operation is as follows: A screen mounted on a friction free rail above the tank, is moving with the water velocity (Shown in figure 3.2.3). The travel time Δt is measured between two fixed points, at section A and B [6].

Through level measurements the water depth d is determined. With known channel geometry of length L and width b, the mean discharge can be calculated by equation 3.2.6 [6, p. 203]:

$$Q = \frac{V}{\Delta t} = b \cdot d \cdot \frac{L}{\Delta t} = b \cdot d \cdot v \tag{3.2.6}$$

The water level should be measured before, between, and after the fixed points (where the travel time is measured), by level gauges installed in the walls. The level gauging methods required for the method, is either point-/hook gauge or pressure transmitters installed in the bottom of the channel [6, p. 205-207].

For an accurate measurement, the screen velocity must be equal to the water velocity. This means that the installation have to be constructed in such way that friction forces do not affect the motion of the screen. By a correct installation of all the components, the moving screen method can reach an uncertainty between ± 0,2- 0,3% [6, p. 209]. The principle of the method is illustrated in figure 3.2.3.

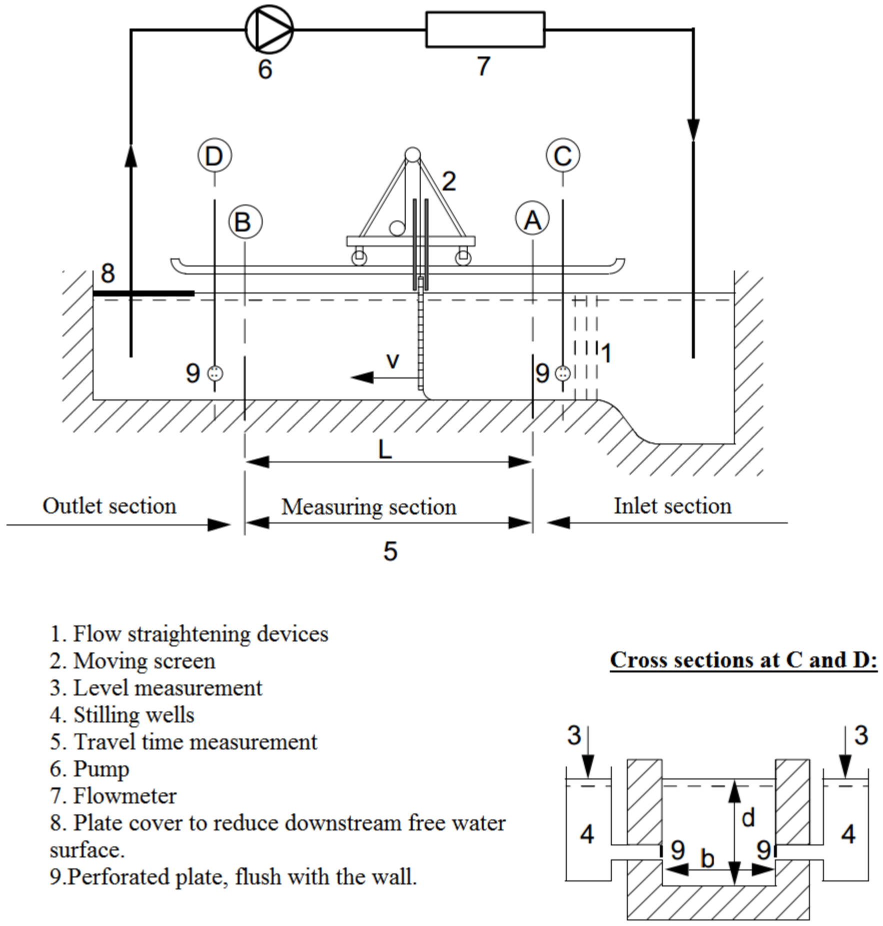

Figure 3.2.3: Moving screen method [6, p.205]

3.3 Uncertainty Analysis

When measuring a physical property in the laboratory, there will always be an interval between measured and real value. This is defined as the error in the measurement [20, p. 32].

During a flow calibration, measurements are carried out for several different quantities. The error in each measurement will propagate and contribute to a total uncertainty in the final flow measurement. This uncertainty is possible to intend, through analysis of the different sources of errors that can occur in the calibration process.

3.3.1 Errors

In the case of model testing, IEC consider three different types of errors [6, p. 339]:

- Systematic errors
- Random errors
- Spurious errors

Systematic errors

Systematic errors are those errors that remains constant for the same operation point and conditions, and will not be removed by increasing the number of measurements. The systematic errors often originate from weak calibrations of the measuring devices, and nonlinearity and drift in the instrumentation. To derive the systematic error of a given quantity, it is necessary to look at each part of the calibration procedure and measurements, that leads to the measured value [6, p. 341]. An example of a systematic error, is a constant offset in the measuring device [20].

If the systematic error is known, the error can be added or subtracted from the measured value and by this remove the systematic uncertainty [6].

Random errors

Random errors arise due to small changes in the measurand, instrumentation or environment, which can prevent the measuring device from showing the real value. Such variations in the conditions may arises from temperature variations, vibrations, or small fluctuations in the water. The random error of an instrument is closely linked to the repeatability of the instrument, which is defined as when the instrument shows a different output for a constant input value [6, p. 339].

In contrast to systematic errors, it is possible to decrease the effect of the errors by increasing the number of measurements [6, p. 339]. To calculate the random errors, different statistical methods can be applied. The methods are explained in section 3.3.3.

Spurious errors

Spurious errors are caused by human failure or failure in the equipment. These errors are easy to recognize and separate from the rest of the measurements. Such errors are not taken into consideration when calculating the total uncertainty [6, p. 339].

3.3.2 Propagation of errors

The theory and derivations in this section are based on the literature "'Physical measurements"' [3, p. 39-42].

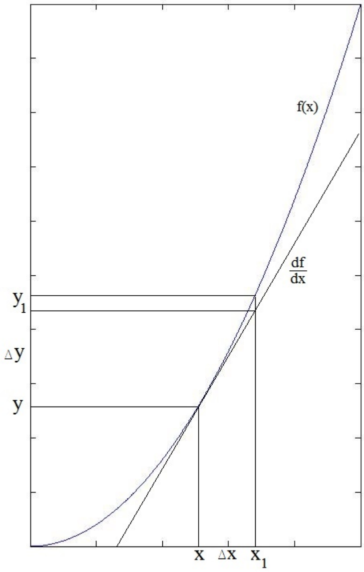

Figure 3.3.4: Error propagation

When measuring a physical quantity, the deviation between the measured value x_1 and the real value x, can be defined as the error Δx.

In case of y as a function of x,

$$y(x) = x^2 \tag{3.3.7}$$

the deviation between real and measured value, will propagate in the calculation of y by a new deviation between y and y_1, Δy (Illustrated in figure 3.3.4). This error can be found from equation 3.3.8:

$$y_1 - y = \frac{df}{dx}(x_1 - x) \tag{3.3.8}$$

If Δx is small, an approximation of Δy is:

$$\Delta y = \frac{df}{dx}\Delta x = 2x \cdot \Delta x \tag{3.3.9}$$

With that, equation 3.3.9 is an expression of how the error propagates with y, by a wrong measure of x.

For a function with multiple variables, the principle remains the same: For the volume of a cylinder, we have the following function:

$$V = f(x, y) = \pi \frac{x^2}{4} y \tag{3.3.10}$$

An error in the measurement of the x, will propagate further in f(x,y) as given in the following expression:

$$\Delta V_x = \frac{\delta f}{\delta x}\Delta x = \pi \frac{x}{2} y \Delta x \tag{3.3.11}$$

And an error in the measurement of y, will propagate further in f(x,y) as:

$$\Delta V_y = \frac{\delta f}{\delta y}\Delta y = \pi \frac{x^2}{4}\Delta y \tag{3.3.12}$$

Maximum deviation in f(x,y) by wrong measurements of x and y, can be determined by summing up each error term:

$$\Delta V = V_x + V_y = \pi \frac{x}{2} y \Delta x + \pi \frac{x^2}{4}\Delta y \tag{3.3.13}$$

A more general expression can be written as:

$$\Delta R = \left|\frac{\delta f}{\delta x}\Delta x\right| + \left|\frac{\delta f}{\delta y}\Delta y\right| + \left|\frac{\delta f}{\delta z}\Delta z\right| + \cdots \tag{3.3.14}$$

However, this formula do not consider that the error can contribute in both positive and negative direction. This means that equation 3.3.14 can be used to determine the maximum error in a measurement [3].

RSS- method (Root-Sum-Square)

If the input values are independent and have the same distribution, the total uncertainty can be calculated by the RSS- method (Root-Sum-Square) In contrast to equation 3.3.14, this method takes into account that the errors can contribute in both directions [6]:

$$\Delta R = \sqrt{(\frac{\delta f}{\delta x}\Delta x)^2 + (\frac{\delta f}{\delta y}\Delta y)^2 + (\frac{\delta f}{\delta z}\Delta z)^2 + \cdots} \tag{3.3.15}$$

the partial derivatives are sometimes referred to as the sensitivity coefficients c_i, which is an expression on how a small variation in the input value effects the output [8].

3.3.3 Statistic analysis

Statistical methods can be used for approximation of the random uncertainty for a measurement in a model test. The uncertainty can be found by calculating the standard deviation and the corresponding confidence interval of the measuring series. For model testing IEC operates with a 95 % confidence level [6, 545], meaning that 95 % of the population is expected to lie within an interval equal to the confidence interval [22, p. 324].

The standard deviation S_x of the samples is calculated by equation 3.3.16:

$$S_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{3.3.16}$$

If the number of measurements is close to infinity, the distribution can be treated as normal- distributed (Gaussian distribution) [22, p. 240]. When the number of measurements decreases, the distribution will change to a Student's- t distribution.

A *Student's- t distribution*, takes into account that the standard deviation increases when n decreases. This is adjusted for through the student- t factor, that can be found in appendix A.1 [22, p. 344].

For a large number of measurements x_{1},$_2$, ... ,x_n (n close to infinity) that varies in a random manner around the mean value μ: A 95% confidence interval can be found by equation 3.3.17 [22, p. 326]:

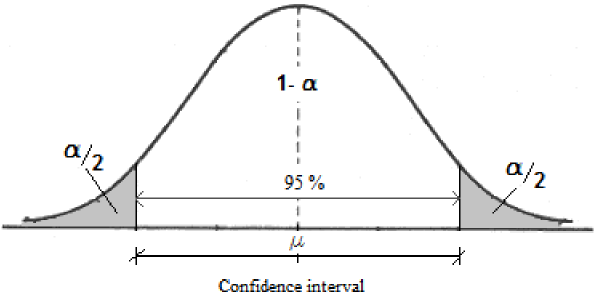

Figure 3.3.5: Normal distribution

$$\bar{X} \pm \frac{1,96 \cdot S_x}{\sqrt{n}} \tag{3.3.17}$$

If the number of measurements decreases which means that the distribution change to a t-distribution, a 95 % confidence interval can be found by equation [22, p. 348]:

$$\bar{X} \pm \frac{t_{n-1,\alpha/2} \cdot S_x}{\sqrt{n}} \tag{3.3.18}$$

The table given in appendix A.1 indicates that the t- factor is converging towards 1,96 when the number of measurements increases.

For a measuring series that varies in random manner around the sample mean, the confidence interval is an approximation of the the random uncertainty at a 95 % confidence level:

$$(e_x)_r = \pm \frac{t_{n-1,\alpha/2} \cdot S_x}{\sqrt{n}} \tag{3.3.19}$$

The error expressed in a relative term;

$$(f_x)_r = \frac{(e_x)_r}{\bar{x}} \tag{3.3.20}$$

3.3.4 Regression analysis

The regression method are based on statistical calculations, to determine a relation between two input variables. When calibrating the flowmeter, a linear relation between the voltage output value from the flowmeter x_i, and the calculated discharge y_i, has to be established. The calibration constants a and b, correspond to the calibration values which later are used to determine the flowrate during a model test. The result of the linear regression for the flow calibration executed in earlier laboratory work, is shown in figure 3.3.21 as an illustration.

$$y = ax + b \tag{3.3.21}$$

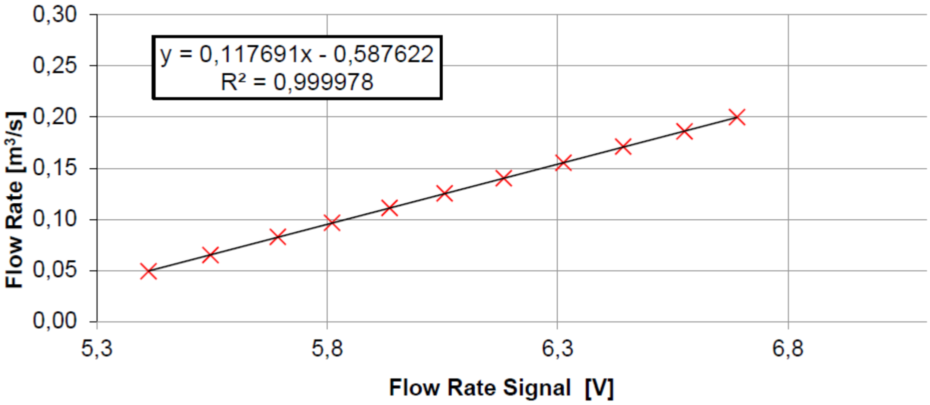

Figure 3.3.6: Calibration curve, flowmeter

Necessary equations for determination of the calibration curve during the regression, is given under. The equations given under are based on the theory in chapter 11 in [28] and ISO 7066 [7]:

S_{xx} and S_{yy} are expressions of how x and y varies individually ,while S_{xy} express the combined variation of x and y [25].

$$S_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2 \tag{3.3.22}$$

$$S_{yy} = \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{3.3.23}$$

$$S_{xy} = \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y}) \tag{3.3.24}$$

The calibration constants a and b, can then be derived:

$$b = \frac{S_{xy}}{S_{xx}} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{y})^2} \tag{3.3.25}$$

a is derived from $\bar{y}$=a $\bar{x}$+b , and the expression of a is given by:

$$a = \frac{\sum_{i=1}^{n} y_i - b\sum_{i=1}^{n} x_i}{n} \tag{3.3.26}$$

The correction coefficient r, expresses the quality of the regression. A correction value of 1, corresponds to an optimal line fitting. The correction coefficient can be determined from equation 3.3.27, which are found in ISO 7066 [7].

$$r^2 = \frac{\sum[(x_i - \bar{x})(y_i - \bar{y})]}{[\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2]} \tag{3.3.27}$$

The standard deviation of the distribution around the calibration curve, can be found through:

$$S_R = \sqrt{\frac{SSE}{n-2}} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - a - bx_i)^2}{n-2}} = \sqrt{\frac{S_{yy} - bS_{xy}}{n-2}} \tag{3.3.28}$$

Equation 3.3.28 are found in [22], and follows the required methods in ISO 7066 [7].

3.3.5 Error contributors during calibration

During a primary calibration of the flowmeter, the following errors are introduced [6, p.345];

Component errors	
f_a	Systematic errors, primary calibration method
f_b	Random errors, primary calibration method
f_c	Systematic errors, flowmeter
f_d	Random errors, flowmeter
f_e	Errors in physical phenomena and external influence
f_f	Errors in physical properties

The error terms described below are based on the evaluation in Annex J, in IEC [6].

f_a - Systematic errors from the primary method

This corresponds to the systematic part of the intrinsic error of the primary method used for calibration. The errors are related to systematic errors in the measuring equipment and components of use in the primary method [6, p.527].

f_b - Random errors from the primary method

This error is also referred to as the repeatability, and corresponds to the random part of the intrinsic error of the primary calibration method. These errors are related to the random errors in the components and measuring equipement used in the primary method [6, p.529].

f_c - Systematic errors from the flowmeter

This term is the systematic component of the intrinsic error in the secondary device used to measure the discharge. For a flowmeter, this will correspond to the systematic error in the voltage output [6, p.529]. The main purpose of the calibration is to remove this systematic error.

Regression error

Since the calibration is based on measuring the flow in a restricted number of operation points, there will arise an error due to the curve fitting/regression. This error will vary for different operation points, with a maximum value at lower and higher discharges. According to IEC the regression error can be set to e_{reg} = 0,05 % [6], or calculated by methods given in ISO 7066 [8].

f_d - Random errors, flowmeter

This is the random component of the intrinsic error of the flowmeter (The repeatability of the instrument), and is mainly due to the random variations in the flow, electronic or water properties. This will cause a random variation in the voltage output signal from the flowmeter [6, p. 529].

f_e - Errors in physical phenomena and external influence

These errors mainly originate from changes in ambient conditions and flow pattern. This will also depend on the how the flowmeter is affected of the surrounding conditions. This error component can be both random and systematic [6, p.529].

f_f - Errors in physical properties

This component arises from determination of physical quantities such as gravity and water density, either through measurements or by use of standardized data [6, p.529].

3.3.6 Total uncertainty

When all the errors are estimated, the total uncertainty for the calibration can be found through the RSS- method;

$$f_{cal} = \sqrt{f_a^2 + f_b^2 + f_c^2 + f_d^2 + f_e^2 + f_f^2} \tag{3.3.29}$$

Chapter 4

Calibration facility design

The design chapter is organized by first clarifying the arguments for the chosen calibration principle, given in section 4.1. Subsequently, the design evaluation for each of the related components are presented. This is done by initially presenting the requirements for each component given in IEC and related ISO- standards. Based on these requirements, different design suggestions is presented for each of the components in the calibration rig.

4.1 Chosen calibration method

The arguments given in this section are based on a study of the primary methods recommended by IEC, economical aspects, accuracy, discussions with technicians at the Waterpower laboratory and the available resources at the Turbine Testing Lab.

An evaluation of the moving screen method, shows that the method is based on many different components, which all have to be well- functioning to get the required calibration accuracy. The construction of a moving screen method, will require an accurate installation of all parts, and continuous maintance to obtain the required accuracy. The method is not well developed, and there is a lack of experience with the method. After correspondance with tecnicians at the Waterpower Laboratory, this method was eliminated as an alternative.

The weighing method is the most prevalent method for calibration of flow measuring devices. An advantage with the weighing method, is the experience and knowledge from the Waterpower laboratory at NTNU. A disadvantage with the method is that the accuracy in the weighing cells increases with load, which require a certain minimum of the tank capacity. This was experienced during a substitution calibration performed at the Waterpower laboratory in 2012, executed together with masterstudent Andrea Stranna.

The weighing tank at the Waterpower Laboratory has a capacity of approximately 70 tons. Due to space limitations at TTL, it can be a challenge to design a tank large enough for this purpose. Another disadvantage is the total costs: a weighing tank system is the most expensive of the three calibration method alternatives, mainly due to the costs for weighing cells and tank size [5].

The volumetric method is considered as a calibration method with accuracy on par with the weighing method. The principle is based on level measurements instead of measurements of mass, and the required equipment will probably be less expensive. As the weighing method, the volumetric method will have increased accuracy due to larger calibration volume. But a big advantage for this method,is that the accuracy will depend on the volume/area- ratio at the measuring section. By designing a small area where the level measurement is conducted, this can reduce the required tank size. Another central advantage, is that TTL already has a volumetric tank available.

According to IEC, both the weighing method and volumetric method are able to achieve an accuracy between 0,1 - 0,2 %. Since the weighing tank most likely will be a more expensive option, and TTL already has a volumetric tank available, **the chosen principle for the primary calibration at TTL is based on a volumetric method.**

For the volumetric method, IEC refers to the requirements given by ISO 8316 "‘Measurement of liquid flow in closed conduits. Method by collection of the liquid in a volumetric tank"’ [26].

4.2 Static and dynamic gauging

The principle of the volumetric calibration can be divided into static and dynamic gauging, depending on how the measurements of level and time is accomplished.

For a *static gauging*, the water is diverted into the volumetric tank for a certain time period. The filling time is measured by an accurate timer, triggered by the motion of the diverter. The level measurement is accomplished after the filling is completed, and the system have come to rest.

With a *dynamic gauging*, the timer is triggered when the water reaches an initial level $z0$, and stops when the water reaches the final level $z1$. Due to system oscillations when the water is flowing into the tank, the measuring devices must be installed in a stilling well [26].

During the design phase, a dynamic gauging design was composed. The design evaluated is illustrated in figure 4.2.1, and the measuring principle is explained below:

The draining valve is kept open until desired flowrate is obtained. Then the valve is closed, and the water level starts to rise. Two level readings are installed in a stilling well, with a calibrated distance. The filling time is triggered when the water reaches $z0$, and stops at level $z1$. Then, the water reaches the emergency weir, and the pump is slowed down to prepare for draining and next calibration point.

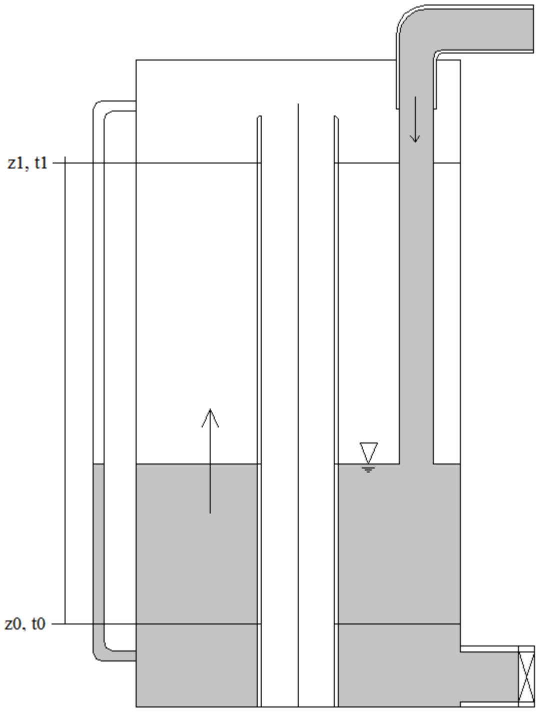

Figure 4.2.1: Dynamic gauging principle

The system described above was composed as an alternative to a deflector mechanism, and by this reduce the total costs. During a small scale test in July it was observed relatively large oscillations in the water, which will affect the accuracy in the level- and time measurements. In addition, dynamic gauging is not defined as an IEC approved calibration principle. Since TTL is working towards a laboratory according til IEC, the dynamic calibration principle is eliminated as an alternative, and the **calibration design which is described in the upcomming sections is based on a static measuring principle.**

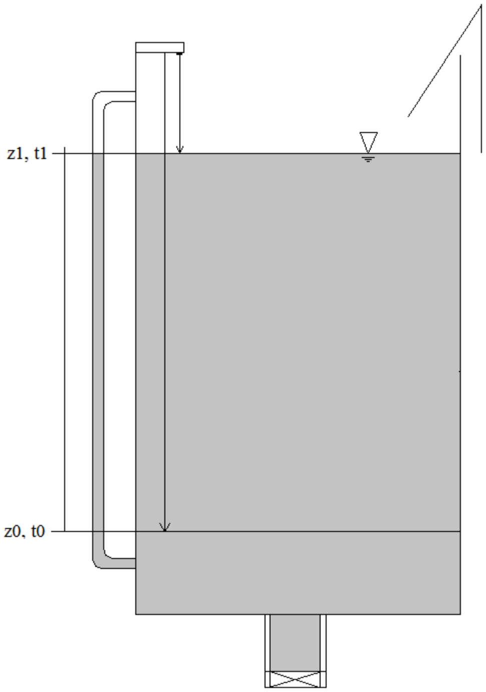

Figure 4.2.2: Static gauging principle

4.3 Volumetric tank

4.3.1 Design requirements and restrictions

The minimum capacity of the tank has to correspond to maximum flow rate multiplied with minimum filling time. The smallest filling time required by ISO 8316 for the calibration is 30 seconds [26]. By using the model turbine which will be installed in the Francis rig as basis for the design, the minimum capacity of the tank can be found: [16, p. 19];

$$V_{tank,min} = Q_{max} \cdot \Delta t_{min} = 0,3046 m^3/s \cdot 30 s = 9,126 m^3 \tag{4.3.1}$$

To add a safety margin which takes into account potensial system failure, the volumetric tank capacity should be designed with a safety factor, S_f. This is evaluated in section 4.8.1.

To increase the accuracy of the flow measurement, the ratio between the area and volume should be as large as possible. Required minimum difference in the level measurement is 1 m. The material of the tank walls must be 100 % leakage proof, and rigid enough to keep a constant shape due to different load. If the tank is burried in the ground, the effect of soil pressure must be evaluated [26].

4.3.2 Existing calibration tank

The existing tank in the laboratory, is made of concrete and has following dimensions;

$$V_{tank,ext} = 4,05 m \cdot 3,95 m \cdot 4,7 m = 75,1883 m^3 \tag{4.3.2}$$

The tank is burried in the ground of the laboratory (see figure 4.3.3), and located next to the pump room. Such a large tank capacity is a major advantage for the total accuracy in the volumetric calibration. The concrete walls consist of rough surfaces, and the tank have not been used for any purposes so far.

In spite of advantages such as a large capacity and that the tank already exist, there are several parts that need to be improved before the tank can be used for calibration purpose. The tank walls needs a large upgrading, and should be sanded down and treated with coating to ensure leakages and possible adsorption. An analysis of the wall structure and strength should be carried out to ensure that the walls can resist the water pressure. The existing tank is shown in figure 4.3.3.

Figure 4.3.3: Existing volumetric tank

The tank will be dependent of frequently maintenance and calibration to ensure an exact calibration volume. Another challenge which may be introduced by use of the existing tank, is drainage of the water between each calibration point. The tank requires an immersed pump system, which will increase the costs of the drain system. There can also be a challenge to ensure that the tank is completely empty between the calibration points, due to rough tank surfaces.

To get an accurate determination of the volume, it is suggested to install a configuration as illustrated in figure 4.3.4, whith reduced area at the level measuring section. Such a design will reduce the errors in the determination of collected volume, since a small error in the level measurement will correspond to a smaller volumetric error.

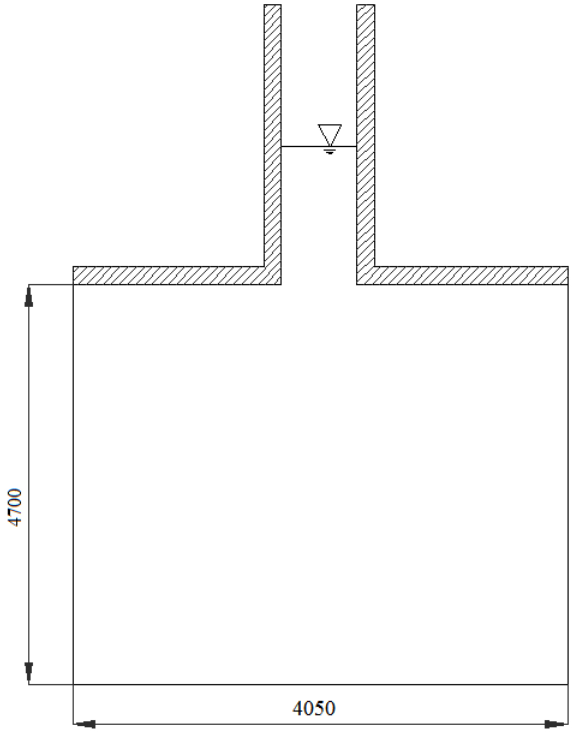

Figure 4.3.4: Existing tank configuration

4.3.3 New calibration tank

To increase the accuracy in the flow measurement, a large calibration volume is essential. At the same time, there are space limitations in the laboratory which puts restrictions on the tank design. Therefore, the maximum flowrate and minimum filling time is used as a basis for the design of the minimum tank capacity;

$$V_{tank,min} = Q_{max} \cdot \Delta t_{min} = 0,3046 m^3/s \cdot 30 s = 9,126 m^3 \tag{4.3.3}$$

Minimum tank capacity corresponds to a minimum tank level $h_{min} = 4540\ mm$. A cylindrical tank is preferred over a rectangular tank, to increase the surface area at the measuring section. The tank bottom must be constructed in such a way that the tank is totally drained during each calibration, and the walls are free of remaining water since this can disturb the volumetric calibration. The tank walls should have a thickness which reduces oscillations during the filling period. After personal conversations with the technicians at the Waterpower laboratory, suggested material thickness is set to 6 mm.

On the basis of the arguments above, suggested tank geometry for the design of a new tank is shown in figure 4.3.5:

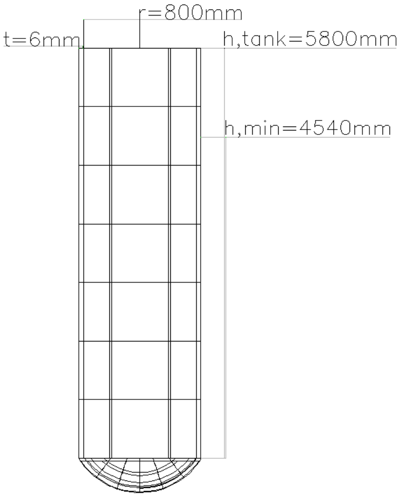

Figure 4.3.5: Volumetric tank

4.3.4 New tank location

For the location of a new tank, two different solutions are suggested (Illustrated in figure 4.3.6);

Alternative 1 is to place a new tank in the available volume in the existing tank area. This solution will utilize existing available volume in the laboratory, which makes a large calibration volume possible. The location does also open for a drain system directly linked with the pump room. A disadvantage with this location, is the slab cuts in the floor which put limitations on the tank size.

Alternative 2 is to install the tank above the main sump, which makes self draining possible. To stay within the dimensions specified in section 4.3.3, an additional pipe run should be designed above the main pipe system. Another alternative is to increase the diameter of the tank, to decrease the height. A disadvantage with this alternative, is the decrease in the area/volume- ratio. There can also be a challenge to shore up the tank.

Based on these arguments, alternative 1 is preferred as location for a new volumetric tank.

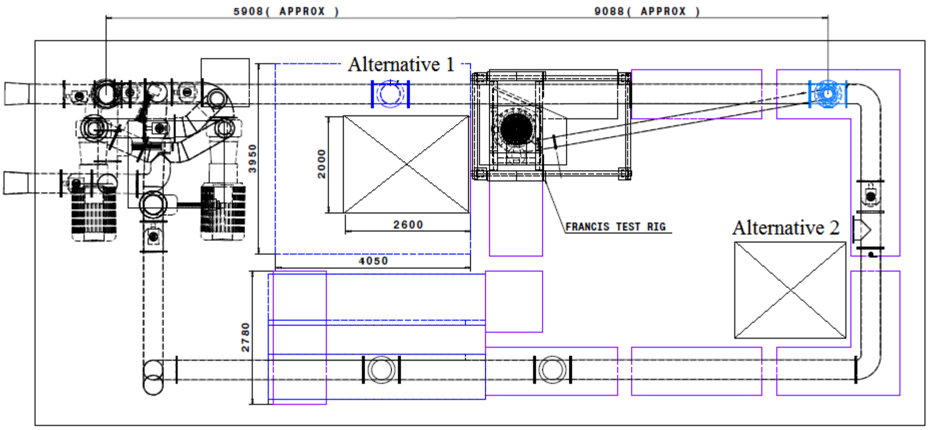

Figure 4.3.6: Alternative tank locations

4.3.5 Tank calibration

The main source of errors in the volumetric calibration method, arises during the calibration of the tank. ISO 8316 suggest two different methods to calibrate the tank [26];

Method 1, which is defined as the most accurate method, is based on weighing the water content in the tank. If the tank dimension is too large, another alternative is to divide the weighing into smaller intervals. This can be done by use of a calibrated vessel and sum up each of the volumes. Through this, a relationship between volume and level must be established.

Method 2, which is the alternative to weighing, is to calibrate the tank through accurate measurements of the tank geometry. This method requires a large number of measurements to ensure the accuracy of the tank volume.

During the calibration, it is essential to monitor the temperature in the water and surroundings. If the variations are significant, the calibration should be carried out at several temperatures or a correction for the temperature variation shall be determined. For both methods, a rating curve with the volume- level ratio should be established, with such small intervals that the final regression will not introduce significant errors [26].

4.3.6 Existing tank versus new tank design

For the tank suggestion, the existing tank and the new tank design are both reasonable alternatives for the laboratory.

The large available calibration volume in the existing tank, is a major advantage for the accuracy in the volumetric calibration. Despite of this, a main challenge for the existing tank is to ensure a leakage free system. This is decisive for the total accuracy in the calibration. Considering the high requirements set for an IEC approved primary calibration, it can be challenging to meet the requirements of the accuracy in the calibration method.

Based on the preceding arguments, the design of the calibration facility is based on a new tank design.

4.4 Level measurement

4.4.1 Design requirements

There are several different principles of measuring water level, described in detail in ISO 4373 - "'Hydrometry- Water level measuring devices"' [27]. Preferred methods are either point or hook gauges, floating gauges or other devices with similar accuracy. As mentioned, the smallest recommended change in water level is 1 m [26]. Based on ISO 4373 and recommendations from technicians at the Waterpower laboratory, the following methods are evalutated for the calibration rig:

4.4.2 Alternative level measurements

Ultrasonic level measurement

The ultrasonic measuring principle is illustrated in figure 4.4.7 and is based on measuring a "'time of flight"' - TOF, which is the time between the signal is released til it returns to the transmitter. From this measurement the distance from the transmitter to the water level can be determined.

An ultrasonic device does not require contact with the water, and therefore it does not disturb the volumetric calibration. The device can be mounted on a beam above the water surface, which makes maintenance easy. This method is used for measuring the sump level at the Waterpower Laboratory, and is recommended by the tecnicians in the lab [17]. For the calibration facility, recommended model by automatician Arve Ottem is *Sitrans Probe LU*, delivered by Siemens [24].

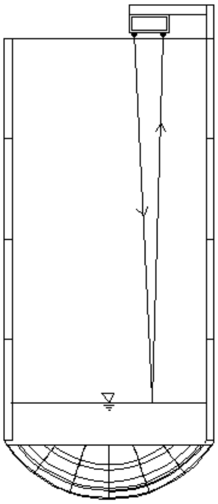

Figure 4.4.7: Ultrasonic principle

Point-/ Hook gauge

According to ISO 4373, this method of gauging is one of the most accurate level measuring devices, and is often used for laboratory setups [27, p. 7]. A disadvantage is that a point-/ hook gauge is depending on contact with the water surface. For the new tank design this can be challenging, since the level measuring range is approximately 6 meters. However, if there is available technology at the marked with this range, this instrumentation is preferred.

Radar instrument

The last evaluated level measuring equipement is a radar instrument. The technology is similar to the ultrasonic, and derives the water level through a TOF-measurement of a wave sent out of a transmitter. The instrument can be mounted on a beam above the water level, without use of a stilling well [27]. After personal correspondance with engineer V. Brathen in Hyptech, this technology is preferred over ultrasonic in case of accuracy [4].

4.4.3 Selected level instrument

Based on the preceding evaluation, ISO 4373, and personal correspondance with technicians at the Waterpower Laboratory, the radar technology is preferred due to accuracy in the equipment [4]. The technology is also easy to install and calibrate. In addition to the level measuring equipment, a stilling well should be installed at the tank wall, to keep control the tank level visually.

The level equipment must be mounted on a separate beam above the water level, to avoid disturbances from the deflection of the water.

4.5 Filling time measurement

The minimum required filling time for maximum flow rate is 30 seconds. The filling time should be measured by a highly accurate, electrical timer, connected to the deflector mechanism, and triggered (start and stop) with the motion of the deflector [26]. The timer will be placed at the "'Mid travel point/ zero line"', as illustrated in figure 4.6.8.

4.6 Deflector mechanism

4.6.1 Design requirements

A critical and essential part of the calibration rig is the deflection of the water. The mode of operation will have a significant impact on the total accuracy in the calibration. According to ISO 8316, the motion time of the deflector should be less than 0,1 seconds. There should also be established a correction equation for the filling time, and this procedure is explained in chapter 5 section 5.3.1.

4.6.2 Deflector design

After discussions with one of the technicians in the lab, Halvor Haukvik [17], a design similar to the diverter installed at NTNU is recommended for the calibration rig. The diverter is sufficiently fast, and able to cover a large range of discharges. Additional covers must be mounted around the deflector mechanism when the installation is finished, to prevent leakages and splashing during the diversion period.

All plates and covers are made of 4 mm steel plates, which can be welded together on the workshop at Kathmandu University. The needle/ diverter screen must be reinforced with double plates, 2 x 4 mm, to withstand the forces during the diversion. The main beam and support are made of 4 x 10 mm steel beams. The rotating motion is released by two pneumatic pistons, as illustrated in figure 4.6.8.

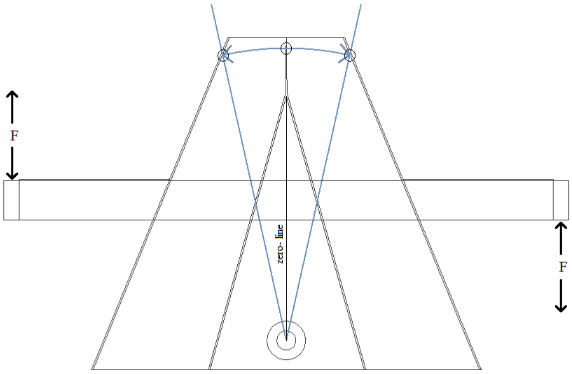

Figure 4.6.8: Deflector design

4.7 Nozzle

4.7.1 Design requirements

Before the discharge is diverted by the deflector mechanism, a nozzle must be installed. This is done to reduce the area of the flow, to simplify the deflection of the water and prevent splashing during the diversion. According to ISO 8316, recommended design of the nozzle is a length between (15- 50) x width. The pressure drop over the nozzle should not exceed 20 kPa, in order to avoid turbulence and splashing in the flow [26].

4.7.2 Nozzle design

The proposed nozzle design is illustrated in figure 4.7.9. The ratio between length and width is set to 20. The nozzle is fixed, while the water is diverted by the rotation of the needle/ diverter screen.

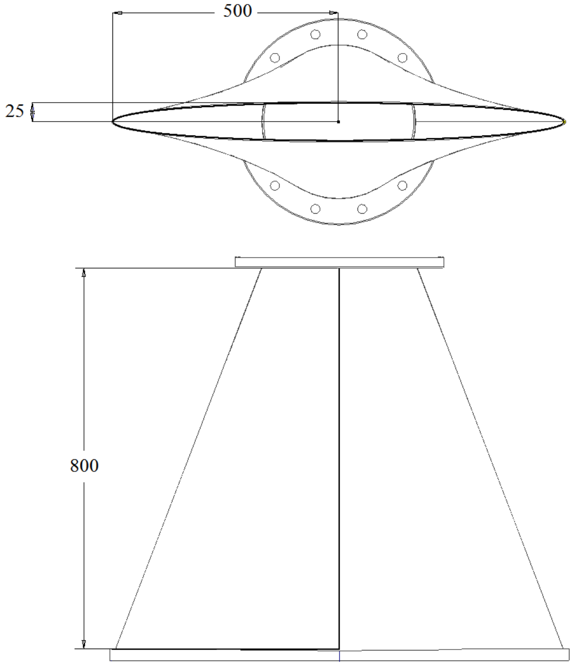

Figure 4.7.9: Inlet nozzle design

4.8 Pumps and drain system

The tank bottom has to be construced in a way that ensure a total drainage between each calibration point. An inspection of the tank wall should be carried out in before the calibration starts, to ensure that the tank walls are completely dry. The drainage pipe will be located at the lowest point in the tank, with a manually operated valve outside the tank. The drain system can be reached from the first floor by using a fixed ladder. The tank bottom corresponds to a volume of $0,86m^3$.

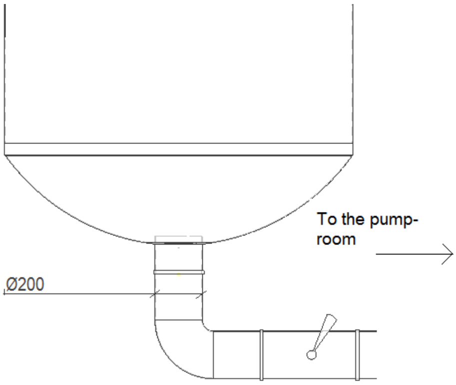

Figure 4.8.10: Drain system

With a tank location as illustrated with alternative 1 in figure 4.3.6, the outlet of the drainage pipe will be lower than the zero- sump level. This means that the water must be pumped back to the sump, by one of the following alternatives;

Alternative 1, is to install a drainage pump outside the tank, and direct the water back to the sump above the zero- level.

Alternative 2, is to connect the drainage pipe to the main loop/ pump room. This will depend on how the pumps are constructed, pipe dimensions, and where the different valves are located.

After a closer study of the pump and pipe system, one suggestion is to connect the drainage pipe with the main pump system (illustrated in figure 4.8.11). The drainage pipe from the calibration tank can be welded on at section i, on the straight pipe run between valve 1 and valve 2/3. The drainage of the tank can be carried out by first closing the main valve from the sump/valve 1, open valve 2 and 3, and then open the drain valve outside the calibration tank.

The suggestion is discussed with the technicians at the Waterpower Laboratory. If the drawings and descriptions made for the pump room are correct, this solution is fully feasible and will reduce the costs of the drainage system.

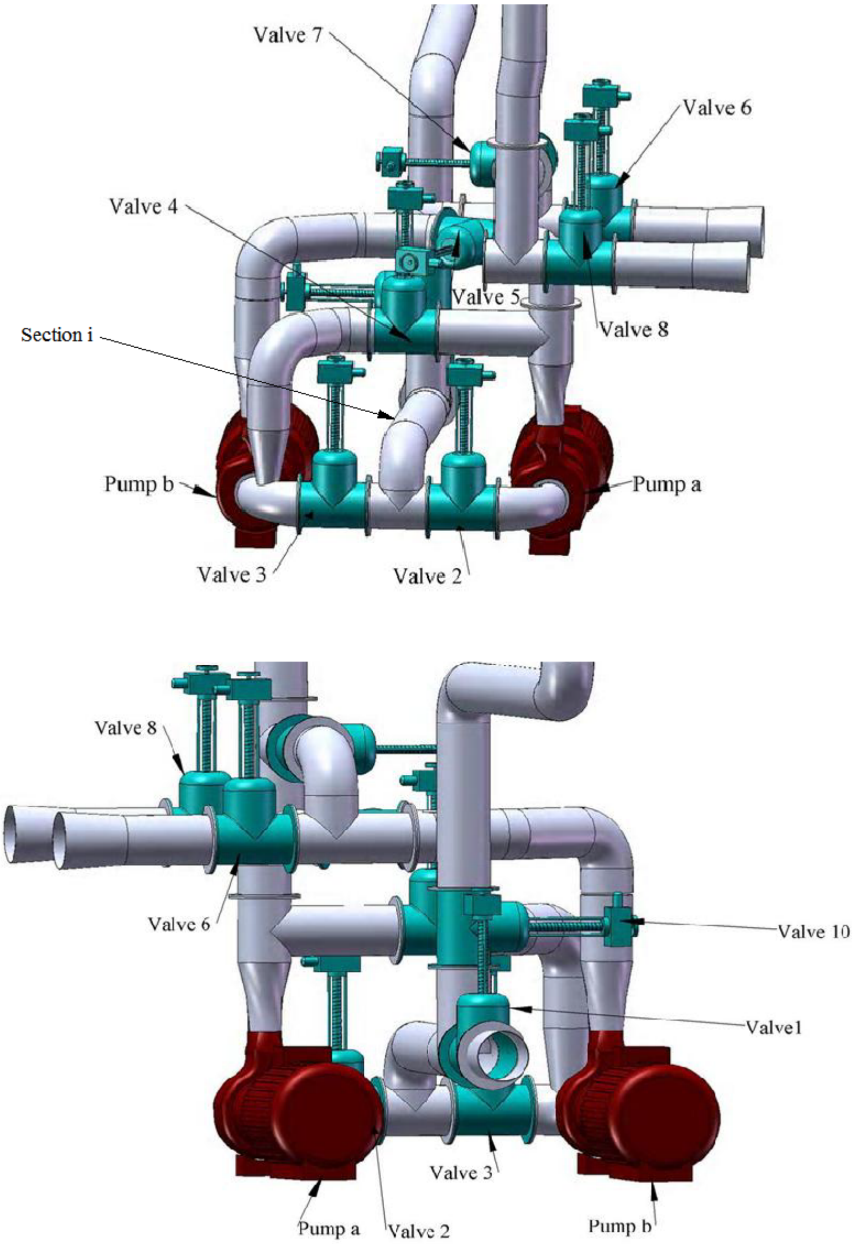

Figure 4.8.11: Pump system

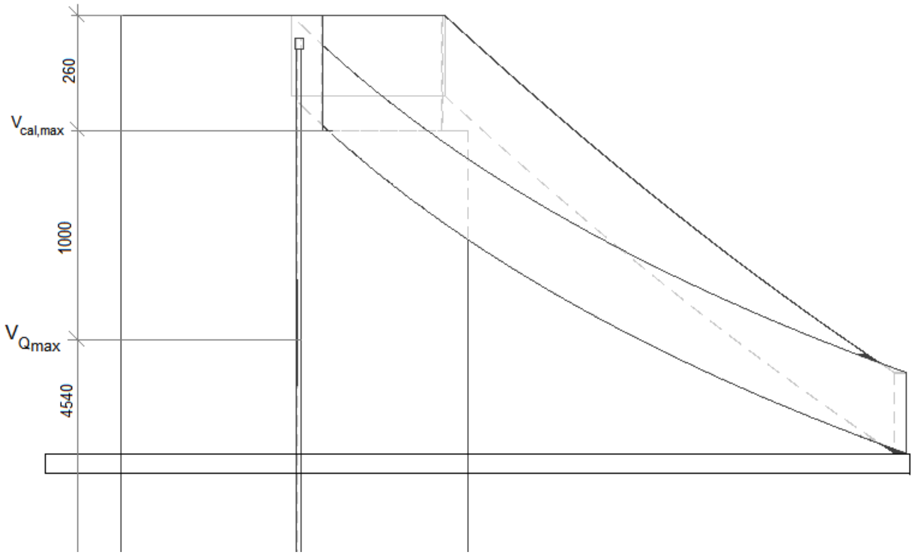

Figure 4.8.12: Gutter and emergency weir

4.8.1 Gutter and emergency weir

When the deflector mechanism diverts water away from the tank, the water is directed to the sump through a gutter. The gutter is connected to an emergency weir. If a technical failure occurs, this will secure the lab from an overflow situation. If the tank level exceeds a level of 1 meter above the maximum calibration volume, the water is directed out from the tank and in to the sump. The maximum level correspond to a maximum available calibration volume of:

$$V_{cal,max} = Q_{max} \cdot \Delta t_{min} \cdot S_f = 12m^3 \tag{4.8.4}$$

The gutter and emergency weir are not pressurized, so the configuration can be constructed to handle free water flow.

4.9 Pipe system and valves

During the calibration, water is directed from the sump through the pump system, by opening valve 1. The water is further pumped up in the main pipe system and through the flowmeter, and passes a 90 degree cascade bend. A closed valve (valve a) installed just after the t- joint, directs the water into the calibration facility. The water is flowing through a new 90 degree bend, before entering the inlet nozzle and the deflector mechanism. Finally, the water is directed in to the volumetric tank or to the sump, depending on the deflector mode.

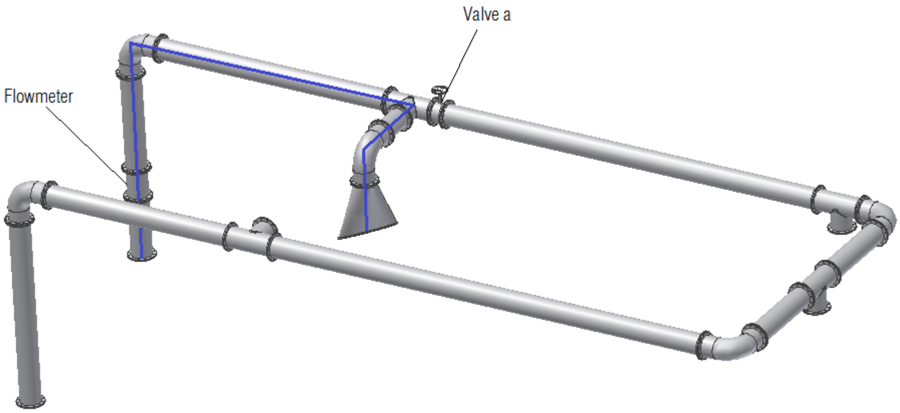

Figure 4.9.13: Pipe system

4.10 Temperature measurements

A thermal sensor should be installed at the flowmeter, and in the calibration tank. This is done to keep control with the system temperature during the calibration.

Temperature sensors suggested for the calibration rig is PT100, with corresponding data logging equipment. The sensor in the volumetric tank must be installed at the conical bottom, below the critical level z_c, to ensure that the sensor does not affect the volumetric measurement.

4.11 Flowmeter

Selection and location of flowmeter is an important factor for an accurate flow measurement. It should be mentioned that for a flowmeter which will be calibrated in situ, it is mainly the repeatability of the flowmeter that is of significance. The systematic uncertainty will by removed when the calibration is done.

Employees at the TTL have already suggested a flowmeter location in the vertical pipe, above the pump room. The proposed flow meter is MS2500, delivered by ISOIL. An alternative flowmeter is evaluated for the testing facility, to look at improvements of the measuring conditions. This flowmeter is described in section 4.11.2.

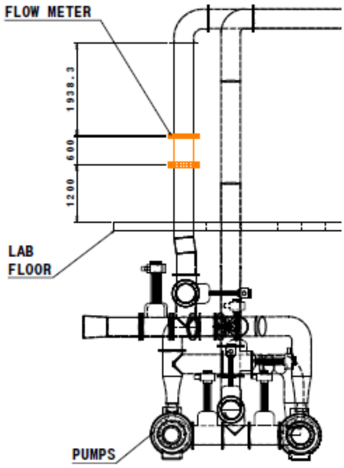

Figure 4.11.14: Pipe run at the flowmeter

4.11.1 MS2500, ISOIL

TTL has proposed the flowmeter MS2500 with a nominal diameter of 400mm, delivered by ISOIL [19]. The flowmeter is located at the vertical pipe above the pump room, with ascending flow, to ensure that the measuring section is completely filled with water.

According to technical data sheet for the MS2500- model, and personal conversations with engineers in HYPTEC [4], the location is within the installation requirements (3 x DN in front of the flowmeter and 2 x DN downstream the flowmeter). This is also guaranteed after correspondance with sales engineers in ISOIL in august [2].

Hydraulic conditions

According to the technical specifications for the flowmeter, the range of the MS2500- model is between 0-1.28 m^3/s. After conversations with technicians at the Waterpower Laboratory, a flowmeter within the same range as the actual operation area, will increase the accuracy of the measurement [15].

The design of the calibration facility is based on the Jimhruk/ Kulekhani III- model, where maximum flowrate is Q_{max}= 0,2046m^3/s. This corresponds to only 20 % of the range of the flowmeter. At small flowrates this will lead to critical low velocities at the measuring section, and increased uncertainty in the flow measurement [19].

4.11.2 Optiflux2000, Krohne

An alternative to the flowmeter suggestion by TTL, is *Optiflux2000* with a nominal diameter of 250 mm, delivered by Krohne. The flowmeter is delivered with IFC100- electronics. The reduction in diameter will increase the accuracy in the measurements due to higher velocities.

To compare *Optiflux2000* with *IFS4000* (Which is a slightly more expensive model installed at the Francis-rig at NTNU), the flowmeters are equally good as long as the medium used is water. The main difference between the two models, is that *IFS4000* is meant for industrial purposes and can handle rougher environments and mediums [10].

The *Optiflux2000*- model is covered with hard rubber instead of teflon, and the accuracy and repeatability specified by the manufacturer is 0.3 % / 0.1 %. By changing the electronics from IFC100 to IFC300, the discharge is measured with an accuracy close to 0.2 % by use of calibration values from the manufacturer [10].

Improvement of hydraulic conditions

After an evaluation of the location of the flowmeter, the short distance between the pumps and flowmeter is critical. After personal conversations with professor Ole Gunnar Dahlhaug, a minimum distance to pump disturbance is 20 x DN[9]. A suggestion for improving the hydraulic conditions at the flowmeter is therefore evaluated, and the suggested improvenment is illustrated in figure 4.11.16:

A decrease in diameter from 400 mm to 250 mm, will lead to higher velocities through the flowmeter, and thus better measuring conditions.

A flow straightner is implemented just above the pump outlet, at section 1. The suggested flow straightner, consists of small pipes with pipe diameter of 57 mm, welded together inside a DN400− pipe (Illustrated in figure 4.11.15). The purpose of this configuration, is to improve the flow profile through the flowmeter.

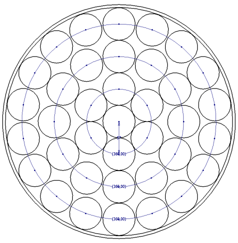

Figure 4.11.15: Cross section of the flow straightner

At section 2, there will be installed a pipe contraction which will increase the velocity of the water through the flowmeter. The contraction angle is set to 2 x 4,29 °, within the required maximum angle (< 30 °) [9].

The expansion angle at section 3 is set to 2 x 2,96°, which is within the required limits for expansion angle (< 6 °) [9]. The existing cascade bend at section 4, will improve the flow conditions through the bend.

This design will correspond to a straight pipe run in front of the flowmeter of approximately 8 x DN, and a straigt outlet run of 6.8 x DN. This is a great improvement of the flow conditions at the flowmeter, compared to the conditions for the MS2500- model with diameter of 400 mm.

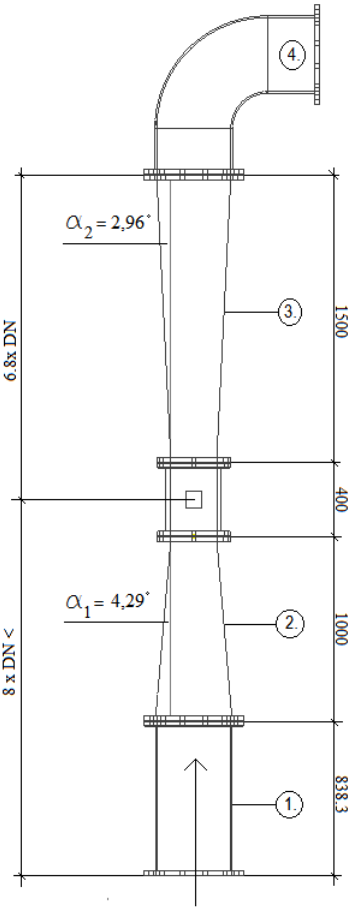

Figure 4.11.16: Flowmeter conditions

Chapter 5

Evaluation of accuracy

This chapter goes through a step by step- evaluation of the error contributors and corresponding uncertainties that can occur during a volumetric calibration. When the final calibration facility is installed at TTL, this evaluation can be used as a basis to calculate and determine the total uncertainty in the volumetric calibration method.

5.1 Accuracy in the volumetric method

The uncertainty calculation shall be carried out in accordance to ISO 5168 - "Measurement of fluid flow- procedures for the evaluation of uncertainties" [8]. With a correct installation, calibration procedure and maintenance, an accuracy between ± 0,1 - 0,2 % is reachable for the volumetric method [26, p. 2]. The uncertainties evaluated in this chapter, are all given with a 95 % confidence level.

5.2 Requirements

To obtain as accurate flow measurements as possible with the volumetric calibration, the following terms must be fulfilled for the calibration facility[26, 4.2.2]:

1. Ensure a leakage free system.
2. Ensure a completely filled pipe at the measuring section (No air in the system).
3. No unwanted flow into the tank, deformation or absorption of the volumetric tank walls.

4. The level- volume relation is obtained by one of the calibration methods described in section 4.3.5.
5. Required accuracy of level- and time measurements is reached.
6. The travel time of the deflector is short compared to the total filling time.
7. The water temperature is constant through the calibration system, or corrected for when calculating collected volume.

5.3 Error contributors during calibration

For a volumetric calibration of the flowmeter, the error contributors from the calibration can be divided into the following terms [6, p. 345]:

Component errors	
f_a	Systematic errors, volumetric calibration method
f_b	Random errors, volumetric calibration method
f_c	Systematic errors, flowmeter
f_d	Random errors, flowmeter
f_e	Errors in physical phenomena and external influence
f_f	Errors in physical properties

Each term will be evaluated step by step in the next sections.

5.3.1 f_a - Systematic errors, volumetric method

The main source of systematic errors in the volumetric calibration method originates from the volumetric tank and its calibration, the level measurement, operation and motion of the deflector mechanism, and the filling time measurement [6, p. 527].

To reach a total uncertainty less than ± 0,2 %, each systematic component error in the volumetric method should not exceed ± 0,05 % [26, p. 9].

Volumetric tank

For the volumetric tank, the main error contributors occur during the tank calibration, and establishment of the level- volume relation. This is due to temperature variations during the tank calibration, and error introduced due to an assumption of a linear relation between level and volume [26, p. 9].

According to ISO 8316, it can be assumed that the error varies in a random manner from V1 to V0, and the error in the determination of ΔV = V1-V0, will contribute with a total relative systematic error of [26, p. 9];

$$(f_{\Delta V})_s = \frac{\sqrt{2} \cdot (e_{\Delta V})_s}{\Delta V} \tag{5.3.1}$$

$(e_{\Delta V})_s$ corresponds to the total absolute systematic error in the determination of the calibration volume.

Level measurement

The systematic error from the level measurement is depending on the quality of the level gauge. Similar to the volume determination, ISO 8316 assumes that the uncertainty will vary in a random manner from one level to another with a factor of $\sqrt{2}$. The corresponding uncertainty in the level measurement Δ Z = Z1 - Z0 can be found through equation 5.3.2 [26]:

$$(f_{\Delta z})_s = \frac{\sqrt{2} \cdot (e_{\Delta z})_s}{\Delta V} \cdot \frac{\delta V}{\delta z} \tag{5.3.2}$$

The derivative term takes into account the change in volume due to variation in level, and is related to the area-volume ratio of the tank geometry. The term $(e_{\Delta z})_s$ corresponds to the absolute systematic error in the level gauging instrument.

Timing device

The timer is triggered by the motion of the deflector mechanism. If the timer is of high quality with a resolution $<$ 0,01 % of the deflection time, this error is assumed as negligible as long as the absolute error is less than 0,1 mS [26, p. 9].

$$(f_{\Delta t})_s = \frac{(e_{\Delta t})s}{\Delta t} \tag{5.3.3}$$

Deflector mechanism

The water is diverted into the volumetric tank by a deflector mechanism. The timer is started when the diverter is between *a* and *b*, and stopped between *c* and *d* (Illustrated in figure 5.3.1). Since an instantaneous diverter motion is impossible, a small amount of water will be directed into the tank outside the measured filling time [1, p. 69]. This will contribute to a timing error caused by the deflector motion, $(f_{deflector})_s$.

The error will depend on the flow rate, deflector design, the relative velocity of the diverter, and the location of the timer. According to ISO 8316, experience shows that this error generally lies within 0-10 mS, and can be considered as negligible. But before the error can be treated as negligible, the error must be estimated

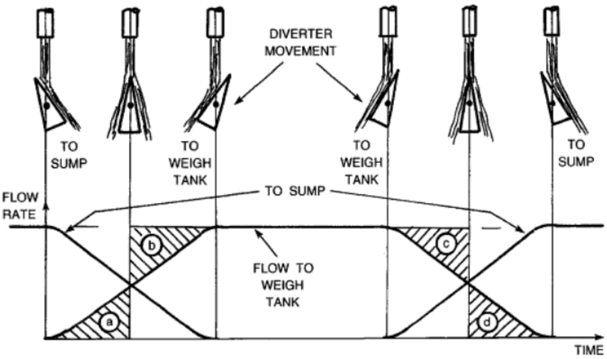

Figure 5.3.1: Motion of the diverter [1, p. 71]

through an experimental analysis of the motion of the deflector mechanism [26, Annex A]. In the suggested method described below, the error is treated as an error in filling time:

Method to determine the filling time- correction

The described method is given in Annex A, ISO 8316:

Similar to the normal calibration procedure, a steady flow rate is established for a certain operation point. The volumetric tank is filled in short intervals, without resetting the timer. By summing up the volume and time intervals, the total sum can be found. In addition to this total- sum estimation, a second standard determination is done before and after the total- sum estimation. In the end the preceding results are compared. If the results shows to be of approximately same value, the following equation can be used to find a correction term for the filling time at different operation points [26, Annex A]:

$$\frac{\Delta t_{cor}}{t} = \frac{1}{n-1}\left[\frac{q}{q`}\frac{\sum_1^n \Delta V_i / \sum_1^n t_i}{(V_1 - V_0)/t} - 1\right] \tag{5.3.4}$$

(V_1-V_0)/t corresponds to the normal procedure to calculate the flowrate during the calibration.

$\sum_1^n \Delta V_i / \sum_1^n t_i$ is the flow rate determined from the sum- total volume and sum-total time for n deflections [26, Annex A].

The main object with the correction estimation is to determine a correction for the error in Δt, which later can be used to correct for the error in the motion of the diverter. Through this, the systematic error can be removed from the total error calculation [26].

$$(f_{deflector})_s = \frac{\Delta t_{cor}}{\Delta t} \tag{5.3.5}$$

Total relative systematic uncertainty in the volumetric method:

$$f_a = \sqrt{(f_{\Delta V})_s^2 + (f_{\Delta z})_s^2 + (f_{deflector})_s^2} \tag{5.3.6}$$

5.3.2 f_b - Random errors, volumetric method

To reach a total calibration accuracy of ±0,2 %, each random error component in the volumetric method must not exceed ±0,1 %. The random errors in the volumetric method mainly arises in the determination of the collected volume (The random uncertainty in the level measurement is included in this term), and in the motion of the deflector mechanism [26]:

Errors due to level/volume determination

The random errors due to collected volume are usually dependent on flowrate. Similar to the systematic error in section 5.3.1, the error component shall be multiplied with $\sqrt{2}$, since the collected volume is a combination of two seperate level measurements.

An expression for this component error can be found by calculating the standard deviation, S_R, of the calibration points around the regression curve for the tank calibration [26, p. 10]. The scatter around the curve can be treated as t- distributed, and the standard deviation can be calculated by the following equation [22, p. 401]:

$$S_R = \sqrt{\frac{S_{yy} - b \cdot S_{xy}}{n-2}} \tag{5.3.7}$$

S_{yy} and S_{xy} for the tank calibration curve, can be determined through the equations given in chapter 3, section 3.3.4. The term b in the equation, corresponds to the calibration constant found during the tank calibration, $y = ax + b$.

As an estimation of the absolute random uncertainty, a 95 % confidence interval can be found:

$$(e_{\Delta V})_r = \frac{t \cdot S_R}{\sqrt{n}} \tag{5.3.8}$$

the student- t factor is found in A.1.

An expression of the relative random uncertainty due to volume/level- measurements is given as:

$$(f_{\Delta V})_r = \sqrt{2}\frac{(e_{\Delta V})_r}{\Delta V} \tag{5.3.9}$$

Deflector mechanism

Similar to the systematic error for the deflector mechanism, this error is found through experimental methods. A summary of the method suggested by ISO 8316 is described beneath [26, p. 10];

Establish a steady flow rate, and repeat the diversion in series of 10. A 95 % confidence limit shall be found for each diversion series by calculation of the standard deviation S_x (The formula for the standard deviation can be found in section 3.3.3). The confidence level will correspond to the random variation in the deflector motion.

It is recommended to inspect several operation points, as the uncertainty can vary with flow rate [26]. For a well designed system, the random error will decrease with increasing diversion periods, as illustrated in figure 5.3.2:

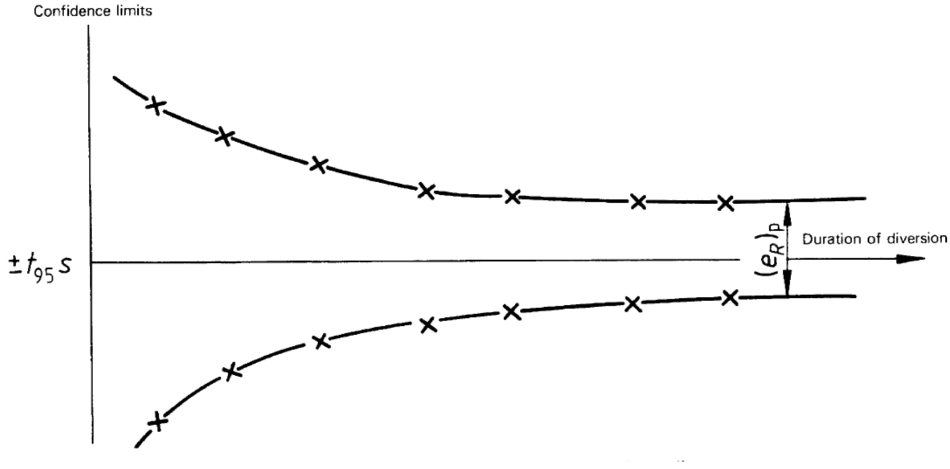

Figure 5.3.2: Evaluation of random errors in the deflector motion [26].

$$(e_{deflector})_r = \frac{t \cdot S_x}{\sqrt{n}} \tag{5.3.10}$$

and the relative random uncertainty can be derived through:

$$(f_{deflector})_r = \frac{(e_{deflector})_r}{\Delta t} \tag{5.3.11}$$

Total relative random uncertainty in the volumetric method

$$f_b = \sqrt{(f_{\Delta V})_r^2 + (f_{deflector})_r^2} \tag{5.3.12}$$

5.3.3 f_c - Systematic errors, flowmeter

The main purpose of a primary calibration of the secondary instrument (conducted *in situ*), is to remove the systematic uncertainty in the flowmeter output signal.

In the same way as the tank calibration introduces an error due to the curve-fitting, this will occur for the main calibration curve. This error is defined as the regression error:

Regression error

Similar to the curve fitting from the tank calibration, an error will be introduced when assuming a linear relation between the voltage value and the calculated flowrate. This uncertainty can either be evaluated in accordance to the method in ISO 7066 [7], or by use of an estimated value given in IEC [6, p.349]. Estimated value given by IEC for the regression error is;

$f_{regression}$ =±0,05%

5.3.4 f_d - Random errors, flowmeter

The random errors in the voltage output from the flowmeter, arises due to small variations in the electronics, flow pattern or variable water properties. During a measurement, this voltage value can be treated as normal distributed as long as the number of samples is close to infinity. In other words, by increasing the sample rate and filling time when the calibrating, the random error in the voltage signal can be neglected.

Assuming that the series of measurement is normal distributed, an estimation of the random uncertainty can be found from calculation of the standard deviation, and a 95 % confidence interval around the mean can be determined:

$$S_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{5.3.13}$$

$$(e_{voltage})_r = \frac{1,96 \cdot S_x}{\sqrt{n}} \tag{5.3.14}$$

Expressed as relative random uncertainty:

$$(f_{flowmeter})_r = \frac{e_{voltage}}{V_{avr}} \tag{5.3.15}$$

5.3.5 f_e - Error in physical phenomena/influence quantities

This uncertainty contribution appears as both random and systematic, and is mainly dependent on the following factors [6]:

- How the flowmeter is affected by variations in the physical properties of water such as temperature, density, pressure and viscosity.
- How the flowmeter is affected by influences from the surroundings.
- How the flowmeter is affected by fluctuations and unsteadiness in the flow.

After personal correspondence with Krohne [10] and ISOIL [2], both of the flowmeters are independent of changes in the water properties.

For the flowmeter location at TTL, the proximity to the pump room can lead to fluctuations and unsteadiness in the flow through the flowmeter. Such unstable flow conditions, can contribute to an error in the flow measurement.

The proposed design and improvement of the pipe run at the flowmeter (See figure 4.11.16), can reduce potential error contributors due to unstable conditions at the flowmeter.

The flow straightener is installed to improve the flow profile through the flowmeter. The pipe- construction upstream the flowmeter, will increase the velocity through the flowmeter. This can improve the flow conditions, as long as the reduction angle is less than totally 30°. The expansion angle downstream the flowmeter, must not exceed 6°. The change in flow diameter from 400 mm to 250 mm, in combination with the proposed pipe run, will increase the upstream straight run from 3xDN to 8xDN.

The improvements mentioned here, can reduce the errors due to unstable flow conditions.

5.3.6 f_f - Error in physical quantities

For a volumetric calibration, the collected volume is obtained directly through level measurements and a corresponding volume-level relation found during the tank calibration. As a result of this, the error due to density calcualtions, will not affect the calibration in the same manner as for the weighing method (Where the density is used to calculate the flowrate).

Errors due to temperature variations

Water is often referred to as incompressible, because of the minimal density variations due to changing water temperature. Yet, since volumetric calibration is based on accurate measurements of level and volume, this is evaluated to prevent errors related to temperature changes.

A thermal sensor is installed both at the flowmeter and in the volumetric tank. A variation in temperature between the two measurements will introduce a small error in the calibration curve, as illustrated in figure 5.3.3.

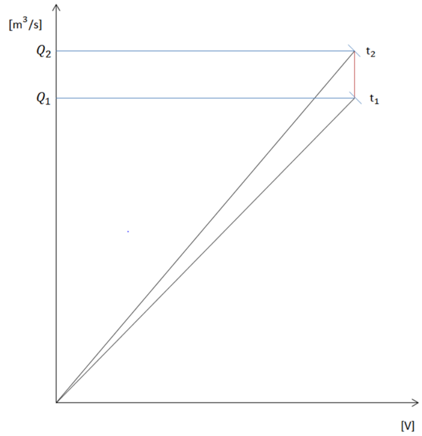

Figure 5.3.3: Temperature error during calibration

If this temperature deviation is significant, the corresponding deviation in volume due to density changes shall be corrected for [26, p. 3]. A correction equation can be derived through equation 5.3.16[12], and solve for V_0:

$$\beta = -\frac{1}{\rho} \cdot \left(\frac{\delta\rho}{\delta T}\right)_p = \frac{1}{V_0} \cdot \left(\frac{\delta V}{\delta T}\right)_p \tag{5.3.16}$$

$$V_0 = \frac{V}{(1 + \beta \cdot \Delta T)} \tag{5.3.17}$$

β is the thermal expansion coefficient, and can be found in tables for thermal properties of water. Since β varies with temperature, each temperature step have to be calculated and summed up.

It should be mentioned that by introducing β, this introduces a systematic error that may should be evaluated.

During the tank calibration and establishment of the level-volume relation, temperature deviations can introduce errors which must be taken into account and corrected for.

During the main calibration a temperature deviation between the flowmeter and tank is assumed as negligible, provided that the level measurement is accomplished immediately after the system has come to rest.

5.4 Total uncertainty in the calibration

The total uncertainty in the calibration (At a 95 % confidence level) can be derived by combining each of the terms evaluated (From section 5.3.1 - 5.3.6) by the RSS-method:

$$f_{cal} = \sqrt{(f_a)^2 + (f_b)^2 + (f_c)^2 + (f_d)^2 + (f_e)^2 + (f_f)^2} \tag{5.4.18}$$

$$f_{cal} = \sqrt{(f_{\Delta V})_s^2 + (f_{\Delta z})_s^2 + (f_{def})_s^2 + (f_V)_r^2 + (f_{def})_r^2 + (f_{reg})^2 + (f_e)^2 + (f_f)^2} \tag{5.4.19}$$

Chapter 6

Data acquisition and software

The collected data from the calibration have to be processed and treated in a systematic and reasonable way, in order to obtain the final calibration curve. This chapter goes through suggested procedure, signal conditioning and software for the calibration.

6.1 Data processing

The main objective with the calibration, is to determine a linear relation between voltage output from the flowmeter, and the calculated flowrate. This relation is found by a linear regression method (As explained in chapter 3, sec 3.3.4). The x-value input for the regression is the mean voltage value from the flowmeter V_{avr}, while the corresponding y-value input is the calculated flowrate, Q_{cal}.

To derive the calculated flowrate Q_{cal},the filling time Δ t and level measurements z0 and z1, have to be registered. The corresponding volume is found from the linear level-volume relation from the tank calibration.

System temperatures should be measured in the volumetric tank θ_{tank}, and at the flowmeter ($\theta_{flowmeter}$), to control the temperature during the calibration process. If any significant deviation exists, this shall be corrected for when deriving the collected volume.

Measurements for level, filling time, and system temperatures is registered manually, and processed in the suggested "Calibration sheet 1", given in appendix A.5.

The output signal from the flowmeter is the only value treated in LabView (Explained in section 6.4). The output signal is logged continuously during the filling time, to remove the random variation in the voltage values. The voltage signals are averaged, and the mean voltage value is used for the linear regression is V_{avr}.

6.2 Procedure

The calibration is conducted for the entire operation range of the runner, from 0-300 l/s with steps of 20 l/s. To increase the accuracy in the calibration curve, the intervals can be increased at small and large flowrates. Shortest filling time at maximum flow rate is 30 seconds, according to the requirements given by ISO 8316 [26]. The rest of the calibration points have a filling time which corresponds to maximum volume, to utilize available calibration capacity. A suggestion for calibration intervals is given in appendix A.5, "Calibration sheet 2".

The principle of the calibration, is to fill the calibrated tank, in a measured time interval Δt. By level measurements accomplished before and after filling, z0 and z1, the calibration volume ΔV is found through the level-volume relation curve from the tank calibration. When the collected volume ΔV and filling time Δt is determined, the corresponding flowrate can be calculated.

If any significant temperature deviation occur during the calibration, equation 5.3.17 can be used to determine the corrected volume V_{cor}.

Before the calibration starts, ensure that the water level is above the critical level, z_c. The critical level, is the lowest level the tank is calibrated for. Do also make sure that the tank walls are completely dry, with no remaining liquid disturbing the calibrated volume.

When this is clear, level measurement z0 can be registered. When desired flowrate is obtained by regulating the rotational speed of the pumps, the next step in the calibration is to start the filling by releasing the deflector.

The logging of the voltage signal from the flowmeter, is started immediately after the deflector is released, to avoid disturbances in the flow caused by the deflector motion. Similar, the logging is stopped just before the deflector hits back.

For the filling time measurement, the timer is triggered by the motion of the deflector mechanism.

When the water level is stable, perform level measurement $z1$ immediately, to reduce any temperature errors. The temperature in the tank and at the flowmeter should be measured before, during and after the calibration.

A detailed calibration procedure is given in A.4.

6.3 Signal conditioning

The signal from the flowmeter is amplified and filtered, resulting in a standard output ampere signal between 4-20 mA. Before the signal is sent to the computer, the signal has to be converted into a digital value. This is done by the signal converter. The computer receives a voltage signal between 1-10 V, varying with the flowrate. A labview- program (Given in appendix A.6) is processing the voltage values, and saving the values to a text file.

The random uncertainty calculation of the voltage signals, is implemented in the labview- program. By increasing the number of samples against infinity, the random uncertainty is neglected in the total uncertainty calculation.

The random uncertainty calculation implemented in labview are given in equation 6.3.1

$$f_{voltage}[\%] = \frac{e_{voltage}}{V_{avr}} = \frac{1,96 \cdot S_{voltage}}{\sqrt{n}} \cdot \frac{1}{V_{avr}} \cdot 100 \tag{6.3.1}$$

$S_{voltage}$ is the standard deviation of a logging period with n samples:

$$S_{voltage} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}} \tag{6.3.2}$$

6.4 Software

In order to collect the voltage signals from the flowmeter, LabView is suggested as software. LabView is able to collect several input signals, and process a large amount of data. The Labview program/block-diagram is given in appendix 5, and in electronic version. Front panel of the calibration program is given in appendix 6, and the method of use is explained below:

The file path is specified in window 1.1 (Appendix A.7), together with input channel for the incoming data from the flowmeter. In addition to this, the number of samples and sampling rate are specified here.

Old calibration values can be specified in window 1.2 (Appendix A.7), to set up an estimation of the flowrate during the calibration.

The main calibration is carried out in window 1.3 (Appendix A.7), and by pushing "'Start logging"', the program will start to log the output voltage signal from the flowmeter. When "'Stop logging"' is pushed, the program stop the logging process and save the voltage signals in the file specified in window 1.1. To prepare for a new calibration point, push "'Clear graph"' and stop the program.

Chapter 7

Price estimation

7.1 Component prices

7.1.1 Volumetric tank

Nepal Hydro Electric which is a local company located in Butwal, can deliver a cylindrical tank in stainless steel according to the design specifications. The price is an approximation given by NHE in August 2013.

Description	**Dimension**	**Price**
Cylindrical tank	6000mmx1600mmx6mm	2.000.000 NPR/113.000 NOK
Tank fundament		7.000 NOK
Total		**120.000 NOK**

7.1.2 Flowmeter

Based on personal correspondence with sales engineer Jens Ole Ekenes in Krohne in August. The price specificed in the offer (Attached in the appendix) is based on IFS100-electronic. The costs for the IFS300 is included below.

Description	**Quantity**	**Price**
Krohne,Optiflux2100 compact	1	33.740NOK
IFS300 amilifier	1	5000 NOK
Total		**38.740 NOK**

7.1.3 Drain system

The material costs for the drain system, are based on estimations given by Ahlsell in september 2013.

Description	**Quantity**	**Price**
DN200 3m Pipe run	970NOK/m	2910NOK
200mm, 90bend	1	1050NOK
200mm Valve	1	3000NOK
Total		**6960** NOK

7.1.4 Strengthening beams and support

The steel price is based on estimations given by Smith AS, in september 2013.

Description	**Dimension**	**Price**
Rectangular profiles,12m	150x100x(5mm)	4200NOK
Total		**4200** NOK

7.1.5 Deflector mechanism

The price estimation for the deflector mechanism is based on the total price for the diverter installed at the Waterpower Laboratory at NTNU. The estimation is mainly given by head engineer Baard Brandastro in september 2013. The steel components can be welded together at the workshop at Kathmandu University, such that the only costs here will be the material costs.

Description	**Quantity**	**Price**
Material costs (Steel)		5000 NOK
Pneumatic piston system		30.000 NOK
Total		**35.000 NOK** NOK

7.1.6 Level device

Costs for the radar technology is based on a price estimation given by Vegard Brathen in Hyptec [4].

Description	**Quantity**	**Price**
Vegapuls WL61, IP68, 15m span	1	12.000NOK
Total		**12.000** NOK

7.1.7 Thermal sensors

Description	**Quantity**	**Price**
PT100 resistor element	2	2000 NOK
Total		**2000 NOK**

Chapter 8

Results

8.1 Chosen method

For a model test according to the requirements given by IEC 60193, the secondary device used to measure the discharge should be calibrated *in situ* against one of the following primary methods; Weighing method, Volumetric method or Moving-screen method. The calibration facility design at Turbine Testing Lab, is based on the volumetric method.

8.2 Design

Assembly of suggested design for the calibration rig, is given in figure 8.2.1. From the pump outlet the water is directed through a vertical pipe of DN400, where the flowmeter is installed. Further the water flows through a 90 degree cascade bend, and is directed into the calibration facility by a t-valve.

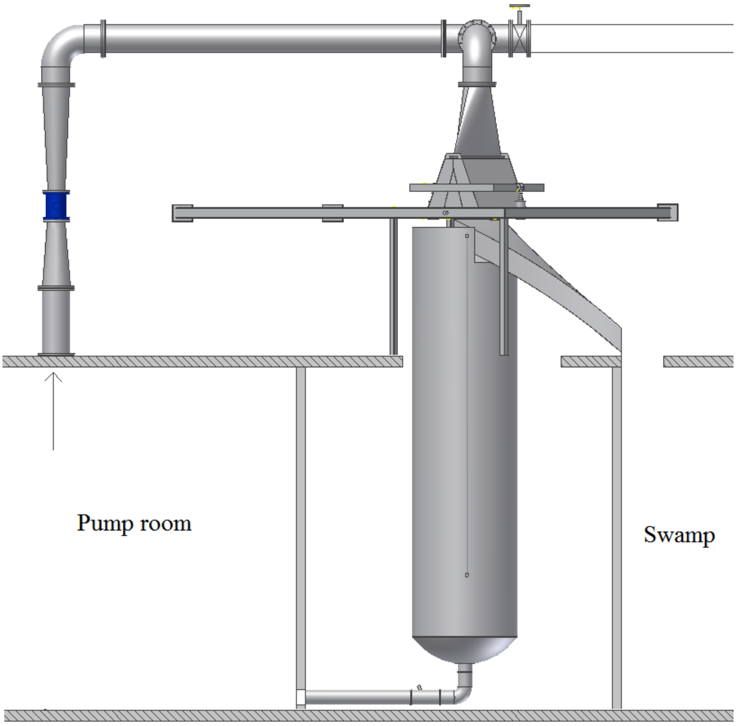

Figure 8.2.1: Volumetric calibration rig

A nozzle is installed in front of the deflector mechanism, with a length equal to 20 times the width of the nozzle.

Design of the deflector is based on the same design as the diverter installed at the Waterpower Laboratory at NTNU. The deflector motion is actuated by two pneumatic pistons, which by rotating around the center shaft deflects the water. The filling time Δt is measured with an electrical timer, located at the mid- position of the deflector and triggered by the motion of the deflector.

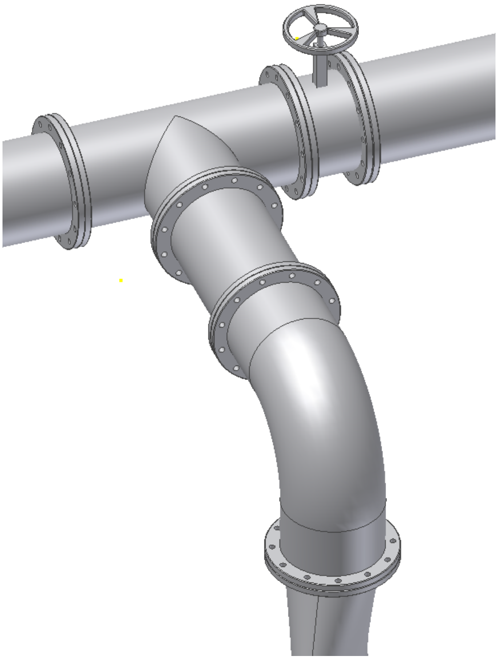

Figure 8.2.2: T- joint, valve and pipe system

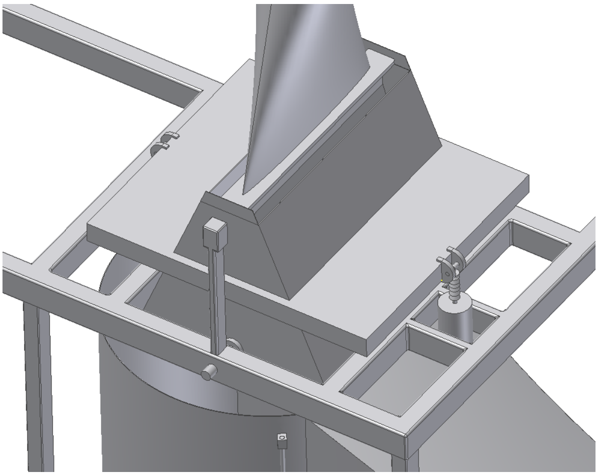

Figure 8.2.3: Deflector mechanism

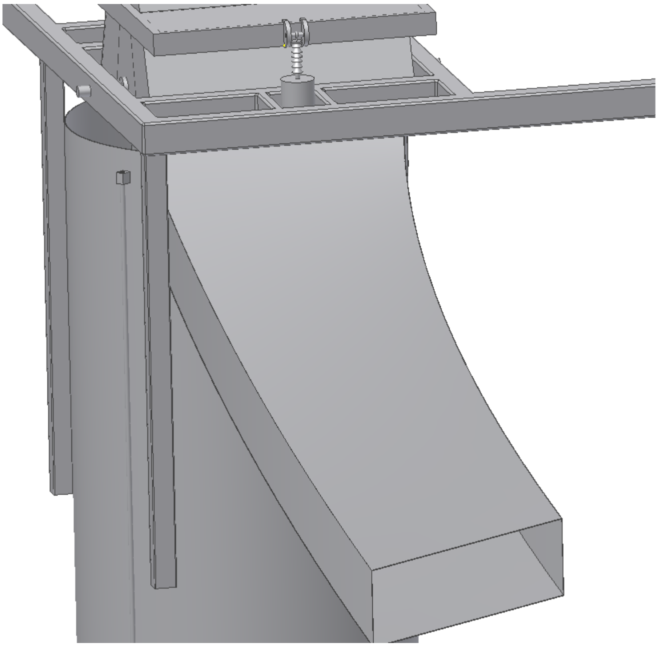

Figure 8.2.4: Tank and gutter-/emergency weir system

The flow is directed by the deflector mechanism into a volumetric tank. This tank design is cylindrical, with a maximum volume capacity of V = Q_{max} x Δt_{min} x S_f = 12 m^3. When the water reaches a level 1 meter above the maximum calibration level, it flows over a weir combined with the gutter and down in the sump.

To determine the calibration volume ΔV, two level measurements are accomplished by radar technology. One level measurement is carried out before the filling (z0), and one after (z1). The radar instrument (Vegapuls WL61) is mounted on a beam above the tank. To ensure loss and gain of water during the deflection period, additional rubber covers are installed over the tank.

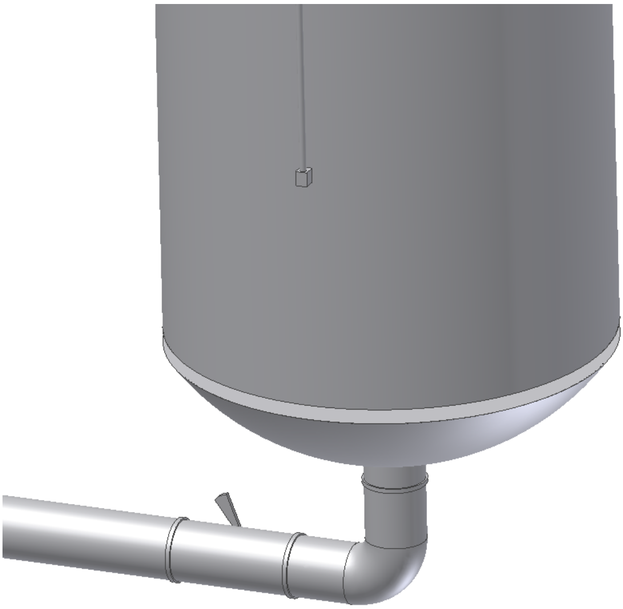

Figure 8.2.5: Drain system

The drainage system consists of a drain pipe of 200 mm with a manually operated valve, and the system is connected to the pump room. Drainage of the volumetric tank is conducted by closing valve 1 from the pump room, opening valve 2 and 3, and then open the drain valve. The drained water is pumped through the calibration system, and back to the sump through the gutter.

An overview of the calibration facility is shown in figure 8.2.6 and 8.2.7. The CAD-model is given as electronic version.

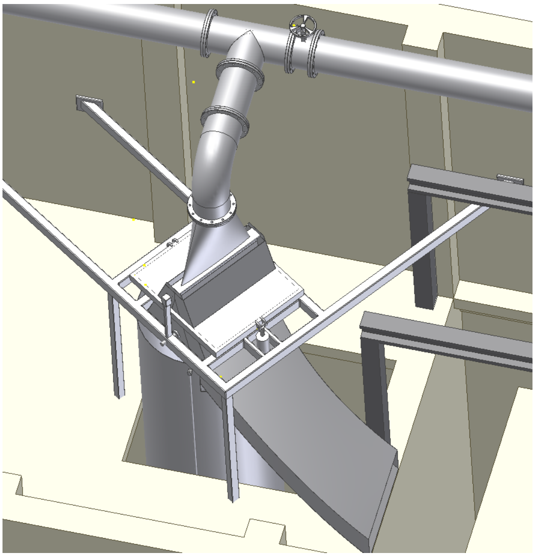

Figure 8.2.6: Calibration facility design

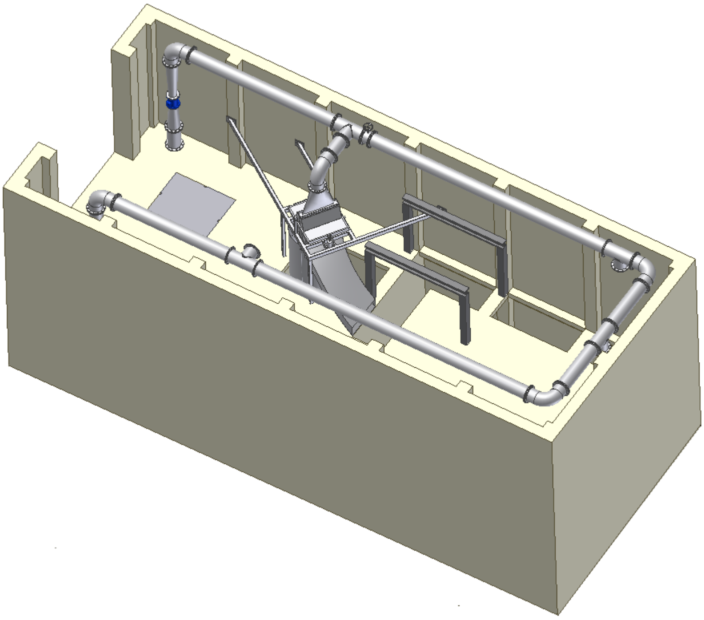

Figure 8.2.7: Overview of installed calibration facility

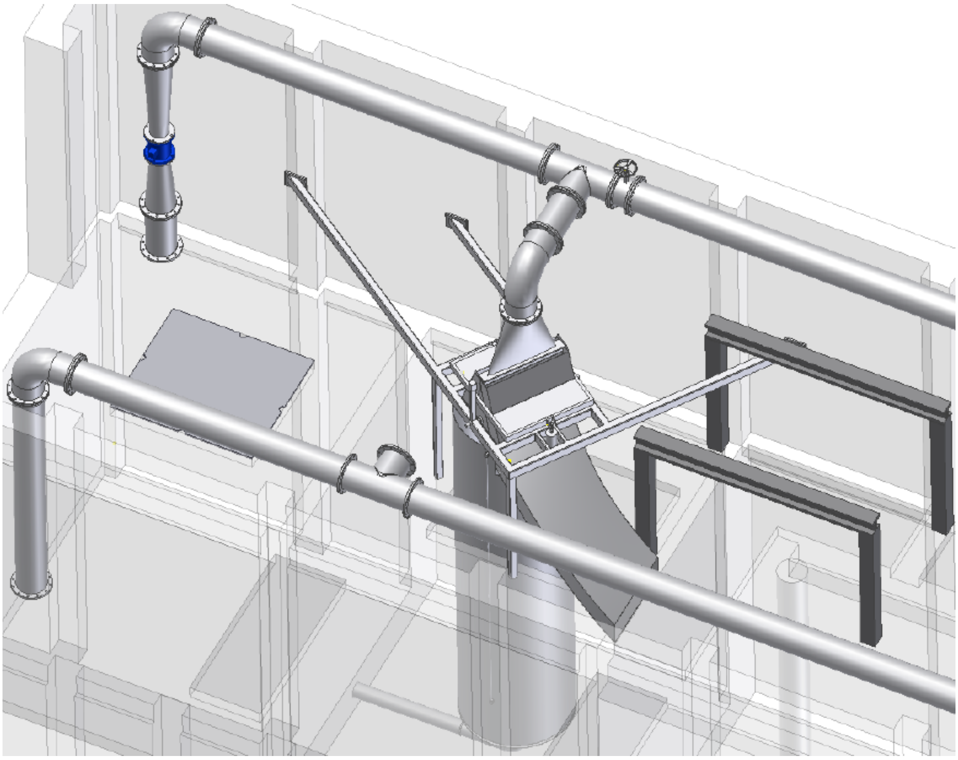

Figure 8.2.8: Final facility design

8.3 Location and suggested flowmeter

The location is kept as the original plan given by TTL: In the vertical pipe above the pump room, with ascending flow through the flowmeter.

Reduction in diameter is recommended from the original DN400 to DN250. New suggested flowmeter is *Optiflux2000* with *IFS300*- electronics, delivered by *Krohne*.

A flow straightener is installed at section 1, with pipe diameter of 400 mm. The flow straightner consist of 37 small pipes welded together, each with diameter of 57 mm.

Upstream the flowmeter (section 2) a conical pipe is installed, with reduction angle of 2 x 4,29°. Downstream the expansion angle is set to 2 x 2,96°.

This design gives a straight pipe run of 8xDN upstream, and 6.8xDN downstream.

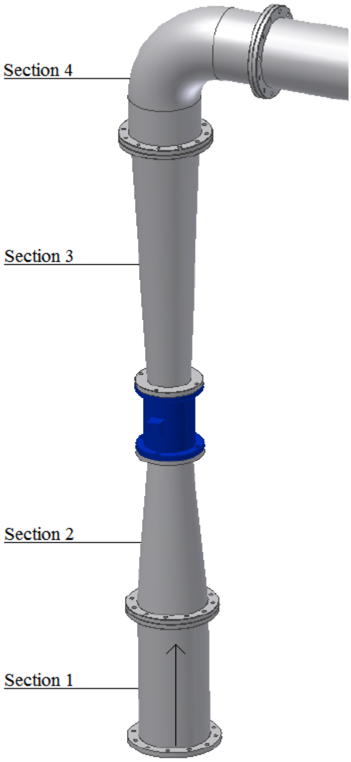

Figure 8.3.9: Improved pipe run

8.4 Accuracy evaluation

If the volumetric calibration is carried out in accordance to ISO 8316, an attainable accuracy for the volumetric method lies within ± 0,1-0,2 %.

An evaluation of the accuracy in the volumetric method is given in chapter 5. Main contributors to the uncertainty in the volumetric calibration, arises in the determination of the collected volume and the corresponding tank calibration.

8.5 Data acquisition and software

A Labview- program for logging and processing of the flowmeter output signal and associated random uncertainty, is given in the appendix A.6/ A.7 and attached as electronic version.

Calibration sheets for processing measured data and suggested calibration steps, are given in appendix A.5. A proposed calibration procedure is given in appendix A.4.

8.6 Approximated total costs

On request by Turbine Testing Lab, a cost estimation is carried out in chapter 7. The total costs specified:

Description	**Quantity**	**Price**
Volumetric tank/Fundament		120 000 NOK
Krohne Optiflux2000/ IFS300 electronics		38 740 NOK
Drain system		6960 NOK
Supporting beams		4200 NOK
Deflector mechanism/Pneumatic pistons		35 000 NOK
Level gauge		12 000 NOK
PT100 elements		2000 NOK
+ additional pipe fittings		10 000 NOK
Total		**228 900 NOK**

Chapter 9

Discussion

9.1 Chosen method

Since TTL is working towards becoming an IEC- approved laboratory, the evaluated primary methods were restricted to the required methods given in IEC 60193 [6]: moving screen method, weighing method and volumetric method.

Moving screen- method proved to be the method with the lowest accuracy. In combination with lack of experience with the method and complicated installation, this method was eliminated as an option for the primary calibration facility at TTL.

Among the three methods, the weighing method is the most prevalent used for flow calibration purposes due to high accuracy. Another advantage is the experience with the method at the Waterpower Laboratory at NTNU. The accuracy in the weighing cells increases with load, meaning that a certain minimum volume is required to reach the attainable accuracy. The weighing tank installed at the Waterpower Laboratory has a capacity of 70 tons, and requires much space. With regards to economic aspects, this method is assumed to be the most expensive, mainly due to the weighing cells and the tank size.

The volumetric method has an attainable accuracy close to the weighing method, provided correct installation. Similar to the weighing method, the accuracy depends on the tank capacity. At the same time, the accuracy will be highly dependent on the area-volume ratio. By designing a configuration with reduced area at the level- measuring section, this can minimize required tank size. Due to space limitations, an investigation of the existing tank condition should be executed as an option for the volumetric calibration.

On the basis of accuracy, economical aspects, space limitations and available resources in the lab, the volumetric method is chosen as a principle for the calibration facility design.

9.2 Design

In the design phase of the calibration facility, the existing tank condition was investigated. The condition of the surface and quality of the concrete, proved to be worse than initially expected. To reach the requirements in ISO 8316 [26] regarding leakages, adsorption and rigidity, the existing tank must go through a significant rehabilitation.

The long term goal of TTL is implementation of a test facility according to IEC and related ISO standards. Based on this, in combination with discussions with technicians in the lab in July [17], it was decided to design a new calibration tank as an alternative to the existing tank. This will ensure an accurate geometry, adsorption- and leakage free walls and a rigid calibration volume.

A new tank also opened opportunities for a drain system directly linked to the main pump system. With a tank design based on a standard geometry and size, this could lead to reduced tank costs due to a broader selection of manufacturers. The tank design requires a small surface area compared to hight, to reduce errors in determination of the volume. Based on this a cylindrical tank was chosen, with a minimum capacity equal to maximum flow rate multiplied with minimum required filling time.

In retrospect, the costs of the new tank turned out to be more expensive than first assumed, hence the economic argument for chosen calibration principle ceases. As a result of this, a closer investigation of the existing tank condition should be performed as an alternative to the new tank. If the existing tank can be used, this will reduce the total facility costs significantly. The suggested configuration illustrated in figure 4.3.4, should then be evaluated and further developed. This principle will both lead to a larger calibration volume, and reduced area at the level measuring section.

9.3 Flowmeter and improved pipe section

The proposal given in the results (Section 8.3), implies a change of flowmeter from the original suggestion from TTL (MS2500- model) to the Optiflux2000-model. This corresponds to a reduction in diameter from 400 mm to 250 mm. A smaller flowmeter will also reduce the costs.

The original flowmeter suggestion (MS2500)[19] covers a range from 0- 1,28 m^3/s, which is a large flowrate in the context of model testing. A typical range for a Francis model test lies within 0- 0,4 m^3/s [5], and the likelihood that TTL will conduct efficiency test which exceed 0,5 m^3/s is small. This will also require a larger calibration capacity, which will take up more space and increase the total costs significantly.

By changing the *MS2500*- model with *Optiflux2000*, this will lead to the following improvements:

A change of the original flowmeter will also improve the conditions through the flowmeter: The flow velocity through the flowmeter is increased due to reduced diameter. The distance from the pump outlet is increased, which will reduce errors due to fluctuations and undeveloped flow pattern. The straight pipe run is increased from 3.7 x DN to 8 x DN upstream and 5.5 x DN to 6.8 x DN downstream the flowmeter. The installation of the flow straightner will improve the flow profile through the flowmeter.

Another advantage with a smaller flowmeter, is the opportunity of a flowmeter installation on the pipe run in front of the Francis runner. This makes it possible to conduct discharge measurements with an accuracy between ± 0,2 %- 0,3 %, both before and during the installation of the calibration facility.

9.4 Accuracy

Provided a correct installation of the deflector mechanism and pneumatic system, the main uncertainty contribution in the calibration lies in the determination of collected volume.

This includes temperature variations during the tank calibration, establishment of the level- volume relation, the quality of the level device, and temperature changes between the tank- and main calibration.

The tank calibration should be carried out at constant temperature, or by establishing a temperature- correction for the tank calibration and corresponding calibration curve. If it is possible, the tank calibration should be conducted at several temperatures.

Provided that the level equipment is of high quality and calibrated against a reference, this error contribution will be small.

For the establishment of the level-volume curve, this is done through a regression. This error can be reduces by use of small calibration steps, to increase the number of measuring point for the regression.

9.5 Chosen software

The only parameter which is treated in Labview is the voltage output from the flowmeter. Therefore, it was decided to examine the data processing and regression in a separate spread sheet. This will make the data- acquisition and processing clear and user- friendly.

One suggestion to improve the LabView program is by implementing the volume-correction due to temperature changes. This can be done by inserting "'controls"'-windows in the program, where the level measurement and temperature measurement can be inserted and processed automatically. It is also possible to implement the regression in the Labview- program.

9.6 Total costs

An evaluation of the total costs is conducted after request from TTL. The only price based on a local supplier is the tank cost estimation. The rest of the cost analyses are based on personal conversations with Norwegian suppliers, assuming that the equipment- and material costs are approximately universal. Hence the price may vary slightly from the total cost estimation.

9.7 Implementation of a flow calibration facility at TTL

In order to achieve the requirements of calibration and traceability set by IEC, the flowmeter must be calibrated in situ against a primary method. Due to high costs of equipment and components, such an installation is a large investment for TTL.

A big advantage with selecting the suggested flowmeter (the Optiflux2000- model), is the possibility of installing the flowmeter on the straight pipe run in front of the Francis runner. Hence, TTL will be able to conduct flow measurements both before and during the installation of the calibration facility. This will contribute to important experience and practice within model testing as soon as the Francis test rig is installed.

This may open for external assignments in projects where an accuracy in the discharge measurement between ± 0,2- 0,3% is sufficient, and traceability in the measurement is less important. Furthermore, this can lead to important experience for applications regarding future financial support of the laboratory.

As soon as the primary calibration facility is installed at TTL, this will be a large step in reaching the goal of an IEC- approved testing facility.

As mentioned in the introduction, the Nepalese government has planned to increase the hydropower capacity with 38.000 MW the next 25 years. This indicates a huge market for turbine manufacturers and model testing in the coming years. An IEC-approved testing facility at Turbine Testing Lab can be a central actor to reach this goal.

Chapter 10

Conclusion

A major goal for the Turbine Testing Lab, is to be able to perform model tests according to IEC 60193. According to this standard, the flowmeter used in model testing, must be calibrated *in sitù* against one of the following methods:weighing method, volumetric method or moving screen method.

The proposed design of the calibration facility at Turbine Testing lab is based on a volumetric method. The method has been chosen on the basis of accuracy, economical aspects, space limitations and available resources at the laboratory.

If the installation is according to ISO 8316, an accuracy between $\pm 0,1 - 0,2\%$ is achievable for the volumetric method. Provided a well functioning deflector mechanism and pneumatic system, the main error contribution in the volumetric method lies in the determination of collected volume and corresponding tank calibration.

It is recommended to reduce the diameter of the flowmeter from 400 mm to 250 mm, and upgrade the pipe run up- and downstream of the flowmeter. This can be done by implementation of a flow straightener and reduction- and expansion pipes. In total, this will increase the velocity and uniformity of the flow, and thereby improve the conditions at the flowmeter.

An implementation of the primary calibration facility at TTL is a central step towards an IEC- approved laboratory in Nepal. A well functioning laboratory will increase the academic knowledge within hydraulic runners, and open doors towards an international market for testing of model turbines in Nepal.

Chapter 11

Further work

- A further research of the alternative tank design as mentioned in *Discussion*, which utilizes the available calibration tank is recommended. This may reduce the total costs of the calibration facility.
- When the calibration facility is installed at the *Turbine Testing Lab*, a detailed analysis which includes experimental evaluation of the uncertainty in the volumetric calibration method should be carried out.
- It is recommended to develop a training program for students and staff at the Turbine Testing Lab, with focus on calibration and execution of model tests accoring to IEC 60193. The Waterpower Laboratory at NTNU will be an important support and collaborator with this work, due to a long experience within this field of model testing.

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Appendix A

Appendix

KROHNE Instrumentation
Ekholtveien 114
1526 MOSS

NTNU
Dept. Energy and Process Eng.
7491 TRONDHEIM
Johanne Seierstad

Tilbud

Nr.: **130598**
Revisjon nr.:
Dato: 04.09.13
Vår saksbehandler: Jens Ole Ekelund
E-post: joekelund@krohne.no
Leveringsbetingelser: Ex works Moss eks.embl
Betalingsbetingelser: Netto pr. 30 dager
Kundenr.:

Pos.	**Nr.**	**Beskrivelse**	**Antall**	**Enhet**	**Enhetspris**	**Rab.%**	**Beløp (NOK)**
1	2100C DN250	Optiflux Kompakt KROHNE Elektromagnetisk mengdemåler med IFC 100 forsterker Anslutning: Flenset DN250/PN10 Byggemål: 400 mm Materiale i: - flenser: karbon stål - rør: austenittisk rustfritt stål - liner: hardgummi - elektroder: hastelloy C22 - spolehus: platestål - konverterhus: aluminium, polyuretan belagt Elektrisk ledningsevne: - ikke vann: minimum 5 µS/cm - vann: minimum 20 µS/cm Nøyaktighet: <+/- 0.3% av M.V. ± 1 mm/s Repeterbarhet: +/- 0.1% Utganger: 4-20 mA, puls, status Spenningsforsyning: 100 - 230 V AC Kapslingsgrad: IP66/67 Funksjoner: Kontinuerlig måling av aktuell mengde, flow hastighet, ledningsevne, masseflow (ved konstant densitet), spoletemperatur samt diagnostikkfunksjoner. Levering er normalt fra lager Moss!	1	stk	33 740,00	25	25 305,00

A.1 Student‘s t distribution

The table is found in ISO 8316 [26, Annex E]

95 % confidence level	
$v = n - 1$	t
1	12,706
2	4,303
3	3,182
4	2,776
5	2,571
6	2,447
7	2,365
10	2,228
15	2,131
20	2,086
30	2,042
60	2,000
∞	1,96

A.2 Water density estimation

The equation is found in IEC [6, p. 169]

$$\rho_m = \frac{1000}{(1 - a \cdot p_{abs}) + b \cdot (\theta - 4 + c \cdot p_{abs})^2 - d \cdot (\theta - 4 + c \cdot p_{abs})^3} \tag{A.2.1}$$

, where

a $= 4,6699 \cdot 10^{-10}$

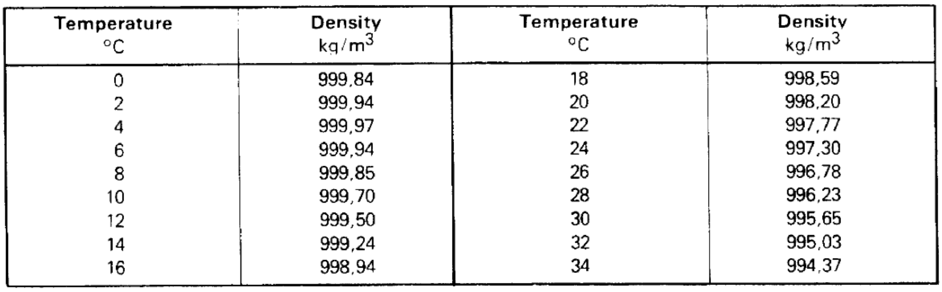
b $= 8 \cdot 10^{6}$

c $= 2,1318913 \cdot 10^{-7}$

d $= 6 \cdot 10^{-8}$

A.3 Density due to temperature variations

Density of pure water at atmoshperic pressure of 101,325 kPa:



Temperature °C	Density kg/m^3	Temperature °C	Density kg/m^3
0	999,84	18	998,59
2	999,94	20	998,20
4	999,97	22	997,77
6	999,94	24	997,30
8	999,85	26	996,78
10	999,70	28	996,23
12	999,50	30	995,65
14	999,24	32	995,03
16	998,94	34	994,37

Figure A.3.1: Temperature/Density table [26, Annex B]

A.4 Calibration Procedure

During the calibration, it is recommended to have two operators available in the lab. Operator 1 is available on the lab floor, and operator 2 in the control room.

Preparatory work

1. Start to set the pipe loop in calibration mode by opening valve 1, opening the pump valve and
2. Check that the level in the volumetric tank is within the critical level, z_c.
3. Check that the drain valve at the volumetric tank is closed.
4. Start up the pump.
5. Find flow rate 1, by varying the rpm on the pump.
6. Clarify the calibration program and software.
7. Operator 2 sets the filling time on the control computer
8. Prepare to start the calibration.

Main calibration

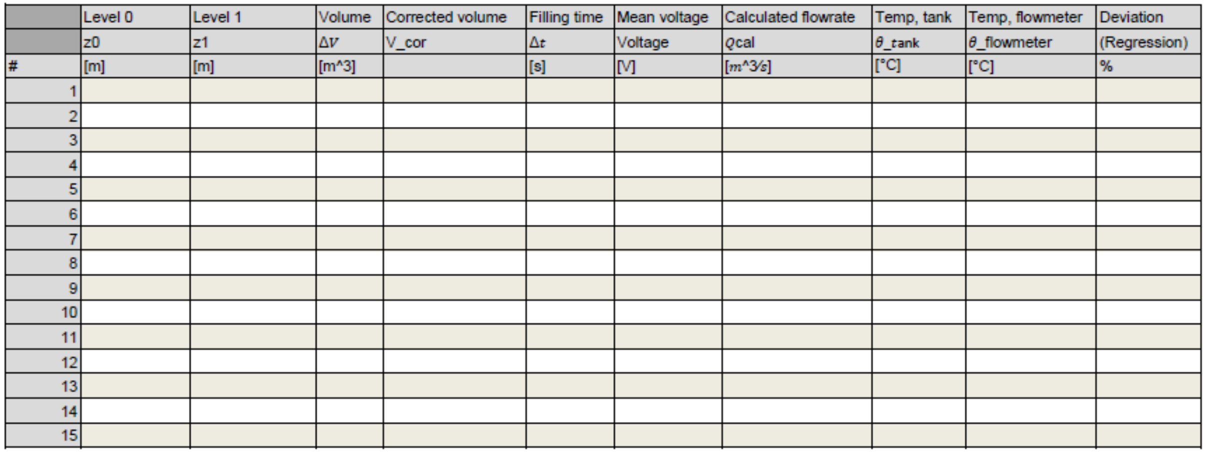
9. Operator 1 conduct and report level measurement 1, Z0.
10. Operator 2 reggister z0 in the calibration sheet, and prepare for logging of voltage values from the flowmeter.
11. Operator 1 releases the deflector mechansism and report to operator 2.
12. Operator 2 starts the logging of the voltage signal immediately after the deflector mechanism is released.
13. Operator 1 reports to operator 2 ten seconds before the filling time ends.
14. Operator 2 stops the logging and save the data.
15. The deflector mechanism hits over to initial position
    and operator 1 reports actual filling time.
16. Decrease the pump speed, and prepare to shut down the pumps
17. When the system comes to rest, operator 1 executes the level measurement Z1 immediately and reportes the result
18. Emtpy the volumetric tank, and prepare for a new calibration session.
19. Be aware of remaining water droplets at the tank wall,
    and ensure the tank is totaly empty before the next calibration point.
20. Register the tank- and flowmeter temperature.

Data processing

21. Reggister all calibration data in calibration sheet 1.
22. Calculated the mean voltage values for the flowmeter voltage output.
23. Determine the calibration curve and values through a linear regression.

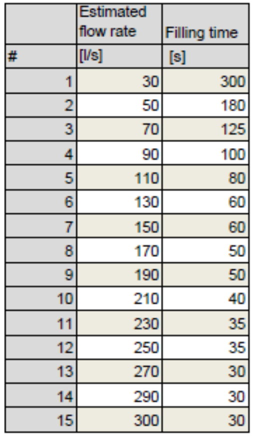
A.5 Suggested calibration sheets

Calibration sheet 1



	Level 0	Level 1	Volume	Corrected volume	Filling time	Mean voltage	Calculated flowrate	Temp, tank	Temp, flowmeter	Deviation
	z0	z1	ΔV	V_cor	Δt	Voltage	Qcal	θ_tank	θ_flowmeter	(Regression)
#	[m]	[m]	[m^3]		[s]	[V]	[m^3/s]	[°C]	[°C]	%
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										

Calibration sheet 2



	Estimated flow rate	Filling time
#	[l/s]	[s]
1	30	300
2	50	180
3	70	125
4	90	100
5	110	80
6	130	60
7	150	60
8	170	50
9	190	50
10	210	40
11	230	35
12	250	35
13	270	30
14	290	30
15	300	30

$$V_{cor} = \frac{\Delta V}{(1 + \beta(\theta_{tank} - \theta_{flowmeter}))}$$

A.6 Labview- program, block diagram

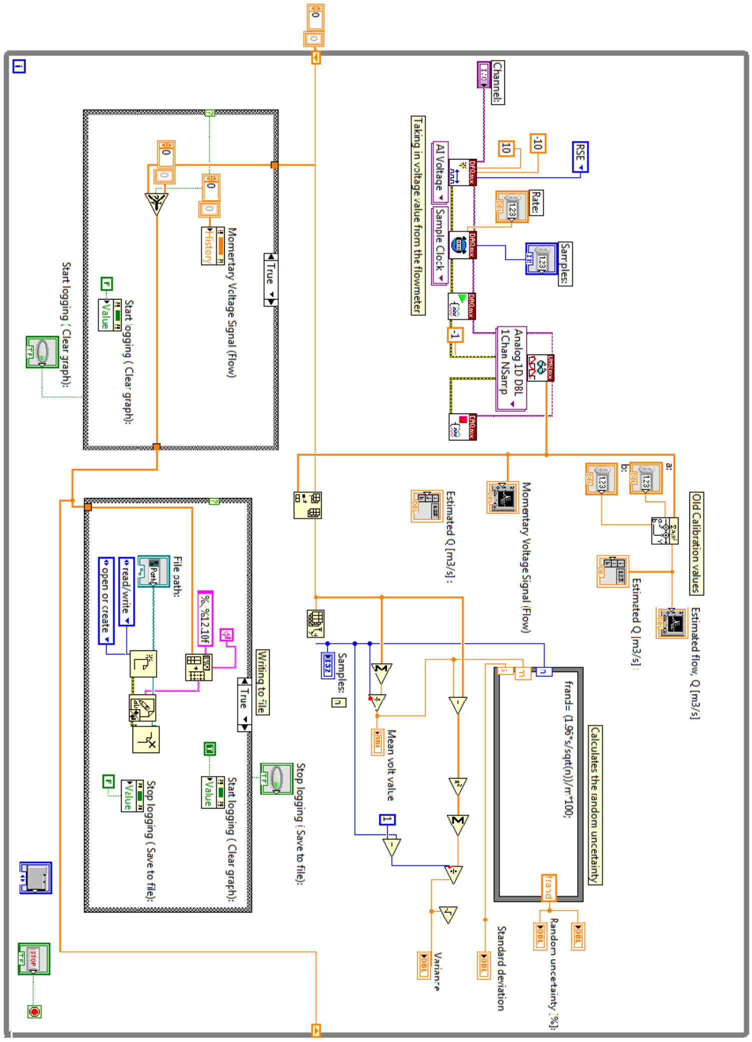
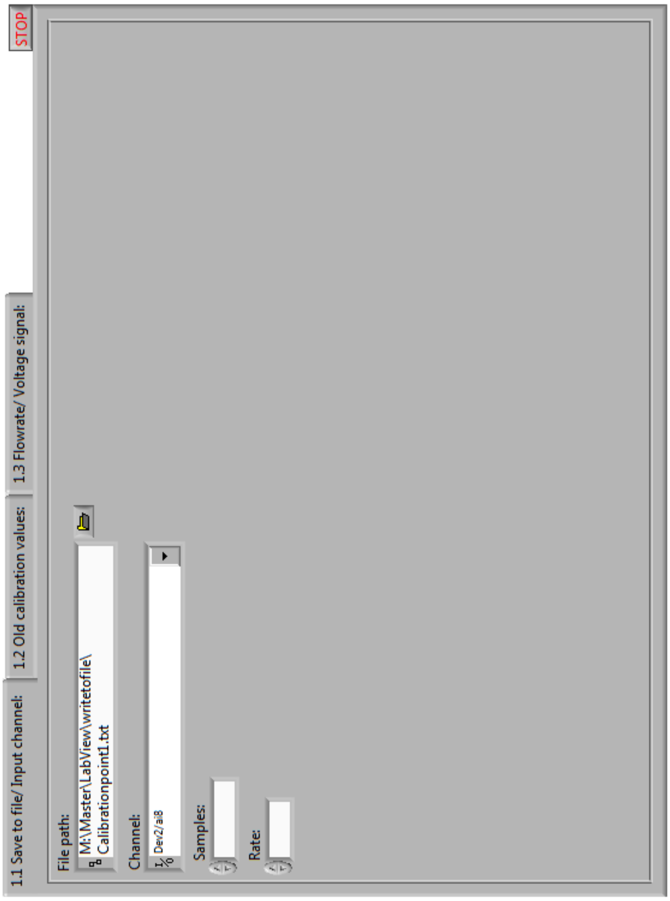


Figure A.6.2: Block diamgram

A.7 Labview- program, front panel

Window 1.1: Save to file/Input channel

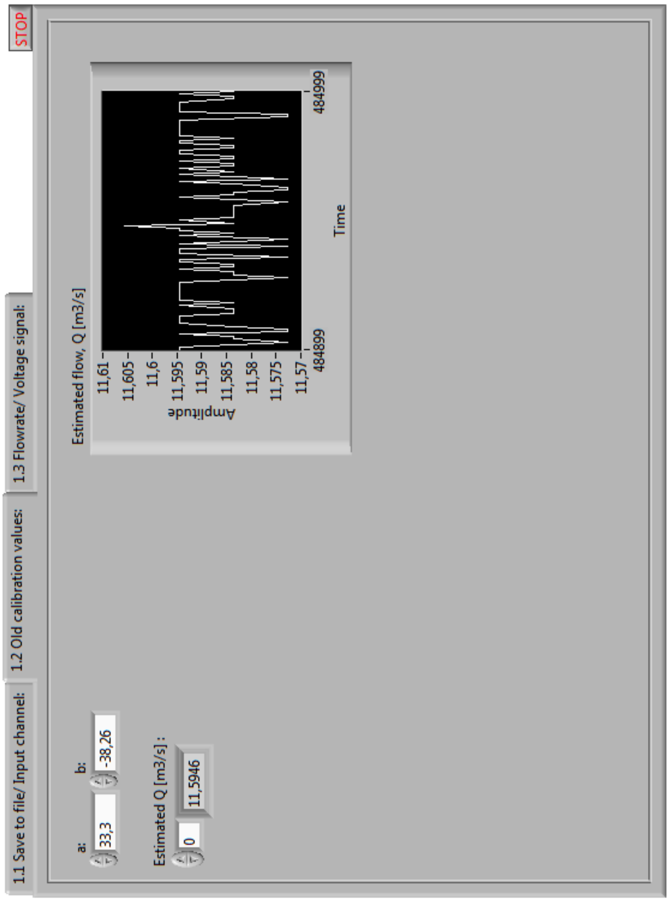


File path: M:\Master\LabView\writetofile\Calibrationpoint1.txt

Channel: Dev2/ai8

Figure A.7.3: 1.1 Save to file/Input channel

Window 1.2: Old calibration values



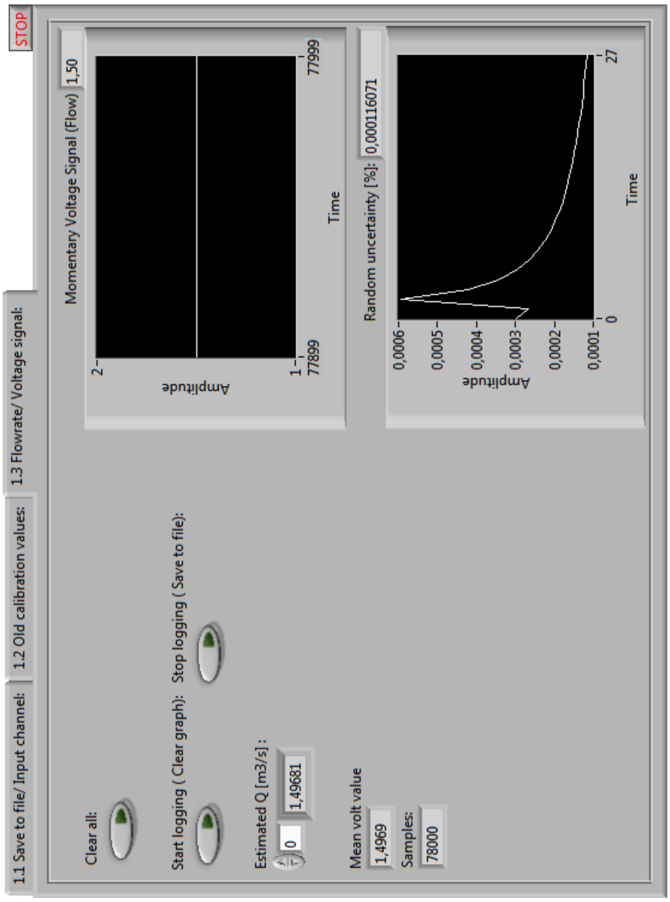
a: 33,3

b: -38,26

Estimated Q [m3/s] : 0 11,5946

Figure A.7.4: 1.2 Old calibration values

Window 1.3: Flowrate/Voltage signal



Estimated Q [m3/s] : 0 1,49681

Mean volt value 1,4969

Samples: 78000

Momentary Voltage Signal (Flow) 1,50

Random uncertainty [%]: 0,000116071

Figure A.7.5: 1.2 Flowrate/ Voltage signal