Study of Sediment Erosion in Guide Vanes of Francis Turbine

Studier av sedimenter erosjon i ledeskovler
av Francis turbin

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MASTER THESIS

for

Student Linda Haugvaldstad

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Study of sediment erosion in guide vanes of Francis turbine
Studier av sedimenter erosjon i ledeskovler av Francis turbin

Background

Sediment erosion in Francis turbines is a large problem for river power plants near the Himalayas and the Andes Mountains. Due to high sediment concentration in the rivers the turbine components are exposed to erosion wear and must be maintained often. During monsoon periods, the sediment concentration is at its highest and the turbines are stopped to reduce the damage on the components. The turbines at Jhimruk Power Plant in Nepal are a good example on how the sediment erosion effects the power plant operation. These turbines need to be maintained annually due to high erosion wear. This result in a reduction of energy production and high maintenance cost. It is therefore of interest to have deeper knowledge of relation between flow behaviour and sediment erosion in these turbines. Cooperation between Kathmandu University and NTNU has started with an aim to develop Francis turbines that can withstand high sediment load.

Objective

The aim is to carry out experimental test to identify effects of sediment erosion on guide vanes of Francis turbines

The following tasks shall be considered in the project work:
1. Literature survey
    a. LDV-measurements
    b. PIV-measurements
2. Software knowledge
    a. Get familiar with PIV and/or LDV
    b. Get familiar with the LabView
3. Preparation of the test rig:
    a. Follow up the production of the test rig
    b. Installation of PIV- or LDV-measurements system
    c. Installation of pressure sensors and make arrangement for a logging system
4. Carry out velocity and pressure measurements
5. Describe the experimental test procedures on the test rig at NTNU
6. Describe the experimental test rig and procedures on a similar test rig at the Turbine Testing Laboratory at Kathmandu University.

If the test rig is not ready to use within the available time; the student will focus more on item 6, include detail drawings, and stress analysis.

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

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

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

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

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

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

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

☒ Work to be done in Waterpower laboratory
☐ Field work

Department of Energy and Process Engineering, 5. January 2015

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Abstract

Sediment erosion wear of Francis turbines is a big problem for power plants near the Himalayas and the Andes Mountains. The turbine components must be maintained often, resulting in reduction of power production and high maintenance cost.

To understand the erosion problem better it is of high interest to study the flow around the guide vanes of a Francis turbine. A test rig which will give the opportunity to study this flow is being designed, and will be used for experimental test at the Turbine Testing Lab at Kathmandu University and it is called *3 GV Cascade*.

The test section of the test rig has geometry similar to the guide vane cascade of the Francis turbines at Jhimruk Power Plant in Nepal. A similar test rig *1 GV Cascade* is being installed at the Waterpower Laboratory at NTNU the spring of 2015.

The purpose of this thesis has been to describe the test rig and create procedures for everything from following up the production of the rig to successful measurements with a special focus on safety. Particle Image Velocimetry is going to be used for the velocity measurements and to visualize the flow in the cascade. Procedures for leakage- and pressure testing and operation of 3 GV Cascade at TTL are based on procedures at the Waterpower Laboratory. PIV setup, optimization and measurement procedures are based on theory and writer's own experience from doing PIV measurements on the Swirl rig at the Waterpower laboratory. Simple bending stress analyses were performed to make sure that the test rig will be able to withstand a pressure of 10 bar.

Theory about PIV and optimization rules has been given with the intention that it will be helpful when PIV setup and measurements on 3 GV Cascade is going to be performed. Procedures for PIV setup on the Swirl rig have also been included, since it has been planned to use that rig as a PIV training facility at the Waterpower Laboratory.

Sammendrag

Slitasje av Francis turbiner grunnet sediment erosjon er et stort problem for kraftverk i nærheten Himalaya og Andesfjellene. Turbinkomponenter må vedlikeholdes ofte, noe som resulterer i reduksjon av kraftproduksjon og høye vedlikeholdskostnader.

For å forstå problemene rundt erosjon bedre, er det av stor interesse å få muligheten til og studere strømningen rundt ledeskovlene i en Francis turbin. En testrigg som vil gi mulighet til å studere denne strømningen er under design og vil bli brukt til eksperimentell arbeid på Turbine Testing Lab ved universitetet i Kathmandu, og har fått navnet *3 GV Cascade*.

Test seksjonen av riggen har lik geometri som ledeapparatet i Francis turbinen i Jhimruk kraftverk i Nepal. En tilsvarende testrigg, *1 GV Cascade*, blir bygget på Vannkraftlaboratoriet ved NTNU våren 2015.

Hensikten med denne masteroppgaven har vært å beskrive test riggen og lage prosedyrer for alt fra oppfølging av produksjon av deler til vellykkede målinger med et spesilet fokus på sikkerhet. Particle Image Velocimetry (PIV) skal brukes til hastighetsmålinger og for å visualisere strømningen i ledeapparatet. Prosedyrer for lekkasje- og trykktesting og kjøring av 3 GV Cascade på TTL er basert på prosedyrer ved Vannkraftlaboratoriet. PIV oppsett, optimalisering og måleprosedyrer er basert på teori og forfatterens egne erfaringer fra å gjøre PIV målinger på Swirl riggen ved Vannkraftlaboratoriet. Enkle styrkeberegninger har blitt utført på det foreløpige designet for å sikre at testriggen vil være i stand til å motstå et trykk på 10 bar.

PIV og optimaliseringsregler er gitt med den hensikt at det vil være nyttig når PIV oppsett og målinger på tre GV Cascade skal utføres. Prosedyrer for PIV oppsett på Swirl riggen er også tatt med, siden det har vært planlagt å bruke den riggen som en opptreningsrigg for PIV ved Vannkraftlaboratoriet.

Acknowledgements

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Linda Haugvaldstad
Trondheim, 10.06.2015

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Nomenclature

Abbreviations

AHEC   Alternate Hydro Energy Center
CCD   charge-coupled device (image sensor)
CFD   Computational Fluid Dynamics
EPFL   Swiss Federal Institute of Technology in Lausanne
GV   Guide vane
HSE   Health, Safety and Environment
IIT   Indian Institute of Technology
JPP   Jhimruk Power Plant
KU   Kathmandu University
LDV   Laser Doppler Velocimetry
NACA   National Advisory Committee for Aeronautics
NTNU   Norwegian University of Science and Technology
PhD   Doctor of Philosophy
PIV   Particle image velocimetry
PMMA   polymethylmethacrylate
PTV   Particle tracking velocimetry
RAM   Random access memory
ROI   Region of interest
rms   root mean square
rpm   Revolutions per minute
TTL   Turbine Testing Lab
USTUTT   University of Stuttgart
VITS   Visakha Institute of Technology and Science
1D   One dimensional
3D   Three dimensional

Roman Symbols

C_f	safety factor
d_p	particle diameter (m)
d_r	pixel pitch (m)
d_τ	particle image diameter (m)
D_I	linear dimension of interrogation area (m)
E	pulse energy
E	modulus of elasticity (MPa)
$\mathbf{F(x)}$	image mapping function of point $\mathbf{x}$ in object space (m)
I	Interrogation window Frame 1
I'	Interrogation window Frame 2
L	half-width of interrogation domain (m)
l	length (mm)
M_0	nominal or paraxial image magnification
N_I	image density
N_S	source density
p	dimensioning pressure (MPa)
r_i	inner radius (mm)
t	thickness (m)
t	time (s)
Δt	time between pulses (s)
δt	illumination pulse duration (s)
Δu	local variation of the velocity (m/s)
$\mathbf{X}$	position vector in image domain (m)
$\Delta \mathbf{X}$	displacement vector in image domain (m)
$\mathbf{x}$	position vector in flow domain (m)
Δz	out-of-plane displacement (m)
Δz_0	thickness of the light sheet (m)

Greek symbols

α	angle
ϕ	cross-correlation function
σ_y	yield stress
δ	maximum deflection (mm)

1 Introduction

Most of the untouched reserves of hydropower in the world are located in developing countries. Many of these countries struggle with increasing electrical demand and a bad infrastructure. To develop hydropower would be a vital catalyst for wider social development; including better health and education locally. In addition it would be beneficial from a global perspective since it is a clean and reliable energy source. Close cooperation between industrialized- and developing countries seems to be the key to a successful implementation of hydropower. Knowledge transfer can make it easier for these countries to meet today's requirements for the energy production to be climate friendly, cost efficient and stable.

Laboratories are very important to progress scientific work. Experiments are crucial for validation of numerical simulations and can be used to improve and enhance simulation programs. Norway, Germany and Switzerland have a great deal of experience in the area of hydropower, and are still

Figure 1 Pelton test rig at Waterpower Laboratory, NTNU (Buljo/NTNU, 2015)

investing in research and further development to ensure a steady and innovative development of hydropower. Today's energy market has led to changed operating conditions for the power plants (off-design-operation, increased number of start-ups and shut-downs). This has introduced new problems and then also new areas of research. Therefore hydropower researches at the laboratories at NTNU, USTUTT and EPFL have moved to investigating secondary flow regimes and phenomena in addition to stability and optimum component design and operation. Although improvements in turbine design are small, they have high impact on energy production and are of great economical value.

Several of the developing countries have training facilities for engineers and technicians. This is a good way to gain more experience and training on how to operate the power plants optimally and safe so that the maximum power can be generated as well as the life of the equipment can be maximized. In addition, this reduces the need of external help which in turn leads to increased employment of locals.

The main purpose of testing facilities in developing countries, like Nepal and India, have been to reinforce and enhance understanding of the fundamentals of fluid mechanics and hydraulic machines. Turbine Testing Lab at KU, Fluid mechanics & Hydraulic Machines Lab at VITS and Hydromechanical System Lab at IIT are labs located in Nepal and India. The last years these laboratories have worked in the direction of meeting national and international standards to be able to perform turbine model tests and certification of mini- and micro-turbines.

Some of the developing countries are facing problems like excessive sedimentation and erosion of turbine components. NTNU has developed a close cooperation with Kathmandu University in Nepal, which is a typical country struggling with sediment erosion of turbine components, with an aim to develop hydropower turbines that can withstand high sediment load. Researches are carried out both at the Waterpower Laboratory and at Turbine Testing Lab in Nepal.

1.1 Objective of this study

The aim of the thesis was to carry out experimental tests to identify effects of sediment erosion on guide vanes of Francis turbines. After Easter it was clear that the test rig would not be finished in time, and the main focus has been on item 6.

The new aim has been to produce detailed procedures for the whole process, from design of test rig to successful PIV measurements, for a similar test rig that is going to be built at TTL in Nepal.

1.2 Outline of the thesis

This thesis is structures by first presenting relevant previous work on sediment erosion, together with an overview of the laboratory at KU in Chapter 2. Chapter 3 presents the basic theory of Particle Image Velocimetry in order to give the one that is going to do measurements on 3 GV Cascade and understanding of PIV and how to obtain successful measurements. Chapter 4 gives a description of 3 GV Cascade including components and instrumentation. Chapter 5 to 8 contain the different procedures for 3 GV Cascade including guidelines for safe use of lasers are presented. A stress analysis of the test rig flow channel has been included in an Appendix D and is commented in Chapter 9. A discussion of the procedures and guidelines are given in Chapter 10. Suggestions for further work are listed in Chapter 12.

2 Background

2.1 Sediment erosion in Francis turbines

At the Waterpower Laboratory, a lot of research has been done on the topic of sediment erosion. Hermod Brekke has been one of the most influential persons in the hydropower industry, and has performed a remarkable amount of research on sediment erosion in hydraulic machinery. The research includes hydraulic design, material properties and development of erosion resistant coatings.

Bhola Thapa gives a throughout study of the erosion mechanism in hydraulic turbines, comparing theory with observations of eroded turbines in Nepal. He performed erosion tests on a jet type of test rig at TTL using sediment samples from different locations in Nepal on steel specimens (Thapa, 2004). Neopane continued Thapa's work and compared the experimental and theoretical data with numerical simulations, by looking at the effect of particle size, shape and concentration. He identified effects of sediment properties on erosion damage (Neopane, 2010).

Figure 2 Eroded Francis turbine runner blade from Kaligandaki power plant (Writer's own photograph).

During the spring of 2011 a Francis turbine design team consisting of Kristine Gjøsæter, Biraj Singh Thapa, Helene P. Erichsen and at that time PhD. Candidate Mette Eltvik started the creation of the Matlab-based hydraulic design tool called Khoj (Eltvik, 2013). Gjøsæter developed Khoj further during both her project and master thesis.

Eltvik used Jhimruk Power Plant in Nepal as a reference. The object of her thesis was to try to improve the design of the Francis turbine, which operates in rivers with high sediment concentration. She used CFD to simulate and analyze the hydraulic flow conditions, and to predict erosion on the turbine components. Her results show that it is possible to design a runner without affecting the main dimensions and hydraulic efficiency, and still get an extended lifetime. However, she also found that sediment

erosion in the guide vanes increased when the runner design was changed to reduce relative velocities in the runner blades (Eltvik, 2013).

Then Biraj Singh Thapa started his doctoral thesis and moved the focus to the guide vanes. He investigates the effects of different flow parameters on flow characteristics around guide vanes. A new test rig, which is designed by Biraj is being built at the Waterpower laboratory at NTNU

Figure 3 Eroded guide vanes from Kaligandaki power plant in Nepal (Writer's own photograph).

the spring of 2015. The test rig represents the flow through two flow channels from the spiral casing to the inlet of the runner in a Francis turbine. Sailesh Chitrakar is coming from KU to NTNU the fall of 2015. Most likely he will continue working with sediment erosion in Francis turbines.

2.2 Turbine Testing Lab

The Turbine Testing Laboratory (TTL) located at Kathmandu University (KU) in Nepal was developed with an aim to support hydropower development in the country and fulfil all the necessities in the Nepalese market. The lab was designed by KU employees with support from NTNU and was finished in 2011. Today there is one Francis test rig, a cross flow turbine test rig and a Pelton bucket test rig installed.

The lab has two reservoirs for storing and circulating water to run turbine test rigs. The upper and lower reservoirs have a capacity of 100 m^3 and 300 m^3 respectively. Due to the topography, the upper reservoir could be placed so that it created 30 m natural head. TTL is the only lab in the world that can perform tests with this high natural head. Prototype tests of turbines up to 300 kW and model test for larger turbines can be performed in this lab.

TTL has some limitations that have to be accounted for when designing test rigs for TTL (space, cleanliness, electricity supply, less experience and a low budget). It is also desired that the rigs are flexible for multifunctional usage, durable and easily maintained (Lab, 2014).

3 Particle Image Velocimetry

Two measuring techniques that use particles as markers of fluid motion illuminated by a laser are Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV). Laser Doppler velocimetry measures an intermediate physical phenomenon, the Doppler shift of light scattered by small particles, and relates the shift to the particle velocity. PIV is used in experimental fluid mechanics to determine instantaneous fields of the vector velocity by measuring the displacement of numerous fine particles that accurately follow the motion of the fluid.

In the context of applied experimental flow engineering, wherein the aim is to observe the changes in flow patterns that are caused by design modifications, single-point measurements like LDV are time consuming and often give little insight. Therefore it was decided to use PIV for the velocity measurements at NTNU and TTL.

3.1 Overview

The basic concept of PIV is based on the infinitesimal movement of small seeding particles illuminated by a thin laser light sheet. By recording images of the particles at two precisely defined times, t and $t + \Delta t$, and inferring the displacements of individual particles (Low Image Density) or the average displacements of small groups of particles from the displacement of the images (High Image Density), it is possible to sense the rate of particle movement.

Since experiments are going to be done with water flow and not air as the circulating fluid, the focus in this part will be on PIV measurements in water.

3.1.1 Qualitative Flow Visualization

Flow visualization is useful both to understand the mechanics of a particular flow field and as an information for rapid feedback during experimental development. If it is done properly, the effects of modifying some aspect of the flow or its boundaries can be revealed quickly by flow visualization. This way it is possible to make the developmental progress more efficiently than if single-point measurements were made (Adrian & Westerweel, 2011).

Testing time in expensive flow facilities is reduced due to the high data acquisition rate of PIV. It is much quicker to take several thousand image frames of a given flow domain

than to systematically survey the same domain with a pointwise measurement device. In addition the image analysis can be done offline, outside of the flow facility.

3.2 PIV fundamentals

3.2.1 Basic Planar System

The standard planar PIV system consists of a double-pulsed laser, light-sheet-forming optics, particle seeding, a monoscopic (single-lens) camera, image digitization hardware, and a computer for data storage and analysis shown in Figure 4. The steps in the procedure for determining the velocity field are shown following the image acquisition.
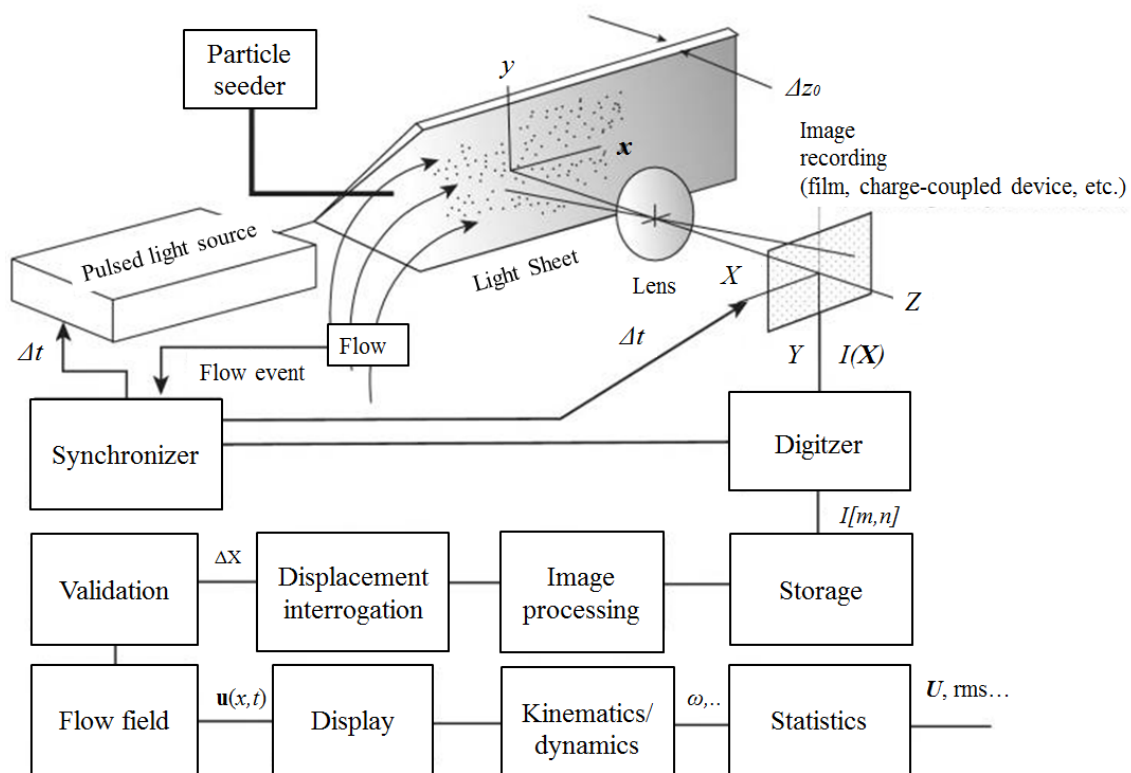
Figure 4 Elements and processes in a planar two-dimensional particle image velocimetry system (Adrian & Westerweel, 2011)

3.2.2 Illumination

To form visible images of micrometer-sized particles, pulsed solid-state laser sources emitting pulses with energy between 5 and 500 mJ are required. The scattering properties of the particles determine the energy needed. The recorded images provide measurements for the particle displacement components on a planar domain defined by the light sheet (see Figure 5).
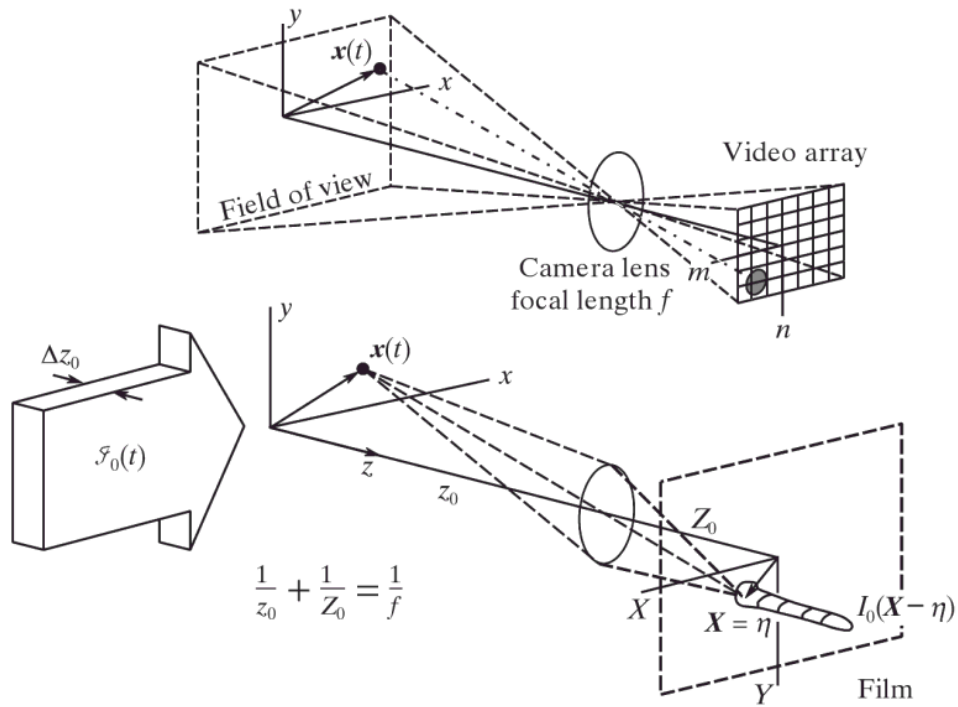
Figure 5 Point particles in the object image plane are imaged to finite-diameter spots on plane surfaces of film or video camera (Adrian, 1991).

The general relation between a position $\mathbf{x} = (x, y, z)$ in the object domain and the corresponding position $\mathbf{X} = (X, Y)$ in the image plane is given by a nonlinear mapping function (S.M. Soloff, 1997): $\boldsymbol{X} = \boldsymbol{F}(\boldsymbol{x})$. The particles in the light sheet plane are focused onto the image plane by adjusting the image plane (Adrian & Westerweel, 2011, pp. 1-7,86).

3.2.2.1 **Light source requirements**

Unequal light sheet intensities, unequal laser pulse energies and partially overlapping sheets are laser related things that can de-correlate the images. By adjusting the laser energy and light sheet forming optics these can be minimized. It is important that the laser is precisely positioned to get correct measurements. If the particle images appear as steaks rather than as circular dots, then the duration of illumination δ_t (pulse duration) is too long.

The intensity of the light sheet must be strong enough so that the scattered light from the seeding particles is detected by the digital imaging device. The required pulse energy E is proportional to the linear dimension L of the area of interest. In water flows $E \sim 100$ mJ is sufficient to illuminate an area of approximately 14×14 cm^2 (Scarano, 2013, p. 135). In

addition the planar illumination requires that the thickness of the light sheet is significantly smaller than its height and width (in order of 1%).

3.2.3 Calibration

The flow coordinate system including the location of the origin, orientation of the x-y plane and scale to, must be established physically with respect to the flow boundaries in a PIV experiment. To inserting a calibration target in the object domain of the test section is the best way to achieve good positional accuracy. The calibration target provides an ideal way to establish the mapping function $F(\mathbf{x})$ and the scale. A calibration target generally consists of a regular grid of markers (dots or crosses) with a precisely known pitch. The PIV software is able to recognize these targets. To ensure the best accuracy for the determination of the mapping parameters, the size and shape of the calibration target should be large enough so that the markers occupy the full field of view of the camera. For single-camera PIV systems it is usually sufficient to acquire a single calibration image. When taking the calibration images it is best to illuminate the target with a white light source and not the laser light.

Obtaining an image calibration from the image of a ruler (or another object) held in the camera field of view is strongly discouraged because it is not accurate enough. An error in the value of magnification factor M_0 will affect the complete measurement result because all data are multiplied by this value. If it is not possible to access the test section to insert the calibration target after it has been assembled, markers should be machined into the flow apparatus before assembling the rig.

If dealing with water flow it is important that the calibration image is taken while the test section is filled with water due to refraction effects.

3.2.4 Seeding particles

Most fluids naturally contain small particles, but they are not only of different sizes but also irregular and sometimes at low concentration. Small particles will produce a cloudy background glow, and the number of particles large enough to produce bright individual images is often less than desired, this will result in poor image quality. Therefore the best PIV measurements are achieved by filtering the fluid to remove uncontrolled particles and then seeding it with carefully chosen ones.

Low particle image density, loss-of-pairs due to in-plane and out-of-plane motion and particle flicker due to nonspherical particles lead to de-correlation of the images. These factors can be minimized by altering the particle concentration. Start by adding small amounts of particles check the correlation and add more if necessary.

If the measurements are to be performed where the fluid contain naturally present contaminants and filtering the fluid is not an option, the use of tracer particles that contain a fluorescent dye is a good optional approach. Then the light that is absorbed by the dye is emitted at a longer wavelength, which makes it possible to distinguish tracer particles from other objects (e.g. reflecting objects, bubbles, droplets in sprays).

For experiments in closed apparatus that cannot easily be cleaned to remove settled particles or stirred to keep them in suspension, naturally buoyant particles are desirable. In forced flow, natural mixing keeps the particles suspended during operation, but the particles coat the bottom and form aggregates that might have to be cleaned away periodically when the apparatus is off.

3.2.5 Image Digitization

The process of converting a continuous image intensity field into a two-dimensional array of analog pixel readings is called *pixelization*. Analog readings are digitized (8- to 12-bit accuracy) and stored, first in the fast memory of a *frame grabber* and then in the random access memory (RAM) or the rotating memory of a computer. A *synchronizer* coordinates all of these events. The synchronizer also performs the following tasks;

- o senses the occurrence of flow events
- o arms and fires the light source(s) at appropriate times
- o opens the camera shutter
- o activates the image acquisition
- o initiates digitization
- o transfers the data via the frame grabber

Sometimes, when imaging small particles on a *charge-coupled device* (CCD), it can happen that the pixel size is larger than the individual particle image diameter d_τ (see Figure 6). Then it is not possible to determine the center of a particle image accurately. This condition is commonly referred to as *pixel locking*.
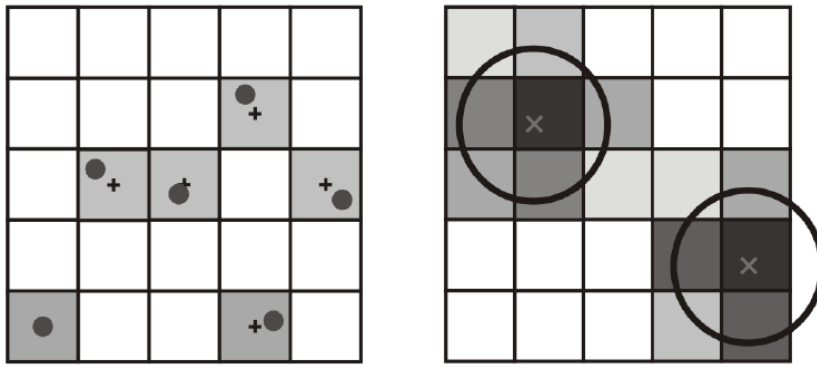
Figure 6 Digital imaging of small particles: under-resolved (left), well-resolved (right) (Scarano, 2013)

In the former case ($d_\tau < 1$ pixel), the particle position cannot be detected with subpixel accuracy, leading to positional errors up to 0.5 pixels. The second case ($d_\tau \sim 3$) is more favorable for PIV because the position of the particle image can be reconstructed from the interpolation of the light intensity distribution spanning several pixels (Scarano, 2013).
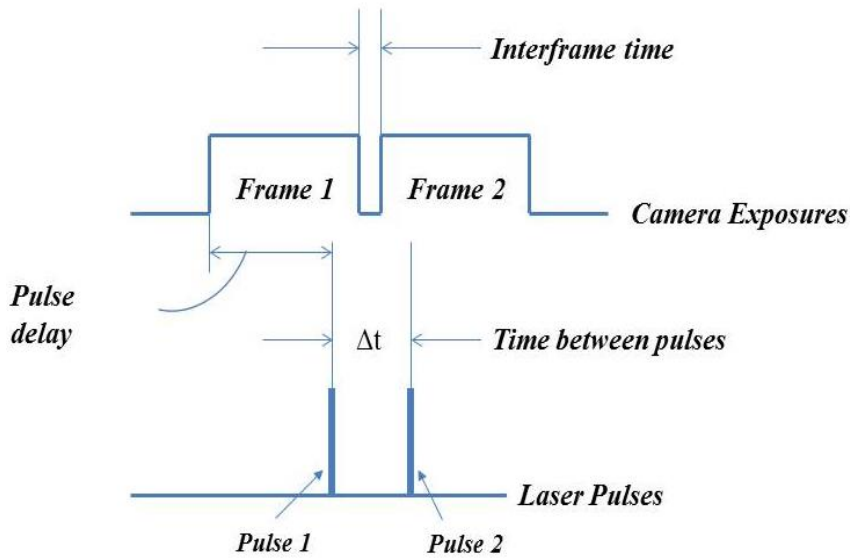
Figure 7 Timing diagram (Made by writer)

The number of images to acquire, time between pulses and the trigger rate are set by the operator. Figure 7 show the timing diagram for a PIV system; Frame 1 and 2 are captured when the particles are illuminated by pulse 1 and 2 respectively. These frames are combined into one double image.

3.2.6 Image processing

Image quality affects the quality of the correlations and the accuracy of the measurements. The images can be improved by digital processing after they have been recorded, to make the images of the particles more visible and less noisy. More information about this can be found in (Adrian & Westerweel, 2011, pp. 241-267). It is always better to have the best images possible in the original recordings. To spend some time working on the setup is therefore very much useful.

3.2.7 Displacement Interrogation

There are three basic methods for implementing the general measurement scheme: *low-image-density PIV*, often called *PTV*; *high-image-density PIV*, often called just *PIV*; and *LSV*. The difference between them is based on the concentration of particles. Low- and high-image-density PIV utilize low-source-density seeding, $N_s \ll 1$, so that the images correspond to individual particles (see Figure 8). LSV employs $N_s \gg 1$ so as to produce speckle. The differing character of these types of images leads to different methods of interrogation and different characteristics of the vector fields that they yield. Only high-image-density PIV is recommended for the measurements on Three Guide Vane Cascade since the density of information that needs to be recorded is high for measurements around a guide vane in a Francis turbine to catch the flow phenomena of interest.

(a) Low image density

(b) High image density
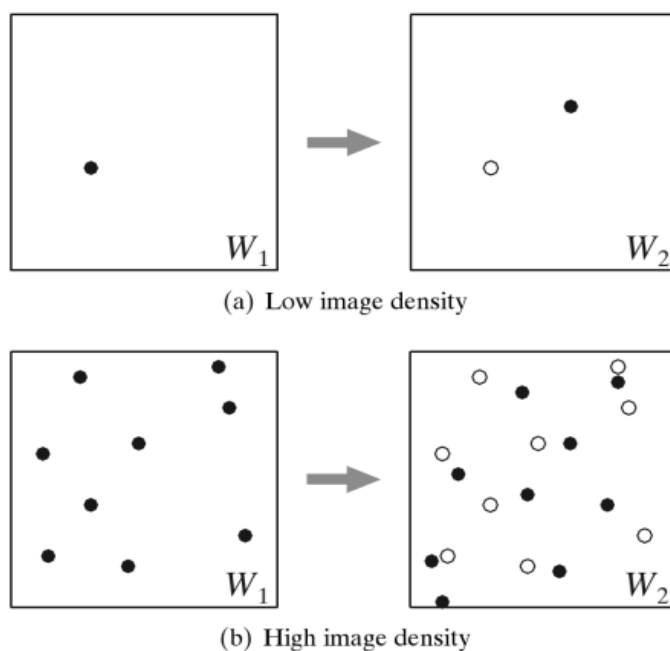
Figure 8 Schematic of the particle images as they appear within the interrogation areas (W_1 and W_2) of two subsequent images. The white and black dots represent the particle images in the first and the second exposure respectively (Adrian & Westerweel, 2011)

To increase the number of valid vectors beyond the limitations of particle tracking, it is necessary to increase the number of particles (the mean number of particles N_I within

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each interrogation area must be $N_I \gg 1$, for high-image-density) and invoke statistical methods that track the displacement of small groups of particles instead of individual particles.

When setting up PIV it is important for the operator to evaluate the motion field of the particle tracers (Scarano, 2013).

1) The most common approach is to divide the entire image into *interrogation areas*. Each interrogation area becomes an individual measurement volume where the local velocity vector is evaluated. Typical sizes of the interrogation areas range from 16×16 pixels to 128×128 pixels.

2) Then a statistical tracking operator can be applied to the corresponding areas extracted from the two exposures. This process returns the discrete cross-correlation map (a two dimensional array), whose peak position relative to the origin indicates the average particle image displacement.

3) The highest peak in the correlation map is selected as that corresponding to the particle motion. Its position is naturally found at the closest integer pixel shift.

4) Velocity is obtained dividing by the known time between laser pulses, multiplying by the size of the pixel and dividing by the imaging magnification.

The entire sequence of operations needed is illustrated in Figure 9.
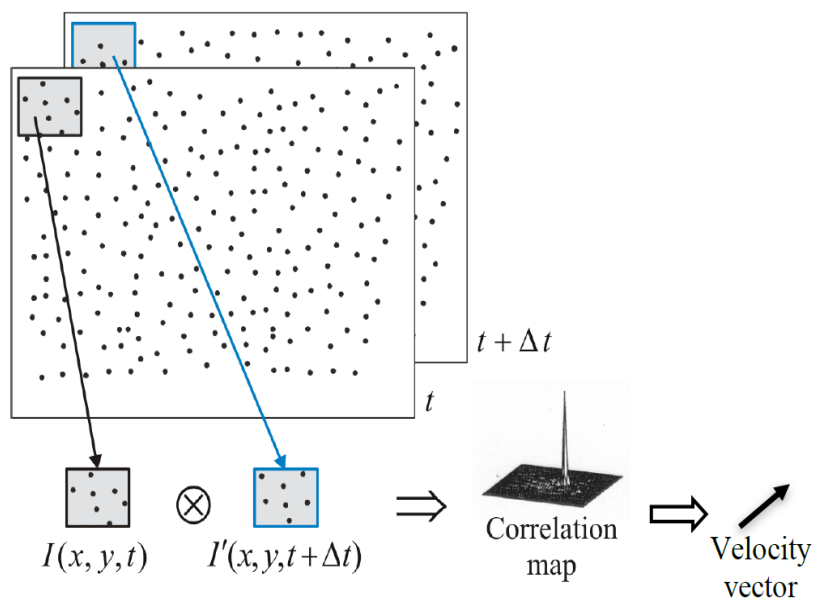
Figure 9 Image windowing and discrete cross-correlation map (Scarano, 2013)

In order to understand how the displacement vector is extracted from the interrogation areas, consider the one-dimensional example of Figure 10. The two interrogation areas I and I' contain three particle images which move 7 pixels during the time between the first and the last laser pulse. The cross-correlation function ϕ exhibits the highest peak ϕ_1 displaced of 7 pixels from the origin (Figure 10-right). The cross-correlation function features additional peaks due to noise and the correlation of non-paired particles. The ratio between the highest peak and the additional peaks are called *signal-to-noise ratio*. High values are preferable because that indicate high robustness of the PIV measurement.
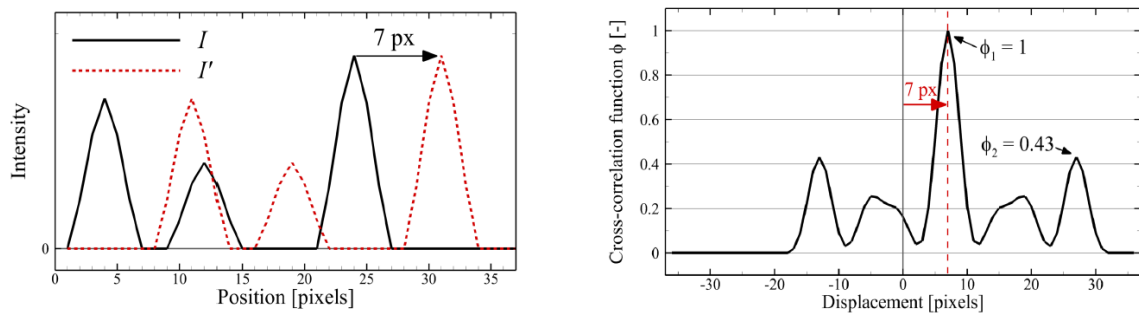
Figure 10 Example of cross-correlation in 1D. Left: intensity recorded at time instants t and t+ Δt. Right: cross-correlation function (Scarano, 2013).

3.2.8 Validating the Interrogation
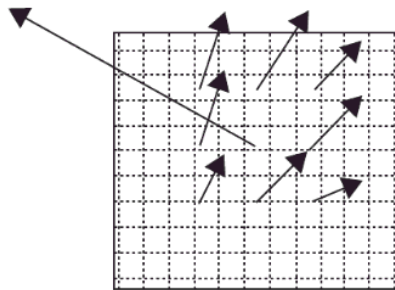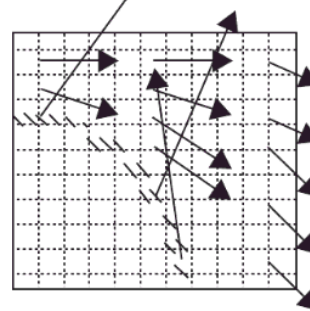
Figure 11 Invalid vectors: a) caused by particle grouping within an isolated interrogation spot. b) caused by image distortion on a boundary leading to a group of invalid vectors (Adrian & Westerweel, 2011, p. 28).

Invalid vectors have values that vary randomly over the full-scale range of the PIV measurement. There are two types (see Figure 11), both occur because the tallest

correlation peak is not the displacement peak. Either the displacement peak is too small or the largest noise peak is too high. Too few particles in one spot, smeared correlations due to large velocity variations or smeared images can all give small displacement peaks. Large noise peaks occur when random particle patterns create large correlations.

By assuming that the fluid flow field varies smoothly one can remove invalid vectors as the ones shown in Figure 11. It is done by exploiting their large, erratic errors, which makes them look very different from the average vector in the total field or from their neighbors.

After removing all these invalid vectors, the validation process proceeds in several steps (Adrian & Westerweel, 2011)

1. Compute the mean over all vectors in the PIV frame and the *root mean square* variation with respect to this mean. These values give a general or *global* estimate of the vectors in the frame.
2. Each vector is compared with the global mean. If it differs too much, say, three *root mean square (rms)* units, it is judged to be invalid. Repeating this process for each vector deletes the obviously invalid vectors, leaving holes in the data grid and some invalid vectors that were not detectably invalid in the first pass.
3. Comparing each vector with the mean or median of its neighboring vectors. Holes in the grid are filled by interpolation using neighboring vector measurements.
4. Once a field of displacement vectors is validated, a low-pass filter is applied to remove high-frequency measurement noise associated with errors in the measurement of valid vectors. The frequency response of this filter determines the spatial-frequency response of the entire measurement.

In order for validation methods to be reliable, the number of valid vectors should exceed 90%.

3.3 Test Section Design for optimized PIV measurements

When designing a test rig one should keep in mind what kind of experiments that are going to be conducted on the rig. To have a good PIV setup it is important to be able to insert a calibration target into the test section. In addition, if the flow medium is water, the calibration should be done with the target in place and the section filled with water
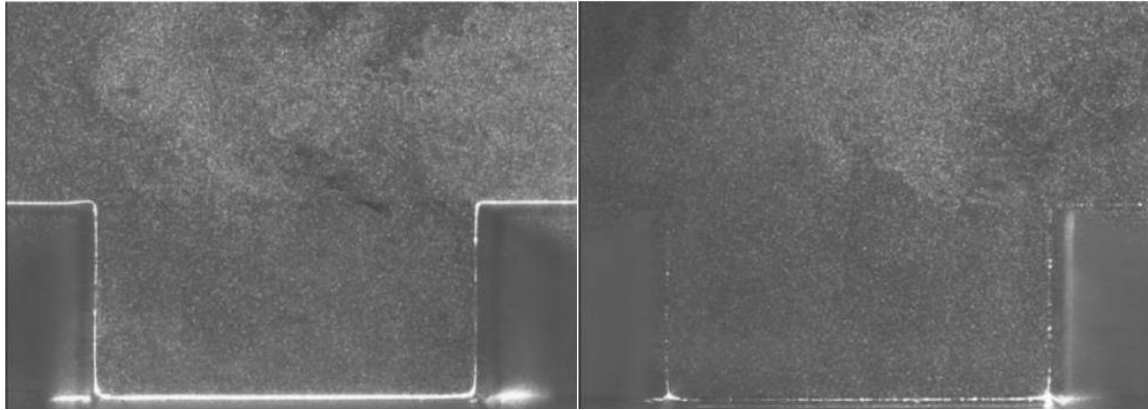
Figure 12 Images of seeded air in an open cavity illuminated by a light sheet from above (Image courtesy of V. Koschatzky & E. Overmars).

due to refraction. Another thing that has to be accounted for during test section design is reflections.

It is difficult to avoid surface reflections when working with PIV close to surfaces and objects. In contrary to what one might think using black paint to reduce surface reflections or surface glare is not very effective. Actually the reflectivity of common black paint is 10 % compared to that of PMMA is only 4 % (see Figure 12).

If the test rig is going to operate in a closed loop system, the designer must arrange for a way to inject the seeding. An injection device installed on a pipe in the low pressure part of the system is recommended. Seed material can settle to the bottom or aggregate into unacceptable large clumps when the rig is not operating. Therefore it is necessary to design the test section so that it can be accessed and cleaned. Another solution is to drain the system when it is not operating, and a stirring device to prevent some of the seeding from settling.

3.4 Optimizing the PIV setup

When all the equipment have been aligned and the software is up and running it is time to optimize the PIV measurement, with an aim to fulfill as many as possible of the design rules below (Adrian & Westerweel, 2011; Scarano, 2013; TSI, 1995, p. 29).

Table 1 Design rules for an optimal experiment

1)	$N_I > 10$	The mean number of particles N_I within each interrogation area must be higher than 10. Tracers should be added in small increments to approach this concentration. This is done while the time between pulses is kept to a minimum value. After adding seeding one takes a few image pairs and determines the spatial correlation.
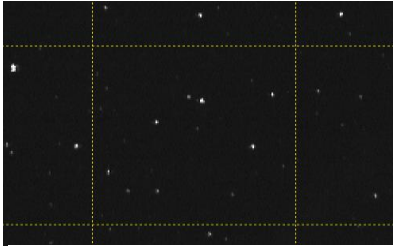
Figure 13 Too low N_I (Image from DynamicStudio)

2)	$|\Delta X| < ¼ \, D_I$	The time between pulses should be chosen in such a way that the majority of particles are imaged in the same IA at both exposures. Therefore, the particle image displacement between the first and the second window in the image domain should not be larger than 25% of the interrogation area. This ensures that the number of particle pairs is large enough.

Figure 14 Correct and too long (Scarano, 2013)

3)	$|\Delta z| < ¼ \, \Delta z_0$	The out-of-plane displacement must be less than 25% of the light sheet thickness. This condition is especially important in cases where the out-of-plane component is strong, e.g. for turbulent flow.
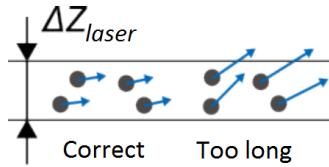
Figure 15 Correct and too long (Scarano, 2013)

4)	$|\Delta X| > 2d_p$	Minimum in plane displacement should be two particle-image diameters.

5)	$M_0 |\Delta u| \Delta t < d_\tau$	The product of the image magnification factor, absolute value of the local variation of the velocity vector and the time between pulses must not be larger than the particle image diameter.

6) $\dfrac{d_\tau}{d_r} \approx 2 - 4$

The pixel resolution requirement.

Figure 16 Pixel resolution
(Image from DynamicStudio)

These rules contain Δz_0, M_0, dr, C, Δt, D_I, and the maximum values of the velocity components and the gradients. The first three are fixed by the system hardware, and D_I will be optimized to achieve the best resolution during the interrogation analysis. Therefore, the particle concentration C and the time between pulses Δt are the values to be optimized first.

1) Start by letting the software fire laser and camera in continuous mode. Start at the lowest value of Δt such to obtain two almost simultaneous exposures.
2) Switch on the grid, inspect the image pairs and estimate the percentage of pairing particles.
3) If almost the totality of particle images is paired, then proceed with increasing the seeding density by following the steps in 8 under *Particles* and monitor the signal-to-noise ratio of the correlation function.
4) Keep increasing the seeding level gradually until a correlation signal-to-noise ratio above 3 is achieved overall in the measurement domain. The experiment has a high chance of success if the flow is uniformly seeded with required concentration. Once a ratio close to 100% between valid and invalid displacement is reached, no further particles should be added.

The next step is to increase Δt, in small increments, towards the target value. By increasing Δt the number of valid data begins to drop. If it drops below an acceptable level before the targeted time between pulses is reached, one can add more tracer particles to further increase the concentration and the rate of valid displacements. This iterative process is repeated until the target Δt is reached, where the design rules are satisfied.

4 Three Guide Vane Cascade

A test rig that represent the flow in the guide vane cascade of a high head Francis turbine is being designed for experimental investigations at TTL. It is called *3 GV Cascade* and the design is based on the geometry of Jhimruk Power Plant in Nepal. CFD simulations are performed to make sure that similar pressure and velocity distributions are obtained in both test rig and prototype. The setup for 3 GV Cascade is designed using the same approach that was applied when designing the *1 GV Cascade* test rig that is being built at the Waterpower Laboratory at NTNU the spring of 2015. More information about the designs and development of these two test rigs can be found in (Thapa, et al., 2015; Haugvaldstad, 2014).

The main objective is to study the flow in the guide vane section and use that to develop a cascade of guide vane passages which has uniform flow conditions from stay vane outlet to runner inlet, with a long term aim of reducing sediment erosion in Francis turbines. Included in this section are recommendations for HSE for TTL, descriptions of the experimental test rig, a stress analysis and procedures for production, leakage -and pressure testing, operation and PIV setup for 3 GV Cascade.

4.1 One GV Cascade vs Three GV Cascade

Compared to 1 GV Cascade, which has two flow channels and one GV, 3 GV Cascade consists of four flow channels and three guide vanes. The reason for this difference is that one can investigate different flow aspects. On 1 GV Cascade it is possible to study;

- influence of clearance gap
- change GV Reynolds number
- investigate the flow around the GV in a full scale Francis turbine
- velocity and pressure distribution around the GV

Since 3 GV Cascade has three free-standing GVs it is possible to study;

- flow at different angles of attack by varying the angle on all three GVs
- different guide vane profiles designs
- different eroded profiles

4.2 Health, Safety and Environment – HSE

The Waterpower Laboratory at NTNU would like to see that TTL start to take actions towards implementing HSE routines that has the same standard as those at NTNU. Therefor as a part of this thesis, recommendations for cleanliness and safety equipment are given, and a procedure for safe laser operation has been made.

The book *Laboratory and workshop handbook* was written with an aim to ensure a healthy and safe working environment. "HSE matters involve leadership and personal responsibility – a duty to safeguard our personal safety, health and environment, and the safety and well-being of our colleagues." (Bovim & Steinsmo, 2014). The handbook includes information about general safety, protective equipment, first aid, fire, risk assessment and hazardous equipment like class 4 lasers. This book can be downloaded from the internet, and is highly recommended to follow for all that is going to work in labs or workshops at KU.

As a minimum requirement all persons working in the laboratory at TTL should attend a HSE course to get a basic introduction and understanding of the importance of HSE. In addition, a tour in the lab together with the HSE responsible to get an orientation of the locations of fire extinguishers, first aid kits and other important features. Before an experiment is carried out, a risk evaluation has to be made and approved. An apparatus card must be placed on the rig at all times, and a work in progress sign must be hung on the rig under the experiments. The experiment need to be reported to the HSE responsible before starting. Important papers like procedures should be in a binder next to the rig. For own protection, protective glasses and hearing protection must always be used when an experiment is running, and the operating procedures have to be followed.

4.2.1 Cleanliness of the laboratory

The laboratory is located in a sandy area and this introduces a lot of dust. The dust covers all surfaces and pollutes the reservoir and all the equipment at TTL. This impacts the density of the water, damage equipment and instruments and can give incorrect results when performing tests and reduce the service life of machines and equipment. From a PIV point of view dust, sand, rust e.g. can make the test results worse since they also reflect the laser light. A possible solution to this problem is to make sure that all windows

and walls are properly sealed and to install a ventilation system with a filter that is changed on a regular basis.

Roof, walls and floors are made of concrete. If sealed and properly maintained a concrete floor can last indefinitely but none of the concrete surfaces at TTL have been treated. This makes the concrete very susceptible to penetration by moisture, which over time can make the rebar corrode and crack. In addition the wearing surface is weak. In a lab like TTL it is important with a clean

Figure 17 Epoxy floor (QLD, 2014)

environment. Therefore, to minimize or eliminate dusting, it is recommended to apply a chemical floor hardener or epoxy. Then dusting will not be a problem and the surface will be more durable and easier to keep clean.

4.3 Production of the test rig

When working with the detailed drawings of the test rig, it important that the one making them has knowledge about how a manufacturer read the drawings, in order to give all information needed. After completing the drawings, they have to be reviewed to make sure all details are correct. When manufacturers have accepted to make the components, meetings to discuss the details should be conducted to make sure there are no misunderstandings or confusions. It is convenient to have only one manufacturer making the whole test rig, because then it is easier for them to understand the total design of the rig.

When the parts start to arrive an important part begins – all parts must be examined to make sure that they are made as prescribed; correct material, surface finish, slots for o-rings, correct dimensions of holes for bolt etc. It is recommended to assemble the parts before the final installation so that design faults are discovered at an early stage.

4.4 Test section of 3 GV Cascade

A description of the test section of 3 GV Cascade has been given with the intention to give the person that will continue the work with this rig (CFD of different test section

design, detailed drawings, instrumentation, production etc.) an introduction. For more information about the rest of the test rig parts, materials and dimensions see Appendix D.

The test section (Part 3 in Figure 18) is designed using free vortex streamlines, GV geometry and CFD optimization. In the flow channel there are three 97 mm NACA 0012 guide vanes.
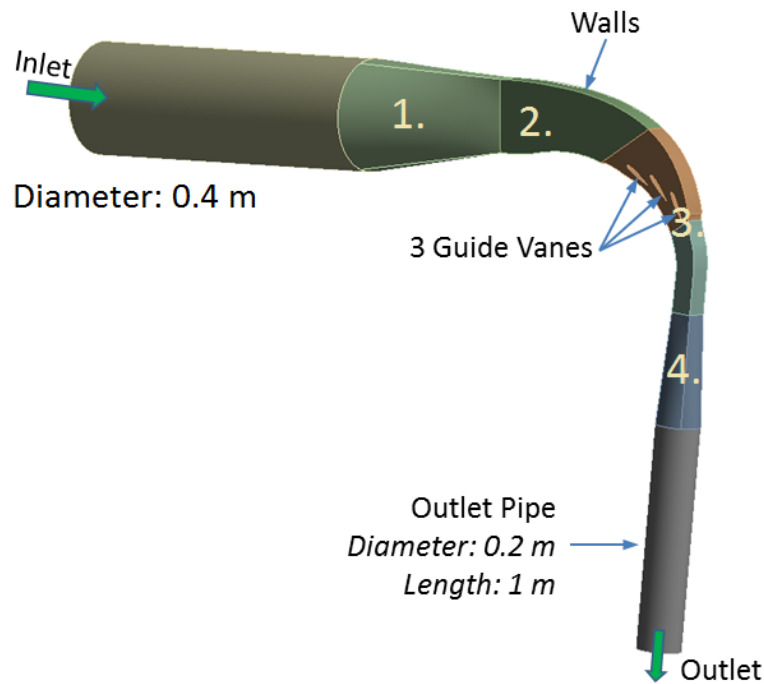
Figure 18 Flow channel of 3 GV Cascade with numbered parts (Thapa, et al., 2015)

It is going to be possible to access the test section from the back side, visualize the flow from stay vane outlet to runner inlet on the front side and do PIV measurements at different points of the test section.

4.4.1 Design suggestions for test section flow channel

The flow channel design has not yet been finalized. To create at test rig takes time and also often cost a lot of money. It is of great importance that the test rig design is flexible, so that several different studies and experiments can be conducted on the same rig without too big modifications. In addition, ensure that the flow in the test rig and CFD model is close to similar by making the design possible to manufacture. Therefore, as a part of this thesis, different design suggestions have been made.

The green lines on the walls of the test section in Figure 19a) have the same shape as NACA 0012 guide vane profiles. It is believed that this is increasing the similarity of the flow conditions in the test rig and the reference case, and CFD simulations show that pressure and velocities are close to the reference case (Thapa, et al., 2015).

a) Design made by Biraj Singh Thapa

b) Modified design made by writer

c) Difference between designs; Inner lines – original design, Outer lines – modified design
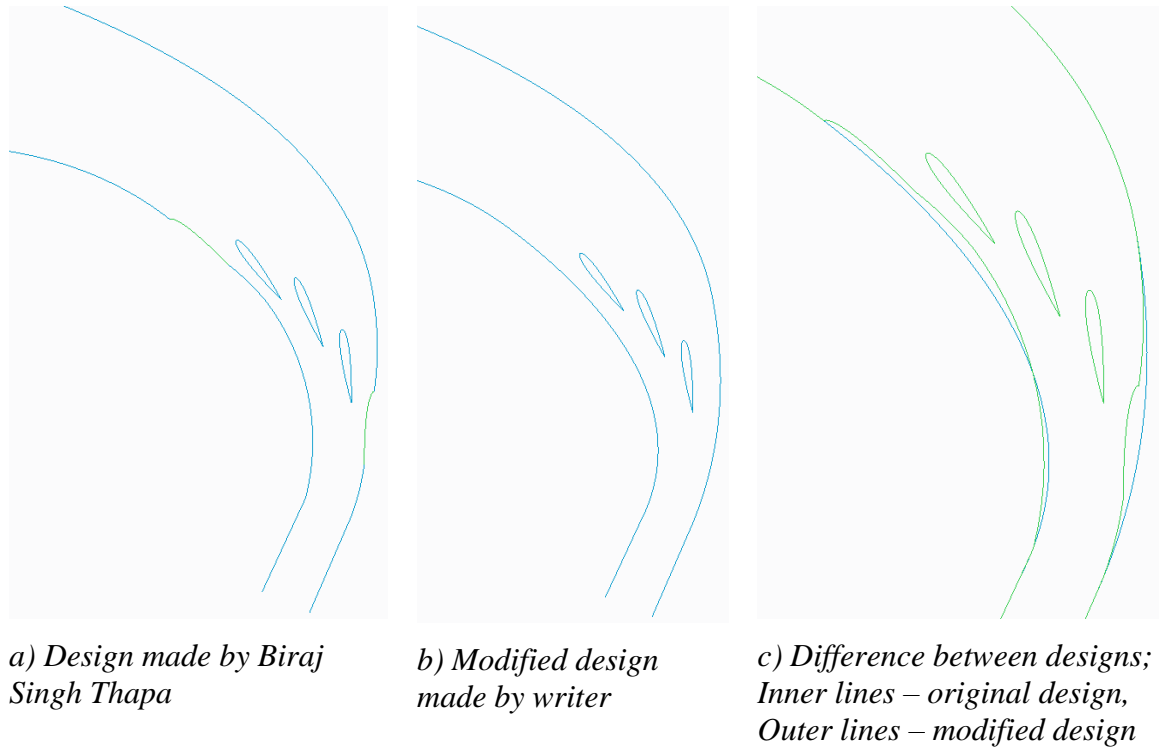
Figure 19 Different flow channel designs (Writer's own drawings)

One of the reasons for making Three Guide Vane Cascade different from the one installed at the Waterpower Laboratory is to have the ability to change between different guide vane profiles and angles. If the walls of the test section have the geometry of a NACA 0012 GV as in the reference case, this will not match the new GV designs or the angles. The same problem will occur when eroded profiles are inserted. On the other hand, this will not be a problem as long as the flow around the guide vane in the middle is not disturbed by the walls. It is therefore recommended to perform CFD analyses on several flow channel designs.

A simpler geometry of the flow section walls will make the manufacturing of the flow section easier, and it will give smoother surface finish that would be beneficial.

4.4.1.1 Guide vanes

For 1 GV Cascade, Biraj Sing Thapa designed one guide vane for pressure measurements and another one for velocity measurements as can be seen in Figure 20. This was necessary because the areas of interest for the two setups are different. The guide vanes are very small, only 97 mm high with a cord length of approximately 143 mm. Hence, manufacturing and installing all the small tubes and pressure taps must be performed with high precision. The guide vanes that were designed for 1 GV Cascade are going to be used for 3 GV Cascade at TTL as well.

The guide vane designed for velocity measurements consists of three main parts that all have holes for tubes and pressure taps. The front part of the GV is made of plexiglass so that the laser light sheet can light through it. The cross section of the front part is visible through the front cover of the test section. The back part is made in five different thicknesses, giving a variation in clearance gap of 0 – 4 mm between the guide vane and the plexiglass on the front side.

a) *Guide vane for velocity measurements*

b) *Guide vane for pressure measurements*
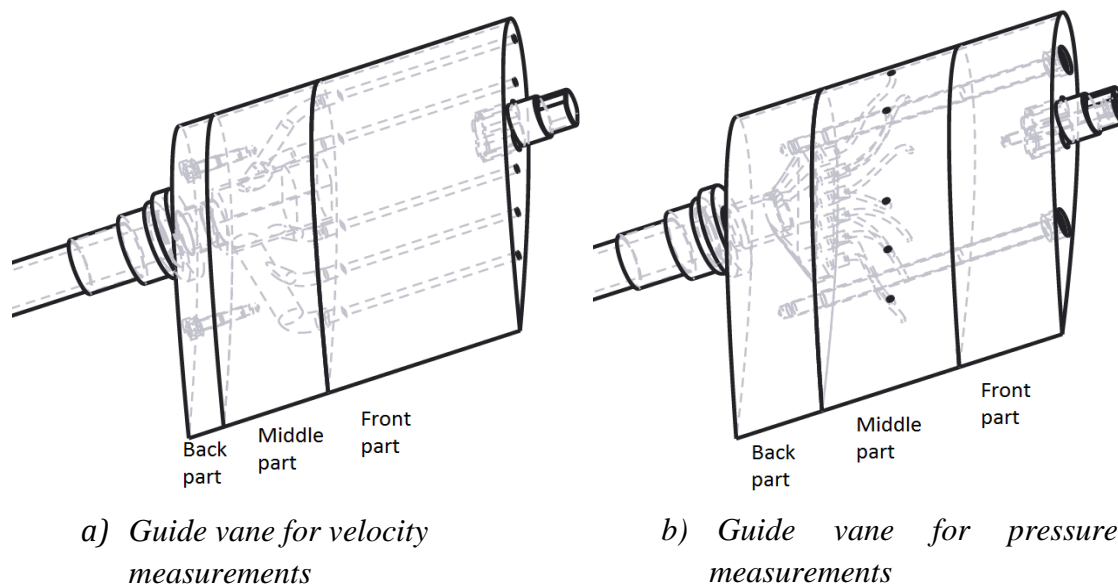
Figure 20 Guide vanes designed for 1 GV Cascade and 3 GV Cascade (Thapa, 2015)

The guide vane for pressure measurements also consists of three main parts; all are made of high strength PA. The back part was made in five versions to create clearance gap from 0 – 4 mm. The middle part has ten holes for pressure taps at ten different locations along the same cross-section in the middle of the guide vane height. Since it is going to be possible to change the GV angle on 3 GV Cascade, it will be possible to measure the pressure difference between the pressure- and the suction side at different angles. That

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can give an insight to the conditions that occur in the reference case when operating outside the design point.

It is important that the two guide vanes for the last two flow channels are made of plexiglass so that the laser light sheet can light through them and illuminate all of the flow sections in the channel.

4.5 Placement and instrumentation

During the visit at TTL, the best options for placing the rig was discussed. There are several options for implementing the test rig at TTL. There are plans of installing two other test rigs, one Pelton and one Francis, at TTL soon. If both of these rigs are installed at the same time, there is only one meter clearance between them at the narrowest point. To install 3 GV Cascade next to these other two rigs will most likely result in a very crowded laboratory.
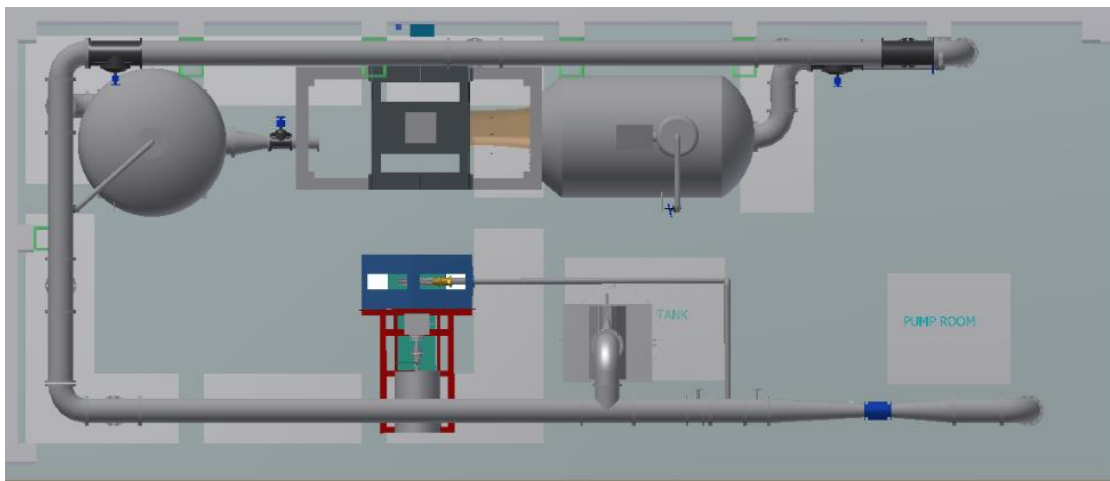
Figure 21 TTL with both the Francis (top) and Pelton (bottom) model test rigs. View from above. (Rasmussen, 2014)

After spending some time working on different ways to arrange the test rigs, the best option seem to be to have the Pelton rig and 3 GV Cascade installed at the same time. Then there will be enough space between the rigs to achieve good working environments for the researchers and one rig can be operated when the other is not. In addition the high pressure tank and other instruments needed like flowmeters, valves, pressure transducers and calibration setup etc. that Inger Johanne Rasmussen made arrangements for can be used for 3 GV Cascade (Rasmussen, 2014, pp. 40-52). Fortunately Rasmussen's recommendations were made with the desire to have a flexible and multifunctional system that could be used for several rigs and not only for the Francis rig.

An illustration of TTL with 3 GV Cascade installed has not been made since the final design of the test rig is not completed.

4.5.1 Pressure tank

It is important to have a system free from air and gas bubbles, at least as close as possible. To achieve this, the velocity and pressure measurements should be done in a closed loop with a high pressure tank in front of the rig. Pressure tanks help to elongate the pumps lifespan because the pumps can run on a constant speed of rotation. Tanks also reduced water hammer instances because they keep a constant water pressure in the irrigation lines.

Today TTL does not have a pressure tank, but Inger Johanne Rasmussen designed one for TTL as part of her master thesis. That tank is also suitable for this test rig. Information about the pressure tank can be found in her master thesis (Rasmussen, 2014).
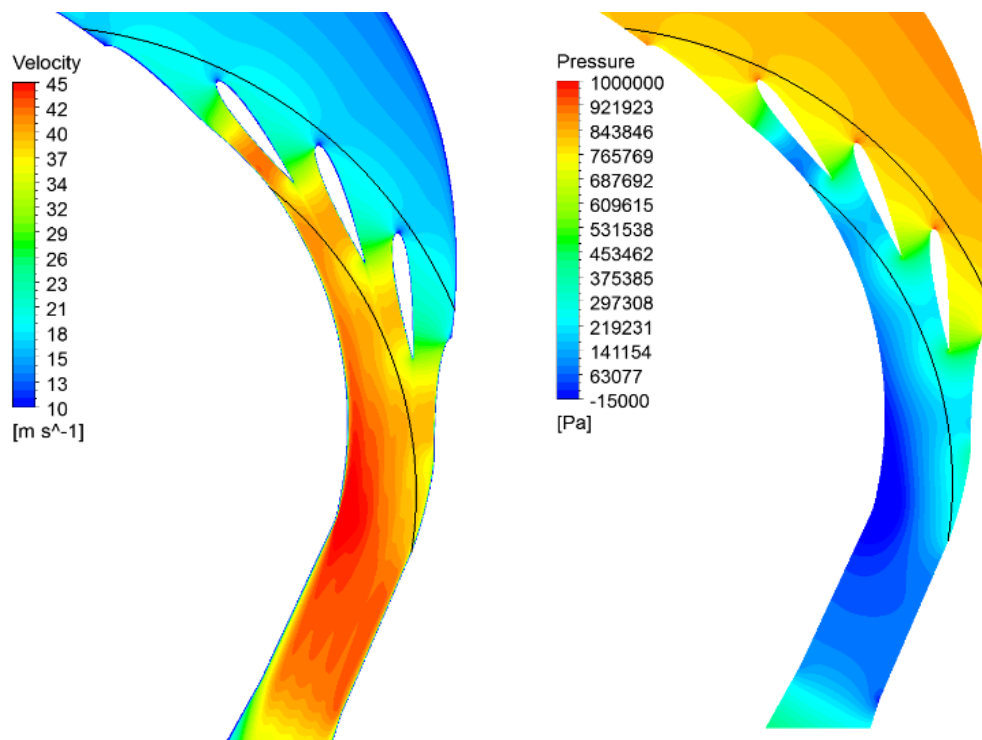
Figure 22 Velocity and pressure profile for optimized 3GV design. The black lines represent the stay vane outlet and the runner inlet of JPP respectively (Thapa, et al., 2015).

For the test setup for 3 GV Cascade it is not necessary to have a low pressure tank, this is based on the CFD simulations in Figure 22. These distributions satisfy the laboratory constraints (maximum pressure of 10 bars) and cavitation in the regions where measurements are going to be taken is avoided.

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4.5.2 Flowmeter

A decrease of diameter at the place of the flowmeter is necessary to get high enough velocity and in turns the required accuracy of the measurement. This involves a decrease upstream the flowmeter and an expansion downstream (α < 6 degrees). In addition the pipe upstream must be longer 10×DN and the downstream pipe must be longer than 2×DN. This location takes up less space since it is 4 meters above the floor, but it limits the ability to read the flowmeter display.

The pipe setup in Figure 23 can be used for all rigs at TTL. Flowmeter DN 100 is for the Pelton rig and DN 200 is for the Francis or 3 GV Cascade test rig.
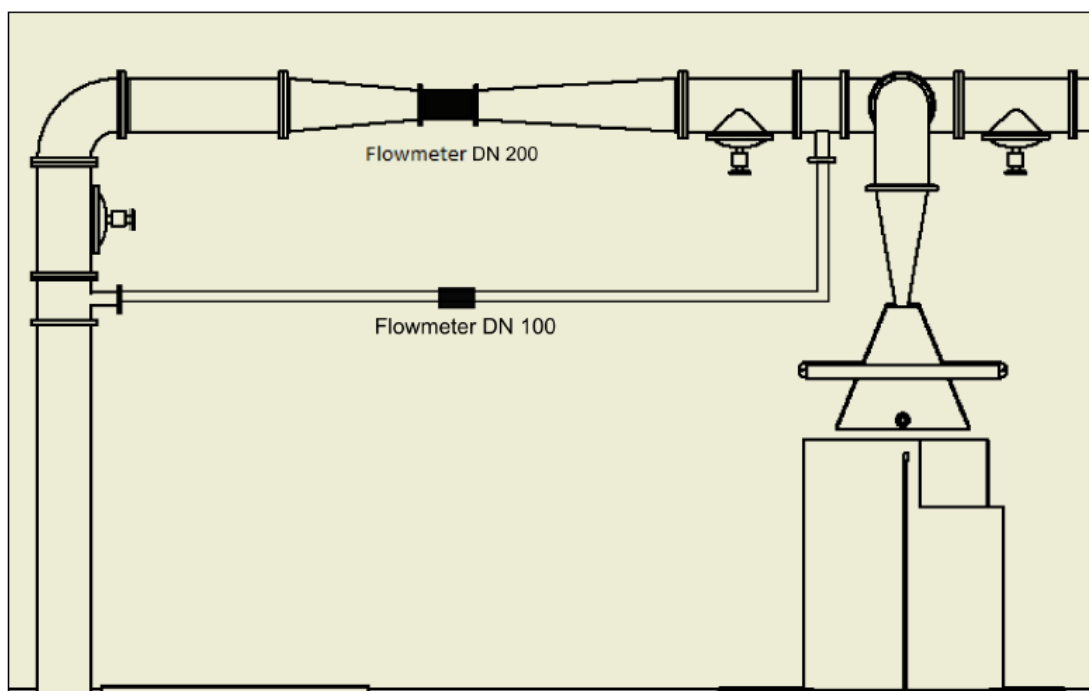
Figure 23 Location of flowmeters and calibration facility at TTL. Location is on main pipe downstream pumps, horizontal after bend (Rasmussen, 2014, pp. 49-52)

4.5.3 Valves

It is necessary to install several valves to be able to operate 3 GV Cascade at TTL; one between the pressure tank and the test rig and on downstream the test rig. This will make it possible to fill the test section with water when doing leakage- and pressure testing. It is also necessary to operate these valves when calibration images are to be taken or preparing the rig for normal operation. In addition valves need to be installed at the pipe system in order to guide the water in the right direction. The valves needed for the Francis rig which Rasmussen made arrangements for can be used for 3 GV Cascade as well. It will not be necessary with additional valves.

4.5.4 Bleed valves

Bleed valves is needed at the top of the pressure tank, at the highest point of the test rig and at some locations on the pipe system in order to vent air out of the system when operating in a closed loop.

4.6 Operating 3 GV Cascade

It is necessary to develop a LabVIEW program where one can control the pumps and see the flow rate in the pipe system when operating rigs at TTL. A logging program for pressure and flow measurements around the pipe system must be made. It should be possible for the user to set the sampling rate for the pressure measurement (not less than 10 Hz) and it must be possible to log to a excel file on the command from the user.

To get a precise calibration it is best to use a calibration target. It is necessary to capture calibration images every time new measurements are going to be conducted. To insert and remove a target from this flow channel will be a time consuming operation. In addition it is recommended from theory that both target and laser sheet is in the same plane in the flow channel and that the calibration target should be large enough so that the markers occupy the full field of view of the camera. It is therefore important to think of how to do the calibration while designing the test section in order to come up with a good solution.

To have a calibration target as a part of the measurement guide vane is one option. It is not ideal since the guide vane only take up a very small section of the view of the camera. Another option is to implement a calibration target in the plexiglass front (inside in the flow section). Then it will not be at the same location as the laser light sheet (where the focus of the camera must be). In addition refraction due to water/wall interface will not be
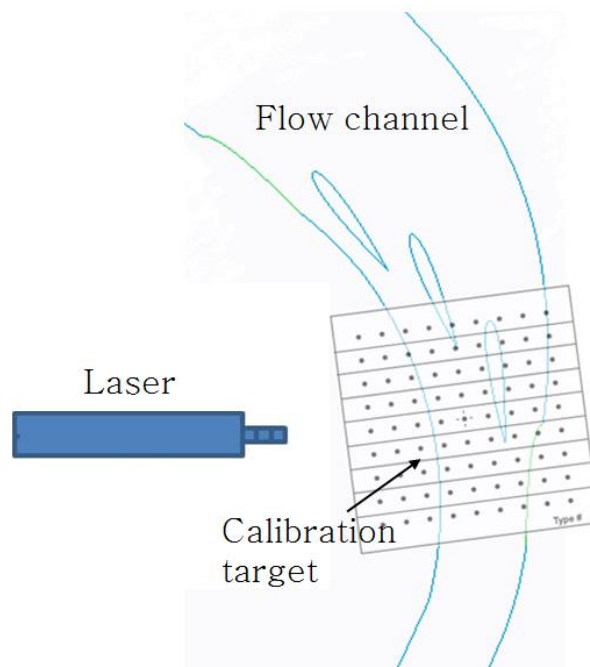
Figure 24 Calibration target as part of back steal plate (Writer's own sketch)

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accounted for.

The best option will probably be to place the target on the inside of the back steel plate. It will still not be in the measurement plane, but then it will at least fill the whole view of the camera. If some part of the target is covered by one of the guide vanes there will probably still be sufficient points for the software to recognize the target. This has been illustrated in Figure 24. The camera would capture from opposite view.
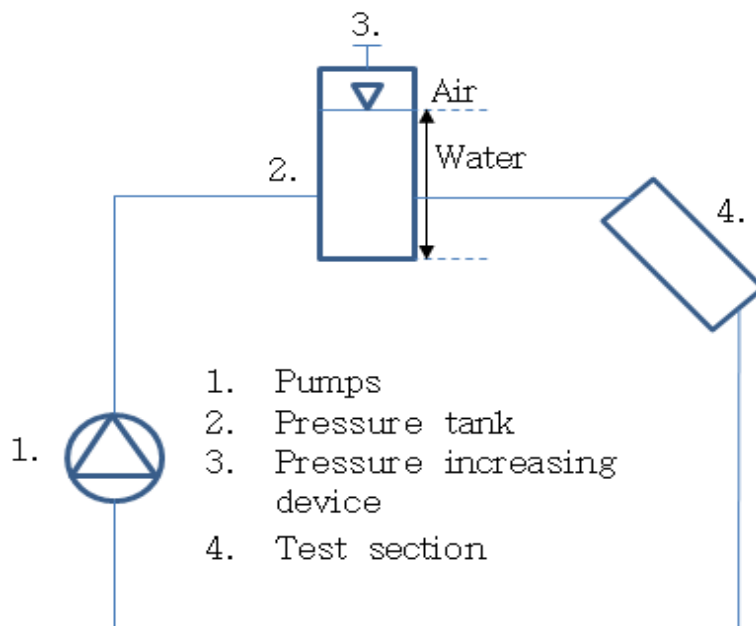
Figure 25 Simple sketch of system
(Writer's own sketch)

The water flows from the pump through the main pipe system to the pressure tank, and is led from there through the test rig and back to the pumps as can be seen in Figure 25. The pressure in the tank can be increased either manually by pumping air into it until the required pressure is reached or by connecting a compressor. It is important for the operator to check that the pressure is higher than the vapor pressure in order to avoid cavitation in the system. This can be controlled by making arrangements for pressure measurement near the outlet of the test section as well as at the pressure tank.

The diagram in Figure 26 illustrates the new design of the test rig setup at TTL, including instrumentation, pipe system, tanks, t-outlets, valves, and test rigs.
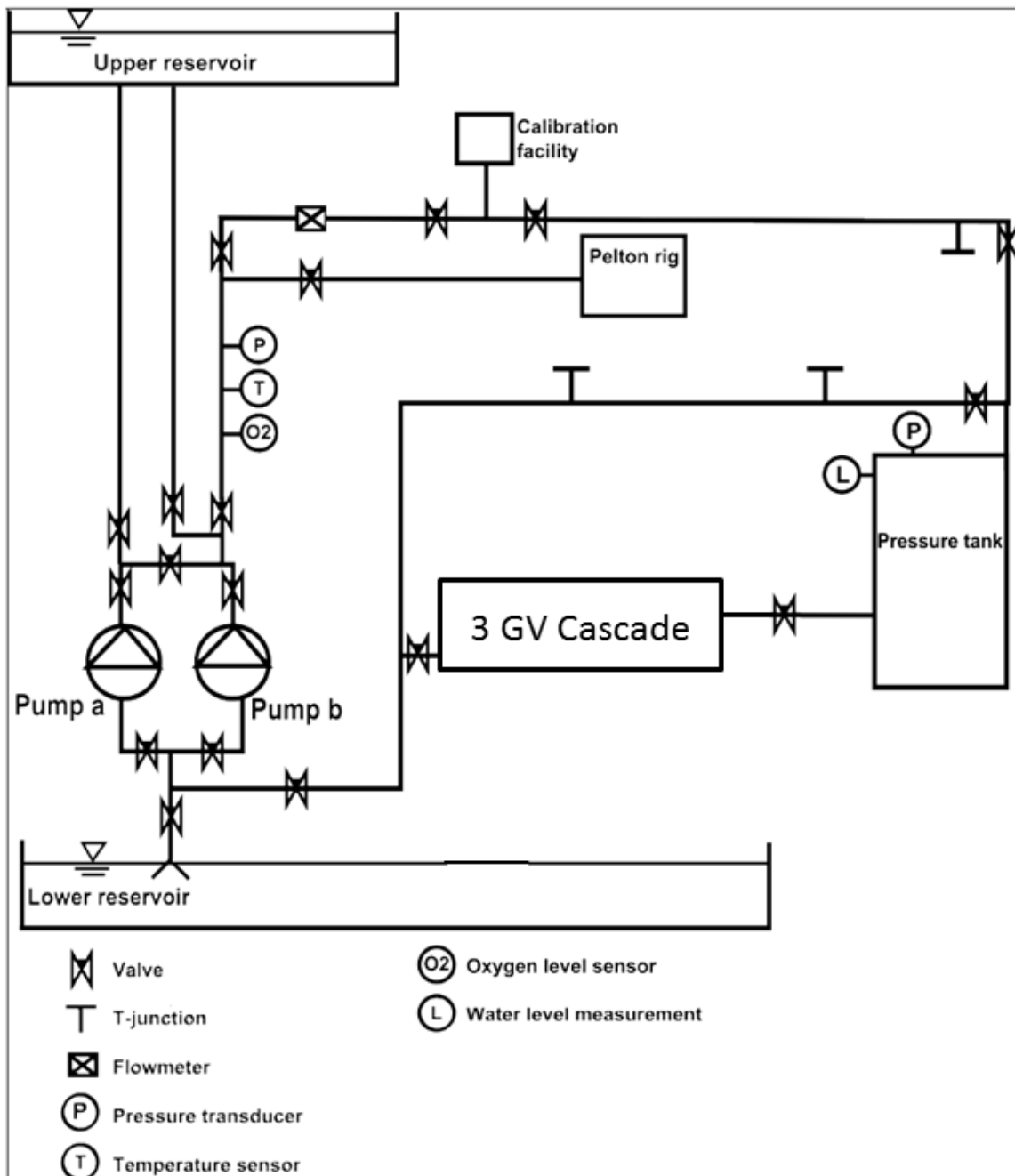
Figure 26 Diagram of the new design for TTL with GV Cascade instead of Francis rig modified by writer (Rasmussen, 2014, p. 63)

To make the 3 GV Cascade test rig function for performing test, a data acquisition program, computers and various software in needed. Choice and design of these components are not within the scope of this thesis.

5 Procedure for leakage - and pressure testing

This procedure has been made based on discussions with Bård Brandåstrø about how leakage and pressure testing will be done on 1 GV Cascade at the Waterpower Laboratory. The procedure should be revised after more experience has been gained from running 1 GV Cascade.

Note: All parts must be flushed with water and visually verified before the leakage -and pressure testing

- Isolate the test rig
    - Close the valves upstream and downstream of the test rig
- Fill the test rig with water from the highest point
    - Leaking $\Rightarrow$ locate the leakage and seal it

Figure 27 Warning sign (Signs, 1996)

Before one can start to run the rig with high pressure and velocities it is necessary to do pressure testing and get the rig certificated for 10 bar pressure.

- Isolate the test rig
    - Close the valves upstream and downstream of the test rig
- Fill the test rig with water from the highest point
- Connect a manually operated water pump to the test rig

Figure 28 Manually operated water pump from Ridgid used at the Waterpower Laboratory (Writer's own image)

- Increase the pressure gradually, in three or more steps up to test pressure.
  - o Check for leakage at the end of each step (1 step should be 5 to 10 minutes)
- Increase the pressure to the test pressure required by local authorities. Measure pressure with manometer.
  - o The test pressure is kept at least 30 minutes.
  - o All connections should be checked visually, and it should not be visible drop on gauges.

6 Procedure for operating 3 GV Cascade

The following procedure is for operating the 3 GV Cascade rig in closed loop. The procedure has been made based on discussions with Bård Brandåstrø about how 1 GV Cascade will be operated at the Waterpower Laboratory.

Note: The loop must be filled with water before starting to run the rig

Filling the rig

1. Prime the pump
2. Turn on the power of the pumps
3. Make an inspection around the laboratory
   Make sure that all drain tubes are closed
   Check for water leakage around the rig
4. Let the ventilation valve on top of the pressure tank be in an open position
5. Open the bleed valves at the pressure tank, the highest point of the test rig and pipe system
6. Set the pipe loop by opening and closing the necessary valves

   Reservoir: OPEN
   Inlet pump: OPEN
   Outlet pump: OPEN
   Inlet pressure tank: OPEN
   Inlet test rig: CLOSED

Figure 29 Warning sign (Signs, 1996)

For Calibration of PIV setup only

1. *Start the pump*
   Start the pump at a 100 rpm
   Increase the speed of the pump gradually until the water start to flow through the test section
2. *Close the back valve and let the test section be filled with water*
3. *Run down the pump, 100 by 100, until 100rpm and then stop it.*

7. Start the pump
   Start the pump at a 100 rpm

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Increase the speed of the pump gradually to start filling the pressure tank. The water level should stand a bit over the outlet to the test rig

8. Open the valve to the inlet of the test rig to fill the rig and pipe system

9. Make an inspection in the laboratory

10. Close the bleed valves when only water is coming out and no air

11. Close the valve to the inlet of the test rig

12. Increase the tank pressure by slowly increasing the speed of the pump or us a manual pumping device or a compressor that is connected to the pressure tank until the desired operating conditions in the test rig is obtained

13. Close the ventilation valve on top of the pressure tank when the intended water level is reached

14. Close the valve to the reservoir

15. Open the valve which guides the water in the pipe system back to the pump

16. Open the valve to the inlet of the test rig

17. Monitor the pressure in the tank

Do an inspection around in the lab, do not forget to check the pump

18. Open the bleed vales to check if there is more air in the system, and close them

Run the test as planned

Shut down

1. Run down the pump, 100 by 100, until 100rpm and then stop it.

2. Turn off the power for the pumps

3. Close valve

Draining down

1. Close the valve to the inlet of the test rig

2. Close the valve guiding the water back to the pump

3. Start the pump and increase the speed

4. Open the valve to the reservoir

5. Open the bleed valve on top of the pressure tank

6. Decrease the speed of the pump slowly to 100 rpm

Keep track of the water level in the pressure tank

7. Stop the pump when the tank is empty
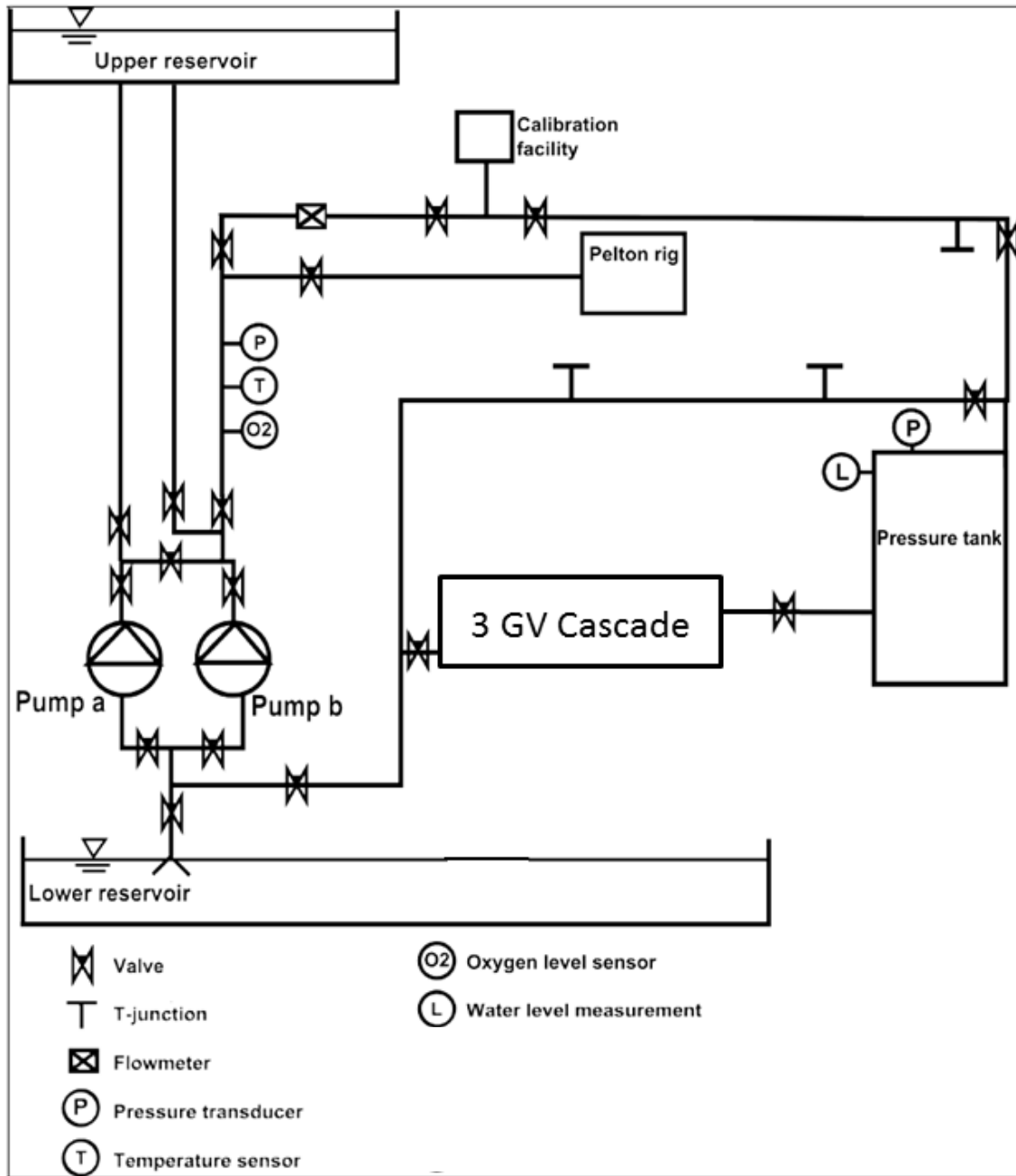
Figure 30 Diagram for TTL, including instrumentation, pipes, tanks, t-outlets, and Pelton test rig, writer included 3GV Cascade where Francis rig was located (Rasmussen, 2014)

7   Guideline for safe use of Class 4 lasers

These guidelines describe the responsibilities related to using lasers and are a summary of the guidelines used at NTNU (HSE, 2013; Section, 2006).

Lasers are divided into danger classes by Norwegian Radiation Protection Authority based on the potential for damage, especially to the eyes. The classes range from 1 (harmless) to 4 (dangerous).

A class 4 laser which generates high-energy infrared radiation that can pose serious risks to eye safety. This radiation is invisible to the eye and can easily pass through the cornea, which focuses it onto the retina in the eye. For this reason it is very important to always wear safety glasses and to be aware of any possible reflections.

Assessment of risk

Before class 3B and class 4 lasers are installed and used, an assessment must be made of the safety of the system in relation to its users, other personnel in the vicinity, the buildings, the environment (e.g. if dangerous gases are used) etc.

Organisation of the users

One of the people working with the laser should have the role as the leader and ensure that people who work with the class 4 laser have sufficient competence to make independent evaluations in terms of safe use of the laser source. Sufficient competence implies apparatus-specific knowledge about starting-up procedures, instrument settings, safety devices, shutting-down procedures, emergency procedures if such apply, the contents of the information binder, any completed measuring of radiation, etc.

Physical barriers

- The laser ray path should be contained as much as possible
- Access limitation to prevent unauthorized persons from entering
- Warning sign with the triangular symbol providing warning about laser radiation on all doors
- Basic information about the radiation and required personal protective equipment

Figure 31 Warning sigh for Class 4 laser (Industries, 2015)

- Laser must be labelled (in the language spoken where it is operated)
    o Exit radiation of the laser
    o Classification
    o Warning against opening the cover of the beam exit point
    o Warning against invisible radiation
    o Label on the laser providing product information

Additional requirements for class 4 lasers
- Visible or audible signal indicating that the laser is on
- The laser should have a device that stops the beam physically, not just an on/off button
- It is required that the laser is equipped with some form of locking control (key, code, etc) and in some cases emergency stop switch

Personal protective equipment

- Laser goggles, labelled and certified so that it is clear which laser they apply for
- Visors, fire-proof clothing, gloves and similar should be available if there are danger of skin injury, which is particularly appropriate in the context of UV lasers and powerful IR lasers
- The equipment required to prevent other persons and enterprises in the vicinity from potential exposure to harmful laser radiation must be available.

Figure 32 Laser googles for Class 4 lasers (Writer's own picture)

Emergency preparedness

The unit must prepare a local emergency plan after assessing the risks associated with its activities and equipment. As a minimum, the emergency plan should include:

- Internal and external procedures for notification/sounding of alarm
- The distribution of responsibilities
- Planned procedures for the handling of specific situations
- Procedures for identifying the extent of an accident/incident

- A description of relevant emergency equipment and where this is found
- Procedures for following up personnel and others involved in the episode

Other persons performing work in the unit, but who are not connected to its academic activities (cleaners, craftsmen etc.), must be informed about the most important properties and dangers connected to the laser, cleaning procedures, the significance of warning signs and warning lights, contact information etc.

Information material

Every class 4 laser should have the following information available. It is recommended to place the information in a visible binder.

- General information (name of person responsible, vital data about the apparatus, assessment of risk factors)
- Operating instructions (starting-up, running, shutting-down, safety precautions, log writing, locking-up etc.)
- Emergency procedures

In case of eye damage

In the case of an accident that may have caused eye damage, the person should be sent to an examination within 24 hours.

In case of proven chronic injury, the employee or student should be referred to an eye doctor for an examination.

Note: It may take some time before eye damage becomes noticeable. If there is any doubt as to whether you have been injured, contact a doctor or eye doctor

Take the following precautions
- Keep the protective cover on the laser head at all times
- Avoid looking at the laser beam, even diffuse reflections are hazardous
- Use protective eyewear at all times. Be sure that your glasses cover the right section of wavelength and radiation intensity
- Expand the beam wherever possible to reduce beam intensity
- The laser intensity must be reduced to minimum every time changes are done

- Establish a controlled access area for the laser operation with a high ambient light level to constrict the pupil of the eye, reducing the possibility of injury
- Post warning signs near the laser operation area
- Set up an energy absorbing target to capture the laser beam, preventing unnecessary reflections and scattering

8 Procedure for PIV setup and measurement on 3 GV Cascade

The test procedures for PIV measurements are based on experiments done on a Swirl rig at the Waterpower laboratory at NTNU using the software DynamicStudio, which is a software delivered by Dantec Dynamics. The Swirl-rig works in an open loop system.

Tent

- Carefully shield the test section to avoid any reflection of laser light from the measurement area to the rest of the premises

Align the laser

- Put up warning sign and lamp and put on protective googles
- Mark the test section where the object plane is supposed to be
- Insert the calibration target
- Start and fire the laser manually
    1. Close the shutter on the front of the laser head
    2. Connect to power supply.
    3. Turn the power supply key switch to the ON position
    4. Set the repetition rate to the minimum position
    5. Press the START/STANDBY button
    6. Open shutter when ready to operate safely
- Operate the laser
    1. Initiate laser firing.
    2. Adjust the repetition rate to the desired setting
    3. Select desired energy level.

Figure 33 Warning lamp (Writer's own picture)

Figure 34 Warning sigh for Class 4 laser (Industries, 2015)

Figure 35 Laser googles for Class 4 lasers (Writer's own picture)

- Align the laser light sheets so that they are parallel to the object plane and flow direction by using a self-leveling laser level

- The light sheets should overlapped to maximize the correlation

- Make sure that the laser will not change position, if possible fix the laser to a table that can be adjusted horizontally and rotated

- Turn down the laser energy and repetition rate to a minimum

- Press the START/STANDBY button

Aligning the camera

- Place the CCD camera perpendicular to the object plane (laser sheet)

- Mark the center of the section that is supposed to be in focus and align the camera by using a self-leveling laser level. Vertically and horizontally.

- Isolate the area around the camera so that it will not easily be touched or moved

- Minimize extraneous light entering the test section

Figure 36 Self-leveling laser level (Johnson, 2015)

Note: Check the default camera pixel resolution in the manual

Focus the camera

o Fill the test section with water (see

- Procedure for operating 3 GV Cascade under *For Calibration of PIV setup only*)

- Open the software, let the camera run while adjusting the camera focus so that the calibration target is in focus

- Use the histogram of the recoded image intensity and check that it has a very large peak near zero intensity, corresponding to the background, and a second peak at higher intensity, corresponding to the target images (assuming that the targets are bright and
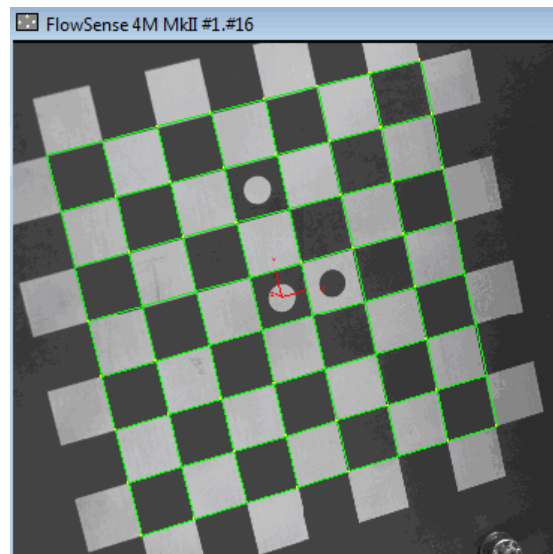
Figure 37 Checkerboard target for 2D calibration (Dynamics, 2013)

42

the background is dark)

Calibration of a single-camera system

1. Close the laser shutter
2. Make sure there is enough light for the camera to capture good calibration images
3. The test section must be filled with water
4. Acquire images, check the quality and save them for calibration
5. Drain the system by opening the back valve and take out the calibration target

Calibration determines the accuracy of the velocity measurement so make sure this is done as accurate as possible.

Particles

It is important that the seeding particles are added to the water flow in such a manner that lumps are not formed or particles are wasted.

Note: Sometimes it is not necessary to add particles, because the water is already seeded naturally or there are some particles left in the system from other experiments. It is therefore important to check this before starting to add more particles.

1. Put on laser googles
2. Fire the laser externally
3. Press the START/STANDBY button
4. Fire the laser and camera
5. Adjust the laser energy from low to higher if necessary
6. Let the camera and laser run and check that he design rules are fulfilled (see 3.4 Optimizing the PIV setup)
7. Stop the laser

Start by adding small amounts of particles check the correlation and add more if necessary.
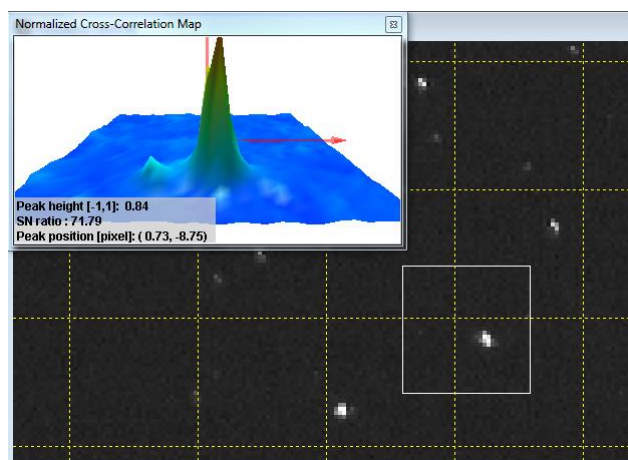
Figure 38 Cross-correlation map
(Image from DynamicStudio)

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8. Pour the particles into a mixing glass/bowl

9. Mix a few droplets of liquid soap with some water in another item

10. Add a spoon of soap water into the particles, mix it and repeat this until the mixture is a liquid

11. Pour more water into the mixture and stir it

12. Pour the mixture close to the intake of the pump or inject in into the closed loop system through an injection devise at a location with low pressure

Note: If it is desirable to study small areas of the flow section or do experiments with swirl then it is necessary with high particle concentration. Reduce the size of the interrogation areas to 32×32 and check that the PIV rules are still fulfilled (see 3.4 Optimizing the PIV setup).

Run the experiments

Turn of the laser

1. Press the START/STANDBY button

2. Close the laser shutter (optional)

3. Turn the power supply key switch to the OFF position

4. Turn the AC power line switch OFF

Note: Do not switch of the power supply until the fan which cools the laser, stops.

9 Comments to the Stress analysis

3 GV Cascade can be designed to withstand a pressure of 10 bar, since it is not going to be operated at higher pressures.

To determine the necessary thickness of the plexiglass and the steel pipes and plates a simple stress analysis was performed. For more information about formulas and theory see (Haugvaldstad, 2014). Plates and plexiglass were considered as beams exposed to an evenly distributed load. Several different areas were investigated (see Appendix D for figures of parts and calculations).

All steel components are dimensioned with a maximum yield stress of 235 MPa (Kruge, 1983) which is the value for Carbon steel S235JR (st37). There is not a lot of available material data for plexiglass, but a German document for pipes subjected to internal pressure claim that plexiglass has a yield limit of 4 MPa (Hatling, u.d.). This is a conservative estimate and has therefore been used in the calculations. The Waterpower Laboratory uses a higher safety factor when using self-designed components than what is normal; this factor is set to 1.8.
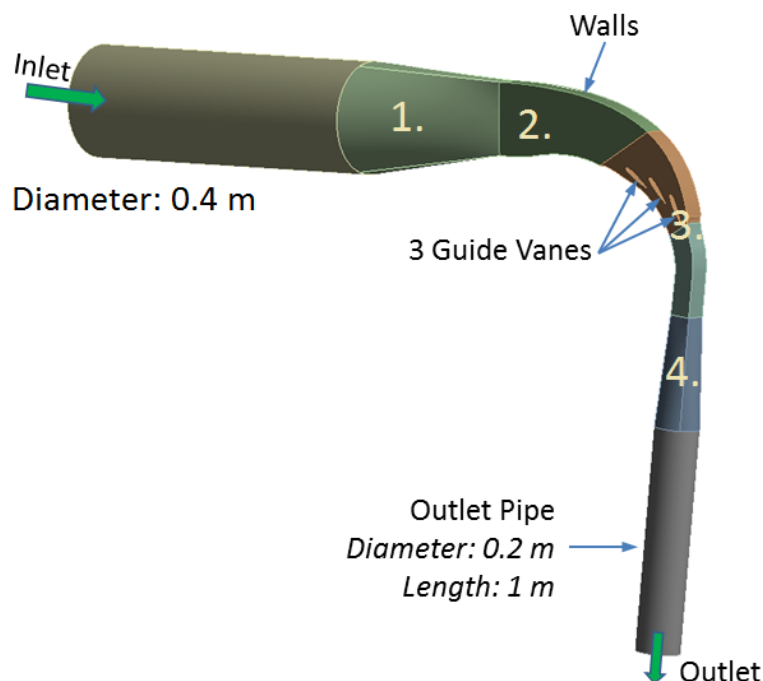

Figure 39 Flow channel of 3 GV Cascade with numbered parts (Thapa, et al., 2015)

On the test section there are three small areas of the plexiglass (windows), which are not covered with steel. At these areas the plexiglass has to be dimensioned to resist the bending stresses that occur. The calculation results show that a minimum thickness of 80 mm for the front cover and 60 mm for the walls are necessary.

It is not desirable to have a high deflection in the flow section of the test rig because that will change the flow area, so that the design will not be exactly as in the drawings. The steel plates that cover the plexiglass will support the plexiglass and hopefully there will not be significant deflections. For part 2, calculations give a minimum thickness of the front and back steel plates of 25 mm. This part is going to have many welded sections which reduce the strength of the material, but it is believed to be a conservative estimate, and that it can be reduced. For the small sections of the upper and lower sides a thickness of 7 mm is recommended. The sections can then still be rolled to get the same curve as the design.

The steel plate covering the back side of the test section is estimated to have a thickness of 18 mm, but it is believed to be a conservative estimate, and that it can be reduced. The rest of the steel plates do not have to be this thick because the plexiglass alone is dimensioned for 10 bar pressure. Part 1 and 4 both have cross-sectional areas going from either circular to rectangular or vice versa. Here the critical areas are where the cross-section is rectangular. A thickness of about 25 mm has been calculated for part 1, which is very high. Before deciding to do a reduction of this thickness, further discussions with competent personnel at the laboratory must be done.

All rectangular flanges should be designed with a thickness of 25 mm. This is an assumption based on dimensions used for circular flanges dimensioned for a pressure of 10 bar and experience from 1 GV Cascade.

The steel parts may be manufactured at Nepal Hydro and Electric (NHE) in Butwal, Nepal. The plexiglass parts may be manufactured in Norway and transported to TTL, as the access to plexiglass is good here. It is very important that the rig is pressure tested and certified before running any experiments.

10 Development of procedures and guidelines for TTL

The focus of this thesis has been to develop detailed procedures for the whole process, from design of test rig to successful PIV measurements for 3 GV Cascade. The procedures have been designed with a special focus on safety. A description of the test rig components and additional instrumentation has been made to give the person taking over the work with 3 GV Cascade an insight to everything related to the test rig.

Procedure for Leakage- and Pressure Testing and *Procedure for Operating 3 GV Cascade* were developed based on other procedures and experience from the Waterpower Laboratory and discussions with Bård Brandåstrø. The procedure should be revised after doing the same tests at the Waterpower Laboratory on 1 GV Cascade. In addition a person that has experience with running the pipe system at TTL should check that the procedure is complete.

1 GV Cascade is going to be pressure tested for 10 bar at the Waterpower Laboratory. It is recommended for the designer of 3 GV Cascade to have some discussions with the personnel that conducted the tests, in order to know it some problems were detected or if they have any recommendations for the design of 3 GV Cascade.

Guideline for Safe Use of Class 4 Lasers was developed because there is a desire to improve HSE at TTL. This can be done by implementing some of the safety routines, guidelines and experiences the Waterpower Laboratory and NTNU have from years of developing and improving their own HSE. The guideline is a summary of the guide lines about laser use at NTNU.

From writer's own experience at TTL there was no safety equipment, warning signs or routines when working with the Class 4 laser. It was not known what severe damage a laser source like this may cause. In addition to the general lack of use of safety equipment and warning signs, there is a problem with dust and the cement floor in the lab. It has been recommended to apply epoxy to the floor to make it less dusty, durable and easier to keep clean, and to install a ventilation system with a filter.

Procedure for PIV Setup and Measurement on 3 GV Cascade was developed based on experience from PIV measurements on the Swirl rig at the Waterpower laboratory at NTNU using the software DynamicStudio, which is a software delivered by Dantec Dynamics. The Swirl-rig works in an open loop system.

PIV is going to be used to capture images and study the flow around the guide vanes. Using PIV makes it possible to obtain quantitative information about the flow structures and simultaneous measurements at multiple points without disturbing the flow. It can be hard to obtain the perfect particle concentration and accurate calibration it the test section geometry is complex.

Experience from the Swirl rig show that the particles settles quite fast if the open loop system is not operated for a while (1-2 days). When starting to operate again all particles seem to have disappeared, and new particles had to be added. This will probably also happen when operating in a closed loop, with the difference that the particles settle on the surfaces of the whole system (if it is not drained) and not in the reservoir. It might be possible to reduce the settling by installing a steering device in the pressure tank and in the lower reservoir that can steer between measurements.

11 Conclusion

Cooperation between NTNU and Kathmandu University (KU) was developed with the aim of solving the problem of sediment erosion in hydraulic turbines. The Turbine Testing Lab at KU was built with the purpose of increasing the research capacity within the field of hydropower in Nepal. It is desirable that the knowledge of sediment erosion at the Waterpower Laboratory and at TTL is at the same level. Therefor two test rigs that are quite similar are planned to be installed at TTL and Waterpower Laboratory.

Placement of the rig at TTL with necessary instrumentation has been suggested in accordance with other existing plans for test rigs at TTL. Space limitation has been taken into account, as well as the desire to have a multifunctional test rig.

Procedures for leakage- and pressure testing for 3 GV Cascade at TTL have been developed. These are based on experience from the Waterpower Laboratory. The procedures should be revised after more experience has been gained from running the same tests on 1 GV Cascade at NTNU.

There is a desire to improve HSE at TTL. This can be done by implementing some of the safety routines, guidelines and experiences the Waterpower Laboratory and NTNU have from years of developing and improving their own HSE. Guidelines for safe use of Class 4 lasers have been summarized since this kind of laser is going to be used for the PIV measurements on 3 GV Cascade.

A procedure for PIV setup and measurement on 3 GV Cascade has been developed. The procedure is based on a PIV setup- and measurements performed on the Swirl rig at the Waterpower laboratory.

The work done in this thesis is an input to the development of 3 GV Cascade at TTL.

12 Further work

This chapter suggests further work for the next stage towards fulfilling the design of 3 GV Cascade and to perform successful PIV measurements at TTL.

CFD of different test section designs

Perform a brainstorming to come up with different guide vane cascade designs and perform CFD analyses. Based on the CFD results, cost and complicity of the design one end up with a final design for the flow channel.

Detailed design of 3 GC Cascade

Design the supportive construction around the whole flow channel for all parts based on the stress analysis in this thesis and experience from 1 GV Cascade.

Development of technical drawings for 3 GV Cascade

Make technical drawings of the detailed design.

Detailed design of high pressure tank and other components needed for the Francis rig and 3 GV Cascade at TTL (Rasmussen, 2014)

Development of procedures for running the 3 GV Cascade

Supplement the procedure made in this thesis with more points from experience gained by running the other rigs at TTL and the Waterpower Laboratory

System for data acquisition

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

Development of system for improving the conditions of the water

Apply Epoxy to the floor, improve the sealing of the windows, install a ventilation system with a filter and improve the cleaning routines for the laboratory.

Appendix A   Operating Procedure for Swirl rig

This procedure has been established based on the writer's own experience from operating the rig and recommendations from Bård Brandåstrø.

1. Mode selection: Click "Manuel" → "Ready"

2. Prime the pump manually by opening the valve down by the pump, placed highest on the vertical thin pipe. Let it fill for quite some time before you close it again.

3. Turn on the power of the pumps

4. Make an inspection around the laboratory
   Make sure that all drain tubes are closed
   Check for water leakage around the rig

5. Set the pipe loop
   Open and close the necessary valves
   (Pelton rig: closed, Swirl rig: open),
   in order to guide the water
   through the open loop
   Green means open,
   black means closed

For Calibration of PIV setup only
   1. *Start the pump*
      Start the pump at a 100 rpm
      Go 100 by 100 to 500 (600) rpm
   2. *Close the back valve and let the test section be filled with water*
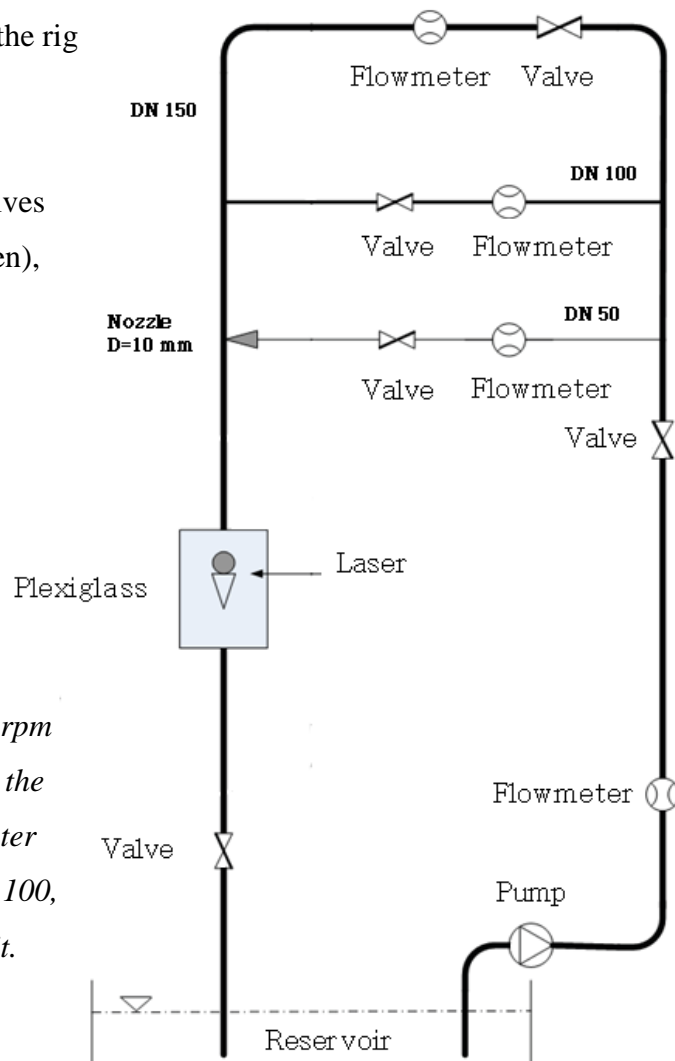   3. *Run down the pump, 100 by 100, until 100rpm and then stop it.*

Figure 40 Schematic presentation of Swirl rig, some modifications by writer (Finstad, 2008)

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6. Start the pump

   Start the pump at a 100 rpm

   Go 100 by 100 to 500 (600) rpm

   10 by 10 to the desirable value

   1. To begin with it is important to remove air from the system. This done by using the venting valves. Follow the step 3-10 in Appendix A given in Skodje's master thesis (Skodje, 2013)

   2. To change the back pressure adjust the throttle valve on the rig; decrease the decent in opening percent as you approach closing. Things can change fast!

7. Adjust operating point by adjusting the different vales

8. Shut down

   Run down the pump, 100 by 100, until 100rpm and then stop it.

   Turn of the power for the pumps

   Close valve

Geometry of Swirl-rig

- D_{pipe}=154 mm

- D = 50 mm (connected tangentially on the main pipe)

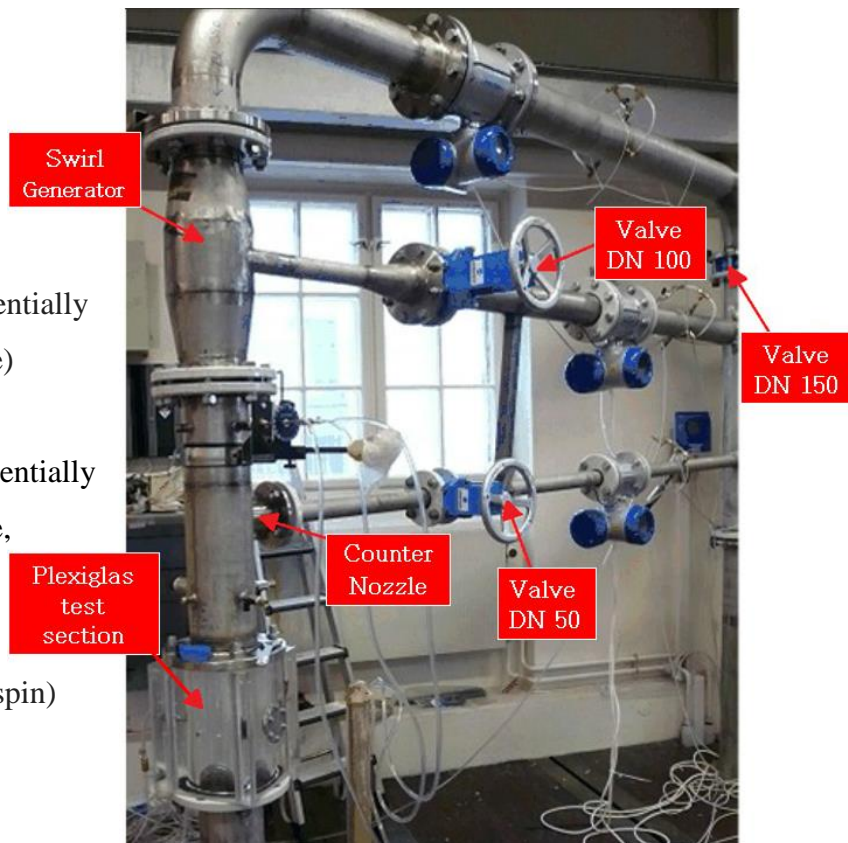- D = 10 mm (Connected tangentially on the main pipe, spraying water in the reverse direction of the spin)

Figure 41 Swirl rig with vales and componentsmodified by writer (Blomli, 2007)

Appendix B   Procedure for PIV setup on Swirl rig

The procedure has been designed for PIV measurements on the Swirl rig at the Waterpower laboratory based on the writer's own experience from setting up the PIV equipment from Dantec Dynamics at the current rig.

Tent

- Carefully shield the test section to avoid any reflection of laser light from the measurement area to the rest of the premises

Figure 42 Warning lamp (Writer's own picture)

Align the laser

- Put up a warning sign/lamp and put on protective googles

- Mark the test section where the object plane should be

- Insert the calibration target

- Start and fire the laser manually

    1. Close the shutter on the front of the laser head

Figure 43Warning sigh for Class 4 laser (Industries, 2015)

    2. Connect to power supply. Set the power switch on the AC entry module to the ON (I) position.

    3. Turn the power supply key switch clockwise to the ON (I) position

    4. Rotate the *Rep Rate* knob counter clockwise to the minimum position

    5. Press the START/STANDBY button until the power supply INTERLOCK led is off and the control panel LASER EMISSION led is on

    6. Now there is a 8 second delay before laser firing can occur

    7. Open shutter when ready to operate safely

Figure 44 Laser googles for Class 4 lasers (Writer's own picture)

- Operate the laser
    1. Press the Fire Laser #1, Fire Laser #2 or both on the control panel to initiate laser firing. If both lasers have been pressed at the same time the lasers will fire simultaneously, it not they will fire alternately.
    2. Adjust the *Rep Rate* knob set to the desired setting
    3. Press the energy high/low button to select desired energy level.
- Align the laser light sheets so that they are parallel to the object plane and flow direction by using a self-leveling laser level
- The light sheets should overlapped to maximize the correlation
- Make sure that the laser will not change position, if possible fix the laser to a table that can be adjusted horizontally and rotated
- Turn down the laser energy and repetition rate to a minimum
- Press the START/STANDBY button

Aligning the camera
- Place the CCD camera perpendicular to the object plane (laser sheet)
- Mark the center of the section that is supposed to be in focus and align the camera by using a self-leveling laser level. Vertically and horizontally.
- Isolate the area around the camera so that it will not easily be touched or moved
- Minimize extraneous light entering the test section

Figure 45 Self-leveling laser level (Johnson, 2015)

Note: The camera is always set to full pixel resolution and 10 bit.

Focus the camera
- Fill the test section with water (see Appendix A   Operating Procedure for Swirl rig under *For Calibration of PIV setup only*)
- Open the DynamicStudio, press *Free run* in the acquisition window and let the camera run while adjusting the camera focus so that the calibration target is in focus
- Use the histogram of the recoded image intensity and check that it has a very large peak near zero intensity, corresponding to the background, and a second peak at

higher intensity, corresponding to the target images (assuming that the targets are bright and the background is dark)

Calibration of a single-camera system

1. Close the laser shutter
2. Make sure there is enough light for the camera to capture good calibration images
3. The test section should be filled with water
4. Acquire images, chose *Single image mode*, check the quality and press *Save for calibration*
5. Right click on the calibration images and choose *Measure scale factor*
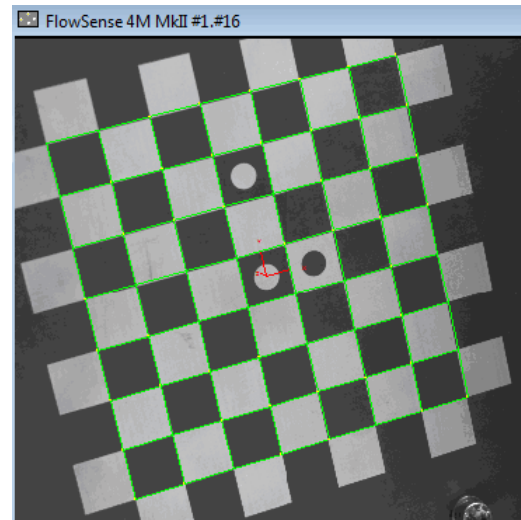
Figure 46 Checkerboard target for 2D calibration (Dynamics, 2013)

6. Drain the system by opening the back valve and take out the calibration target

Calibration determines the accuracy of the velocity measurement so make sure this is done as accurate as possible.
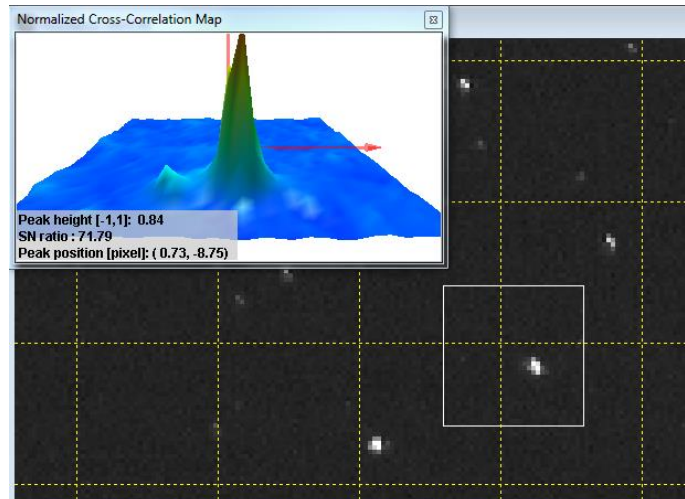
Particles

1. Put on laser googles
2. Switch the laser to *External mode*
3. Press the START/STANDBY button
4. Press *Preview* in the acquisition window
5. Press down the buttons for *Fire Laser #1* and *Fire Laser #2* to activate them (only necessary the first time it is fires externally)
6. Adjust the laser energy from low to higher if necessary
7. Let the camera and laser run and check that he design rules are fulfilled (see 3.4 Optimizing the PIV setup)
8. Press *Stop*

Start by adding small amounts of particles check the correlation and add more if necessary.

9. Pour the particles into a mixing glass/bowl

10. Mix a few droplets of liquid soap with some water in another item
11. Add a spoon of soap water into the particles, mix it and repeat this until the mixture is a liquid
12. Pour more water into the mixture and stir it
13. Pour the mixture close to the intake of the pump

Figure 47 Cross-correlation map
(Image from DynamicStudio)

Note: If it is desirable to study small areas of the flow section or do experiments with swirl then it is necessary with high particle concentration. Reduce the size of the interrogation areas to 32×32 and check that the PIV rules are still fulfilled (see 3.4 Optimizing the PIV setup).

Run the experiments

Turn of the laser

1. Press the START/STANDBY button
2. Close the laser shutter (optional)
3. Turn the power supply key switch to the OFF position
4. Turn the AC power line switch OFF

Note: Do not switch of the power supply until the fan which cools the laser, stops.

Appendix C   PIV measurements on Swirl rig

Aim   To do a correct PIV equipment setup

Reference   See Appendix A for operating
procedure and Appendix B for PIV
setup

Procedure

- Constant back pressure of 70 bar during
  all test
- Constant flow rate of 20 l/s during all test
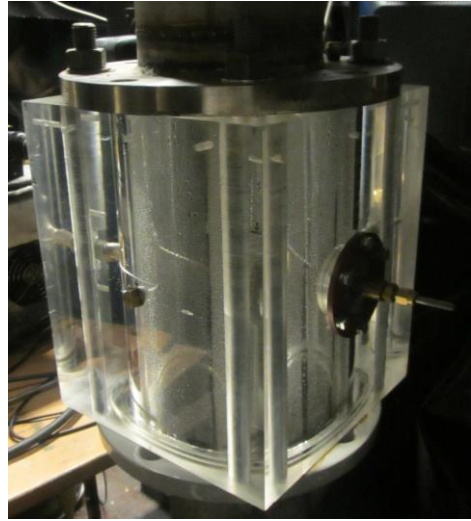- 100 images for each sequence

Figure 48 Plexiglass section on Swirl rig (Writer's own picture)

Four sequences of measurements were performed, where all consisted of 5 runs. During the first sequence the time between pulses (*Δt*) was kept constant at 1000μs, and the trigger rate was varied for each run (1, 3, 5, 7, 8.874 Hz). During the second sequence the trigger rate was kept constant at 3 Hz, and the time between pulses was varied for each run (600, 800, 1000, 1200, 1400 μs). The two last sequences are just as the previous two, except for increased particle concentration.

A DN 150 valve was used to adjust the flow. A DN 150 flowmeter was used to measure the flow rate. On this rig the accuracy of the flowmeter can vary quite much if it is operating at low flow. Therefore a quite high and stabile volume flow was chosen for this experiment. Calibration data for the flowmeter was taken from Håvard Blomli's master thesis (Blomli, 2007). The values measured by the flowmeter was plotted and averaged for each run. The value did not vary much (20.03 – 20.08 l/s) during all runs. The average value was used to predict a velocity through the test section using this formula;

$$V_{calc} \left[\frac{m}{s}\right] = \frac{Q \left[\frac{m^3}{s}\right]}{A \left[m^2\right]} = \frac{20.05 \times 10^{-3} \left[\frac{m^3}{s}\right]}{\frac{\pi \times (0.154\ m)^2}{4}} = 1.08 \left[\frac{m}{s}\right] \tag{1}$$
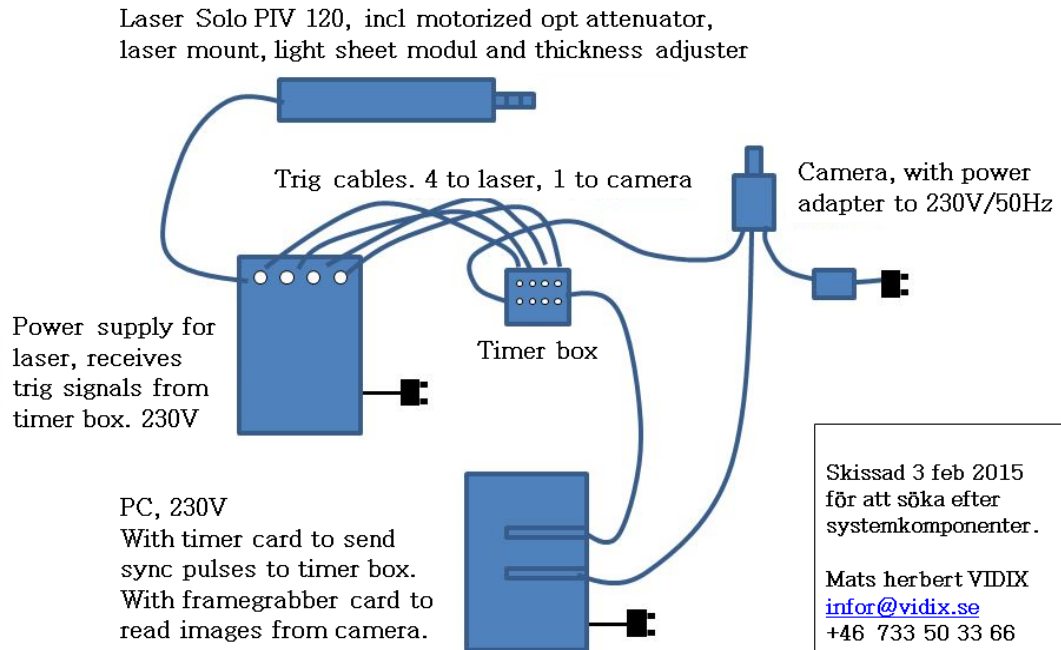
The hardware used is shown in Figure 49.

Figure 49 Sketch of PIV system at NTNU (Mats Herbert, VIDIX)

Calibration images were captured by inserting a steel rod into the flow domain as can be seen in Figure 50.

Figure 50 Calibration image used to measuring scale factor. The distance between each line is 5 mm (Writer's own image).

Two single exposure frames were captured for every measurement, and the image pairs were analyzed with DynamicStudio using *Average correlation* with a final interrogation area of 32×32 pixels with an overlap of 50% between adjacent interrogations.

Results

The measurements done before and after adding more particles are as good as identical. The velocities are very similar in all tests except for two runs where Hz was kept constant and *Δt* set to 1200 and 1400. Figure 51 show velocity vectors after the average correlation of two different runs.
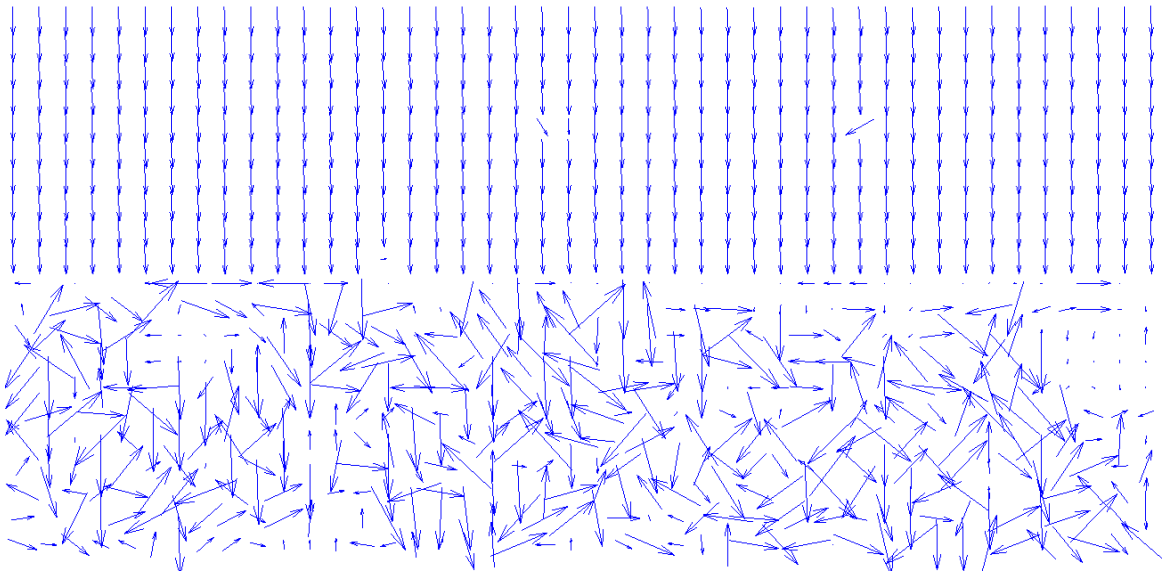

Figure 51 Average correlation for Δt = 1000 μs (above) and Δt = 1200 μs (below)

Figure 52 show the average velocity profile generated from results of 16 runs.
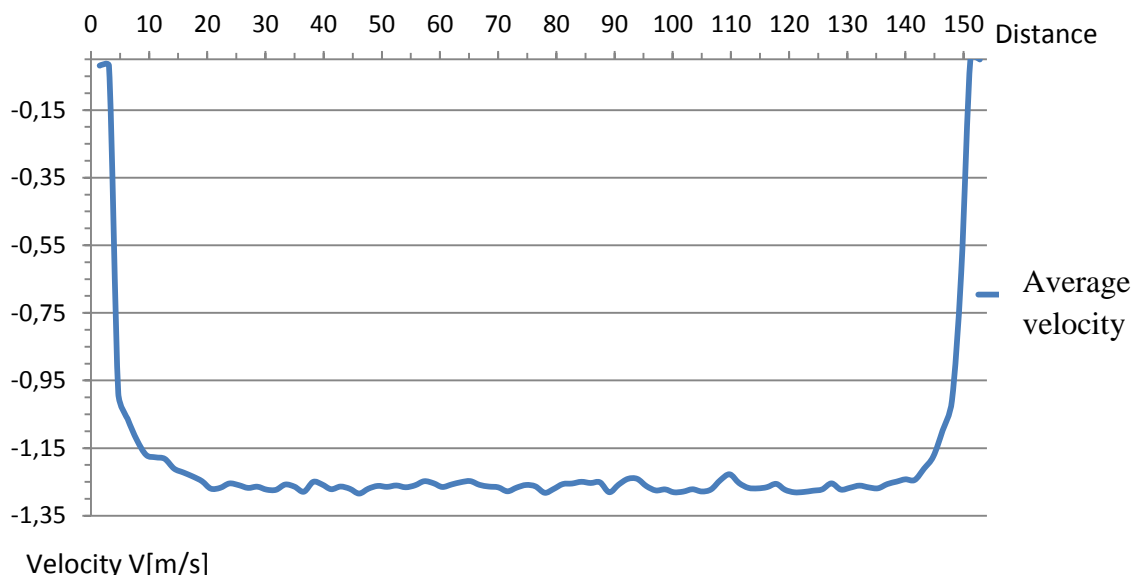

Figure 52 Average velocity profile

Discussion

A velocity profile like the one in Figure 52, matches the theoretical profile for turbulent flow in a pipe quite good. Average correlation is an analysis method that is suitable for this measurement since the flow is constant, without spin and only in one direction. If there are few particles in the flow, it can happen that there are no particles at all in some of the interrogation areas in more than half of the images, only random noise. But in the last half there are sufficient particles which form a correlation. When all the correlations from the whole image series are added together, this forms a correlation peak. The evaluation of the peak is done normally, and it represents the average velocity within the interrogation region and within the number of images recorded. For this method to be valid, a high number of images must be recorded. When this is fulfilled the result is a nice vector map without spurious vectors.

Average correlation of 100 images with interrogation areas of 32×32 pixels and a pixel size of 74 μm gives approximately one velocity vector per 2.4 mm throughout the whole cross section.

When keeping Δt constant and varying Hz the particles travel the same distance between each image pair, but the time it takes to acquire them decrease with increasing trigger rate. Since the flow in the test section is stable, there is not much variation in the measurement results. Both sequences with constant time between pulses gave approximately the same velocities for all trigger rate values. This was according to what was expected.

According to PIV theory on particle should not travel more than 10 pixels between Frame 1 and Frame 2. It is also stated that it should not travel more than ¼ of an interrogation area.

It can be seen in the results for constant trigger rate and in Figure 51 that a time between pulses of 1000 μs gives good average correlations. A time between pulses of 1200μs gives bad average correlation between the image pairs with many bad vectors; most of them show wrong flow direction. A closer look at the image pairs show that particles move further than what is recommended. Many particles disappear from the interrogation areas giving bad vectors. This leads to wrong velocities from these runs.

Conclusion

The velocity profile plot matches the theory about turbulent pipe flow. Theory about determining the time between pulses have shown to be suitable for PIV measurements on the Swirl rig. The PIV setup has been done in a correct way.

Recommendations

- Modify the test section to achieve better calibration. One option of how this can be done is shown in Figure 53.
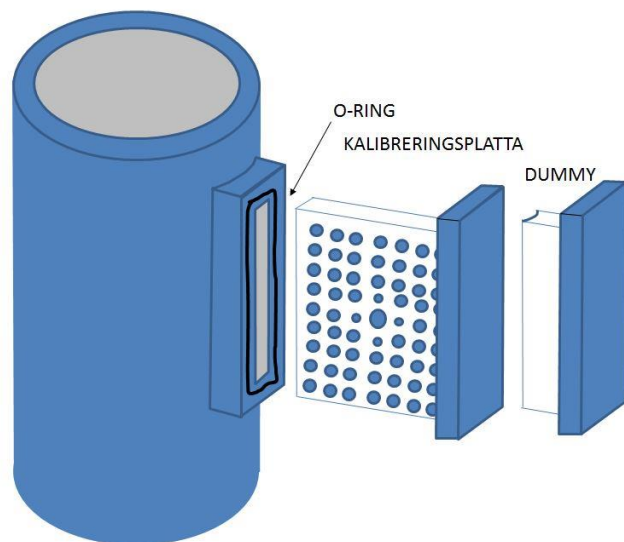

Figure 53 Suggested calibration setup for Swirl rig (Illustration mad by Mads Herbert, VIDIX)

- Values for calibration of the flow meters were taken from another master thesis (Blomli, 2007). Later on it was discovered that new calibrations of the same flow meters had been done (Skodje, 2013), it might be better to use these values from now on.
- The seeding "disappears" if the loop is not operated for approximately 2 days. Therefore it is recommended to do measurements several days in a row. A solution could be to install a stirring device in the reservoir.

Appendix D   Simple strength calculations

Material	Carbon steel S235JR (St 37)	Plexiglass	
Yield stress, σ_y	235	4	MPa
Modulus of elasticity, E	210 000	1,38	MPa
Dimensioning pressure, p	1	1	MPa
Safety factor, C_f	1,8	1,8	-

All custom made flanges will be 25 mm thick and are marked in all the parts. The numbers that have a border around them are the thicknesses that are needed according to the calculations. All figures are taken from the flow channel design of 3 GV Cascade in Creo Parametric.

Carbon steel

Part 1 Inlet Diffusor	Circular cross-sectional area	Rectangular cross-sectional area
Location	Inlet	Outlet
Length, l [mm]	-	328
Inner radius, r_i [mm]	397	-
Thickness, t [mm]	3	25
Maximum deflection, δ [mm]	-	1
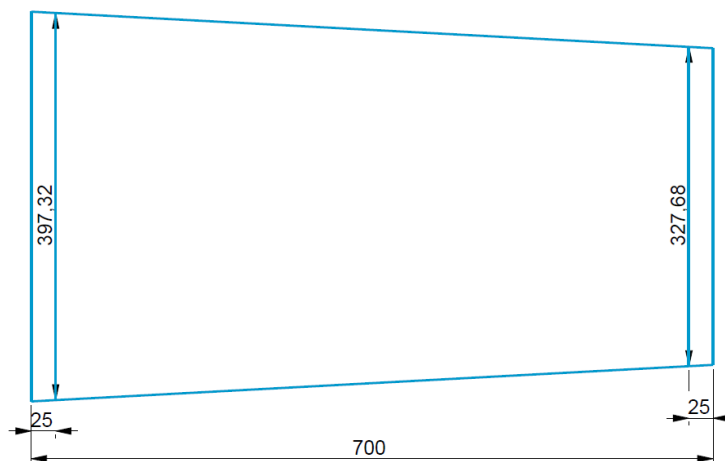
Part 1 goes from circular cross-section at the inlet to rectangular at the outlet.

For the test rig at the Waterpower laboratory this part was made out of eight sections that were welded together. Flange at outlet must be custom made.
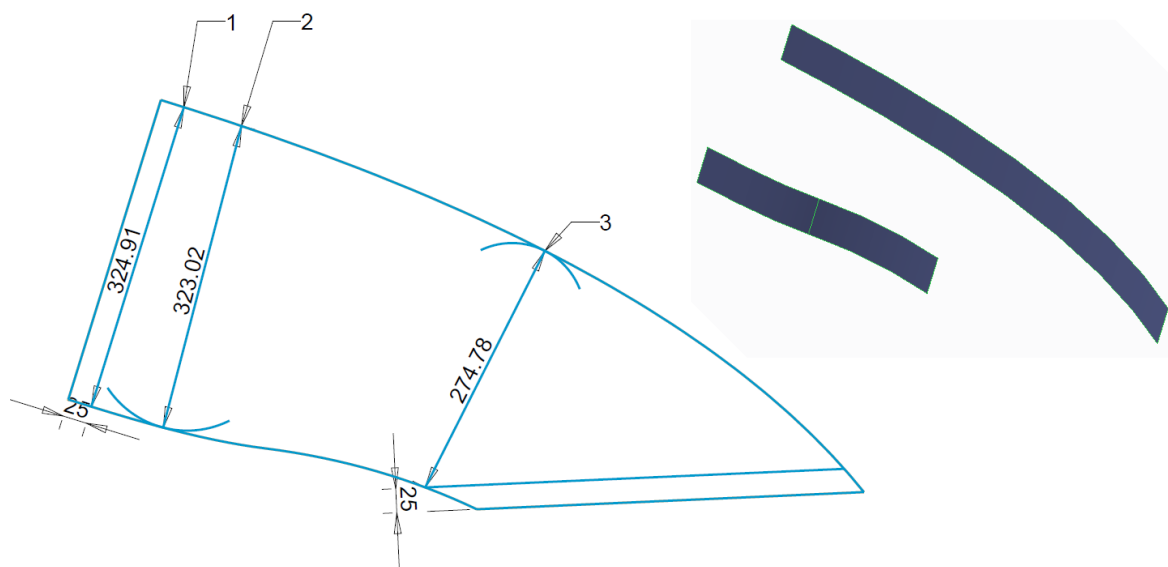
Part 2 Flow Channel Inlet

Front and back sides	Rectangular cross-sectional area		
Location	1	2	3
Length, l [mm]	325	323	275
Thickness, t [mm]	25	24	21
Maximum deflection, δ [mm]	1	1	0

Upper and lower sides	Rectangular cross-sectional area
Location	Channel height
Length, l [mm]	97
Thickness, t [mm]	7
Maximum deflection, δ [mm]	0

Front and back sides are identical and are shown in the figure to the left. The figure to the right show the steel plate that is the upper channel wall and the lower plates make up the lower channel wall. These parts can be cut out from steel plates. The lower channel wall is more complex to manufacture since it has different curves. As shown in the second figure of this part, the wall exists of two steel parts. To achieve the desirable curve, these two plates have to be rolled and then welded together. In addition they have to be quite thick because the water is forced to change direction in this part of the test rig. In addition many welding points weaken the strength of the steel.

| Part 4 Outlet diffusor	Rectangular cross-sectional area	Circular cross-sectional area
Location	Inlet	Outlet
Length, l [mm]	101	-
Inner radius, ri	-	196
Thickness, t [mm]	8	1
Maximum deflection, δ [mm]	0	-
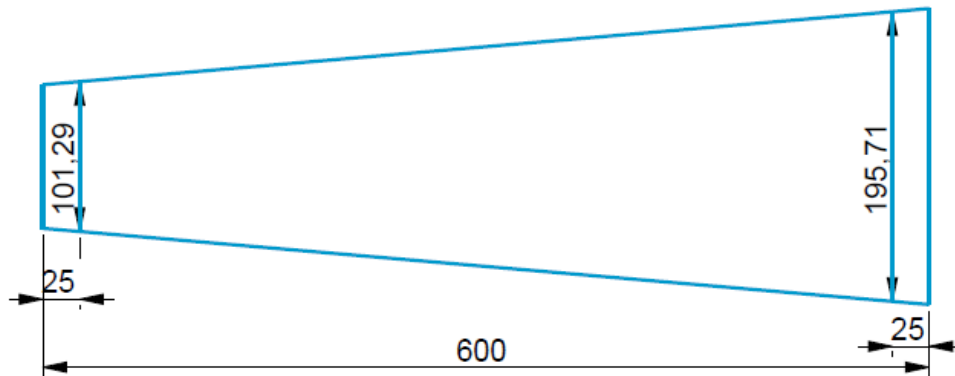
Part 4 has rectangular cross-section at the inlet and circular at the outlet. As for Part 1, this part can be made out of 8 sections and welded together. The flange at the inlet must be custom made.

Part 3 Test section

The test section is going to consist of plexiglass, steel plates and flanges. The flow channel is surrounded by thick plexiglass on three sides and a steel plate on the back. It is made so that the back steel plate can be removed. This provides access to the flow channel so that changes can be made. The Plexiglass is covered with steel plates all around. The steel plates on the upper, lower and front side are going to have holes, so that it is possible to visualize the flow at the stay vane outlet, runner inlet and around the guide vane profiles, and do PIV measurements at different points of the flow channel. All flanges in this section have to be custom made.

Back steel plate	Rectangular cross-sectional area
Location	Channel width
Length, l [mm]	240
Thickness, t [mm]	18
Maximum deflection, δ [mm]	0
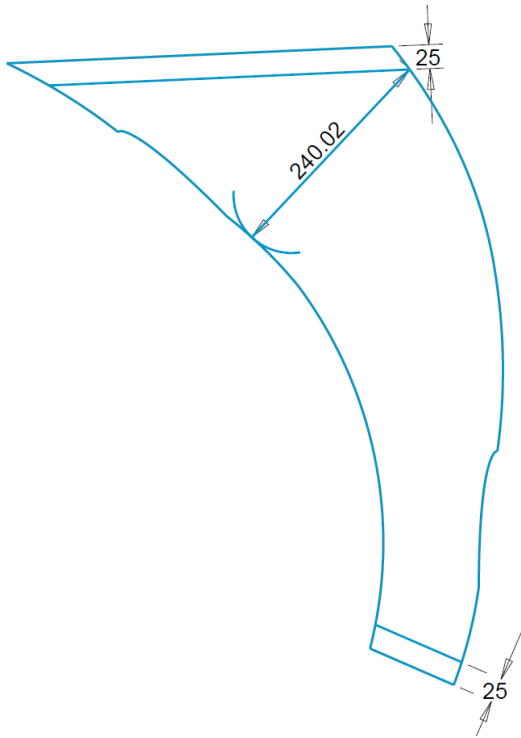
This was used to calculate necessary thickness of the back steel plate which covers the last side of the flow channel that is in direct contact with the water flow.

For the left and right side plates a thickness of 10 mm is suggested as for the rig at the Waterpower laboratory.

Plexiglass

Front cover

Location	Channel width	Assumed window section
Length, l [mm]	240	142
Thickness, t [mm]	139	82
Maximum deflection, δ [mm]	6	4

Left and right side

Length, l [mm]	97	
Thickness, t [mm]	56	
Maximum deflection, δ [mm]	2	
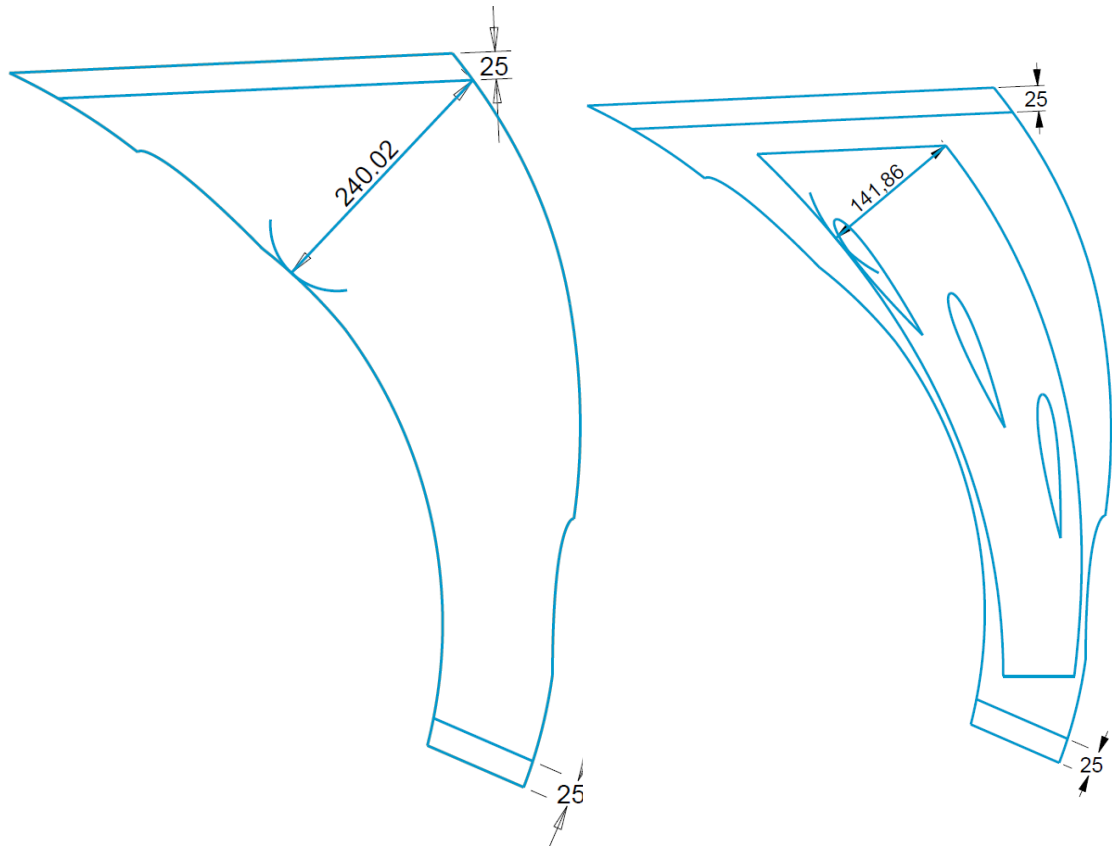
The first figure show where the length in the first calculation has been taken from. The window will not be as wide as this, therefore a second calculation has been performed (length shown in the second figure). It has not been decided how big or exactly where the window is going to be yet, but with this design it is possible to see the flow from the outlet of the stay vane until the inlet of the runner.

For calculations of minimum thickness of left and right side, the flow channel height was used and that is constant 97 mm.

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