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DESIGN AND STUDY OF A HYDROELECTRIC PLANT

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B.Eng(Hons) Renewable Energy and Sustainable Technologies

Final Year Project

DESIGN AND STUDY OF A HYDROELECTRIC PLANT

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Date: May 2012

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Abstract

Hydro power is a renewable resource that can satisfy an important percentage of the global energy demand. This project is about the design and calculation of the parts of a small hydroelectric plant through which the water flows.

Small hydro plants are not usually built, as this idea seem to be not economically feasible. This makes that there is a hole in the development of hydro plants that can be studied. The percentage of energy demand covered by hydro plants would be significantly increased if it was researched.

The report starts with the search of a suitable place for the installation of the hydroelectric plant. Due to the characteristics of the location, the gross head and the flow rate, the appropriate turbine was chosen. Between the three more important kinds of turbines, the best option was Kaplan turbine. The design of the parts is focused in the mechanical study of these elements of the turbine. The calculations to do the study were made following the fundamental principles of physics, specially hydraulics and mechanics. The parts involved in this project are the weir, that has to be modified from its original shape, the channel section, the scroll casing, the guide vanes or Fink distributor, the impeller, the blades and the draft tube. The next step done is the resistive calculation of some elements of the turbine, as it is an important part in the design of these elements. The sizes of them depends on how much stress they can stand. The project finishes with the design of these parts using a software (pro-engineer and pro-mechanica)that shows us that the sizes of the elements are correct.

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1-INTRODUCTION

Aim, description and significance of the project:

The design of a new hydraulic turbine is searched to satisfy a flow rate and a small waterfall. The turbine is made to work in a small amount of power, so the important thing is that the turbine has a good adaptation to the hydraulic condition. As this is a small power production project, the most interesting thing is designing a compact turbine to avoid civil costs. Another important thing is taking care of the facilitates of maintenance of the installation. It is also important the fact that flora and fauna must be conserved, and the water quality as well.

The main goal is the realization of the design of the main turbine and every component of the power station, like the dam, scroll casing, the water intake gates and the blades. The different parts of the power station depend on the height of the waterfall and the flow rate of the river in the place chosen. Another aim that will not be clearly mentioned in the report but can be understood throughout the reading of the report, is showing the importance of these kind of power stations. This project will demonstrate the possibility to design hydro turbines easily, just with some calculations. The town chosen to build the power station has at least another 5 weirs with similar characteristics as the one studied here. This means that the energy provided by 6 turbines like the one designed in the project can satisfy an important part of the energy demand of the town, what makes the project profitable in the long term.

The project is based on the theoretical performance of the model to adapt it to the real conditions of all parts involved. Once known the hydrodynamic scheme of the machine, the calculations of the element from the mechanical point of view must be done, to know the strength of the machine. Throughout these developments, every element calculation with direct influence in the operation of the turbine calculations will be provided. This project will not correspond to the calculation of the electrical components.

The realization of this report is motivated by the personal interest of the project author in turbomachinery, renewable energy and nature in general. Another important reason to do this is the possibility to design and study every aspect that involves small hydroelectric plants. The fact that small hydro plants aren't very common and that they can be developed is another reason to do this

kind of project.

2-AIMS OF THE PROJECT

The purpose of this project is the design of some of the most important parts involved in the performance of an hydroelectric power plant. To do this, an adaptation of the design of the turbine and all its parts for the generation of electricity will be done. This adaptation will depend on the conditions of the river chosen, which are the quantity of water in the river and the head gross.

Another important aim of this project is designing a turbine that provides energy to a reasonable number of people. This project will not involve the economical or feasible part of the installation. However, this project will increase importance and interest with the growth of number of houses that the plant can provide energy.

Due to the length and difficulty of the project, the turbine will not be enormous. Other of the aims is making the author of this project, use, learn and review modules passed throughout his degrees. This will not be possible to do if the turbine is so big that just a small part of the machine can be designed and studied.

These things will make that the design will be focused on reduced power output, but big enough to satisfy the energy demand of more than 150 houses. The construction on hydraulic turbines, has long focused on the exploitation of high jumps of water, what means that a lot of energy was produced. The turbine must suit small rate flows and it is characterized by greater variability in hydraulic parameters. This can also be used in other rivers with similar conditions.

Apart from designing the turbine using the theoretical fundamentals of physics, another phenomena will be studied. For example, cavitation is an important phenomenon that can not be forgotten in the design of any hydraulic machine.

The last and one of the most important aims of this project is the test of the parts designed using a computer software. Computer aided tests are done nowadays to check if the design of the parts of the turbine are correct or not, without the necessity to spend money building models. This is why pro-engineer will be used to do stress and displacements analysis.

3-REVIEW OF LITERATURE

In this part, the research into the subject is done. The theoretical background, like the technical, legal and economic viability and hydropower technology is studied here.

3.1 Project Requirements

Technical Viability:

Building a Hydraulic machine as this one, is completely possible nowadays. Technique is developed enough to allow the manufacture of the machine and install it in every possible situation in which the turbine can operate. The lifetime of this turbines is high, due to the continuous development of knowledge and control fluids. The adaptations and new developments that the turbine can suffer during its life, allows it to have increases in demand. Examples of this are the replacement of blades or suction pipes.

Economic Viability:

The use of this hydraulic turbine involves the construction of a civil work. The utilization of this machines is decreasing nowadays also. However, its use is still realizable. The manufacture of the turbines is tending to build smaller units and more compact ones. This means that the specialization in low power is increasing, so costs are more reduced, although the return period of benefits tends to be higher.

Legal Viability:

The design of this project must satisfy the regulation of hydraulic turbines, and the minimum required of qualities of cavitation. The regulation of hydraulic turbines in UK must be followed carefully in order to design everything with every legal requirement. Regarding to safety issues of the machine, has been taken actions that involves the situation of the machine, and can only be changed by qualified technicians.

As conclusion, it must be done that his project will be made joining the theoretical knowledge of machine designing, and the support of software focused on computer design. Nowadays, methods based in theoretical knowledge are only used to make the pre-dimensioning of this kind of machine. On the other hand, methods based on computers are the most important part of turbines today. For example, the most important developments in turbomachinery, like the study of the blades in 3 dimensions, has been done thanks to this technology.

3.2 Hydropower Technology

The design and construction of hydraulic machines designed to produce energy, would not exist without the development of hydropower. This energy is based on the utilization of potential and kinetic energy of the stream of water, waterfalls or tides. The environmental impact of this type of energy is very small. This is a kind of renewable energy because this energy comes from the hydrological cycle. The geography makes the task of managing these waters through rivers back to the oceans. So that is why we can take advantage of this potential difference, and of the continuous circulation of water through hydroelectric plants.

Hydroelectric plants

Hydro plants are designed to generate electricity. They are the current result of the evolution of the old mills that used the flow rate of the rivers to move a wheel. The water pass through a hydraulic turbine which transmits power to a generator where it is converted into electrical energy. However, Hydro plants are strongly influenced by topography, as the conditions of the river result in different constructive solutions. This is why there are a lot of types of conventional hydro plants. The characteristics of the site condition the design of the turbine.

Different kinds of hydroelectric plants:

The first type according to Figure 1, called run of the river plants, consists basically in deriving water from a river by a small weir and lead it through a channel to retain its potential energy. The water is directed into a pressure chamber, and from here the water is conducted into a power house. After moving the turbine, water is returned to the river downstream using a discharge channel. This kind of plant is called flowing because it does not store energy.

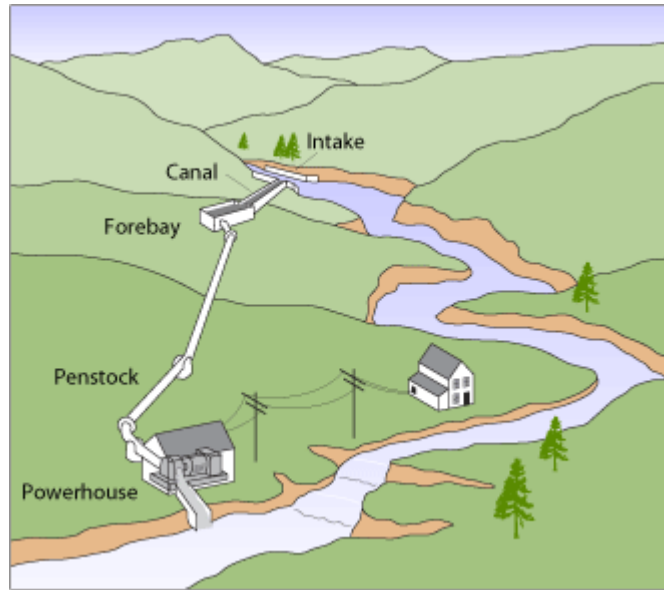


Figure 1, run of the river plant (Energysavers, 2012)

The second type of hydroelectric plant, as it is seen in figure 2, is a kind of plant with a dam and a reservoir of water. The water level reached is near the top of the dam. Halfway up it, to exploit the reservoir volume, is a water intake, and in the bottom downstream of the dam, the power house. The energy released by water falling through a penstock inside the dam is transformed by the generator. Finally the water is directed back into the river through an output channel.

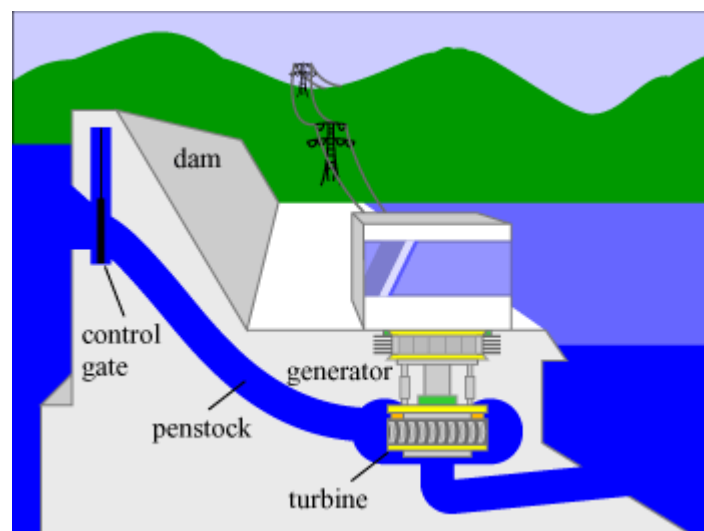


Figure 2, plant with a dam (Hk-phy,2012)

The third kind of hydroelectric plant (figure 3) is The pumped-storage. It consists in producing electricity in peak demands of energy by moving water through two reservoirs that are at different elevations. The excess of energy generated is used to pump water from the lowest reservoir to the upper one. When energy is required, water is released back into the lower reservoir passing through a turbine.

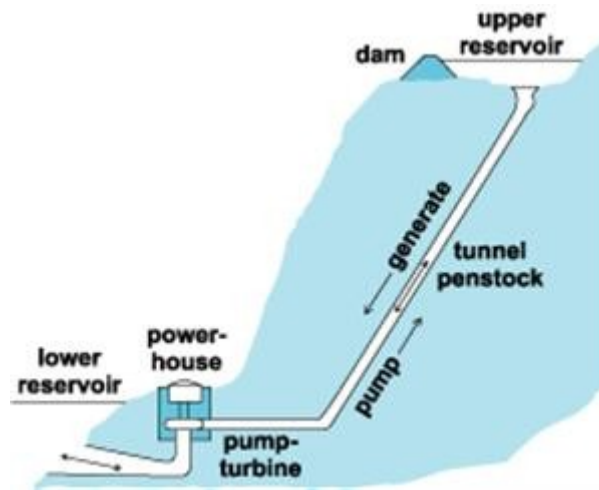


Figure 3, pumped storage plant (pumped-storage,2012)

Characteristics of small hydro power plants

This type of plant uses basically the same technical solutions than conventional solutions. However, it is intended that the initial cost of construction and maintenance is as small as possible. Every consideration specific to the installation must be manifest in the design, with its own hydro graphic characteristics of rivers where hydroelectric development is done. When a small plant is built, the dimensions of this plant are very different to the great rivers that supply conventional power plants. These characteristics influence the variability of the basin, so the water jumps are affected by changes in gross height and flow. For this reason the design of hydraulic turbines for this field should display features that allow them to operate with these variations, avoiding the presence of harmful effects such as cavitation, and keeping the yield curve to changes in height. Another important factor for reducing costs is the main and auxiliary systems of the plant. These must be simple so the technical expertise is the easiest.

The use and application of mini hydroelectric plants, unlike conventional power plants, allows the use specified for certain generation activities. Small plants can satisfy the energy needs that exist in

the area where it is installed, although the main use of electricity generated is selling it to the grid. There are other possibilities. This is the case of rehabilitation of older inactive central old mills, expansion of existing plants (stopped or in use), in which the concessions are made for a period of years and can pick a site where you update the turbine-generator groups. You can also undertake the construction of new mini plants on water pipes or sewage facilities. When it comes to works installed in pipes or conduits for supplying potable water to populations require less civil works and have lower administrative problems.

As it can be seen, small hydro power plants can be adapted to different situations of use, this means that there must be several formulas for the adjustment of hydraulic turbines. This manufacturing system is to have a standard set of models, which are assembled when there is an order, this reduces assembly time as the design is realized with rapid acquisition materials and technology needed for assembly are also intended to be reduced. Getting that few items that need a particular production, such as the blades and the hub of the impeller. Time needed to do a complete assembly of a turbine can change between some months.

3.3 Basic security

This establishes health and safety during the construction of the work, the estimations regarding risk and prevention of occupational accidents, as well as the health and welfare facilities for workers. It will serve to give basic guidance to the contractor to carry out their duties in the field of prevention of occupational hazards.

Duties, obligations and commitments of the employer and employee

Workers have the right to effective protection of safety and health at work. Regarding to the duty of protection, the employer must ensure the safety and health of workers at your service in all aspects of work. The employer must comply with the obligations under the regulations on the prevention of occupational hazards. The Basic principles of preventive action requires employers to implement the measures that integrate the general duty of prevention provided above.

- 1- Avoid the risks
- 2- Evaluate the risks that can not be avoided
- 3- Fighting to the source of the risks

- 4- Adapting the work and the person depending on their job
- 5- Replacing the dangerous works.
- 6- Prevention, planning, organizing and working conditions.
- 7- Adopt measures that put collective protection over individual.

Risks

- 1- Landslides
- 2- Imprisonments of machines and vehicles
- 3- Running over
- 4- Crashes and rollovers
- 5- Staff falls from heights
- 6- Projections of particles in the eyes
- 7- Trapping by sliding and falling
- 8- Dust
- 9- Noise
- 10- Broken water pipes, gas or electricity
- 11- Run over

Protection

Lot of things will be marked correctly using traffic signs, road safety, sound and light machinery, in and out of vehicles, the place where it is the kit and fire extinguisher and the fences of limitation and protection. People shall take appropriate work clothes, helmet, boots, gloves, safety glasses and reflective clothing. All staff should receive on joining the work of teaching methods and the risks that may be involved, with their security measures.

4-DESIGN PROCESS

4.1 Design and Fluid Mechanics

Due to the importance of these fundamentals in the design of the machine, the knowledge that underpin the calculation of this type of hydraulic turbomachines should be known. First the concept of fluid mechanics should be set as part of physics and in particular the continuum mechanics, which includes knowledge of the movement of fluids, both gases and liquids, and the dynamics of these. The interactions between the fluid and the medium must be studied . The fundamental assumption of fluid mechanics is based on the continuum hypothesis.

This hypothesis considers that the fluid is continue throughout the space that contains, ignoring both molecular structure and discontinuities associated with this. Thanks to this hypothesis fluid properties such as density, temperature, can be considered as continuous functions.

4.2 Fundamental design theories

This group of theories are used in this document for the design of the machine. Starting with flow regimes that will be discussed in several sections due to its presence in different ways. Also the description of the fluid and its kinematics because is one of the main characteristics of the design. Fluid dynamics study gives us enough about the loads in which the machine is exposed to the subsequent sizing of the resistance elements.

4.3 Basics of Turbomachinery

Fluid machines are those machines in wich the fluid, or provides the energy absorbed by the machine, or the receiver is the fluid. Because of the fundamental exchange of fluid power and mechanical energy, technology has taken innumerable forms for these machines. The study of turbomachinery has progressed considerably in recent decades, becoming a field of large multidisciplinary technological innovations due to the growing interest in the investigation of the flow within the different teams.

Definition of Turbomachine

Turbomachines are equipment designed to achieve energy exchange between a fluid flowing inside a continuous and an axis of rotation of one or more crowns or fixed blades moving through the change in momentum. The names given to fixed and mobile crowns are, respectively, impeller, impeller or propeller, according to machine type and shell, as appropriate. They differ from the positive displacement machines that there is continuity between the fluid entering and energy exchange. In the case of positive displacement machines energy change is discrete in cycles.

Types of Turbomachines Today

The use of these machines today is focused on Three basic types, Pelton turbines, Francis and Kaplan, and a more limited Turgo turbines, Fixed pitch and crossflow.

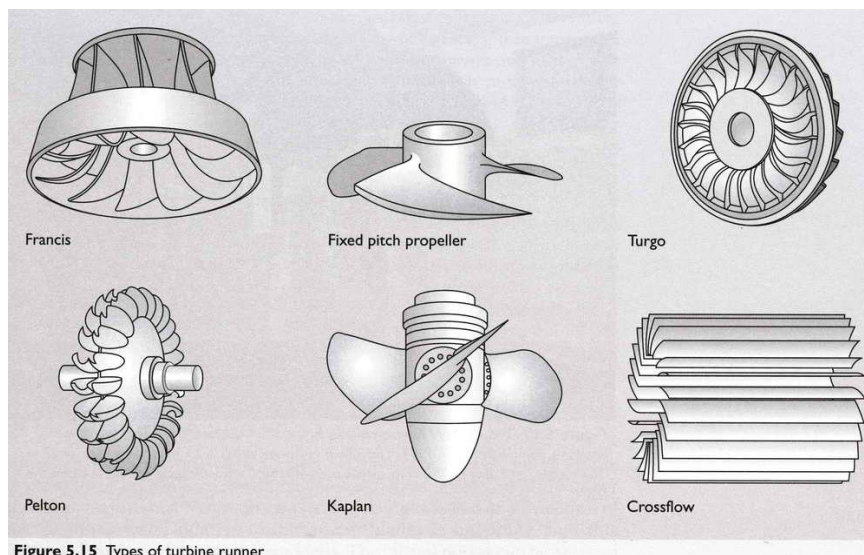


Figure 4, Types of turbine runners (csanyigroup, 2011)

Of the three basic types the one that is more known is the Francis turbine, because the variety of jumps in which it can operate is very big, with reduction in installed cost per kW generated by the improvements introduced in this turbine-driven diffusion own this technological development. The Francis turbine is formed by a drum-shaped rotor where the blades are distributed in numbers ranging around 10 to 40 blades.

Another widespread type of turbine is the Pelton turbine. The turbomachine is focused on big jumps with very small flows, the peak known in these turbines are located at 2000 m net height. One of the great advantages of these turbomachines is its low cost per kW installed, as well as low

maintenance and ease of it. It is based on a wheel of buckets in which one or more jets impinge tangentially, turn the impeller is at atmospheric pressure so that the entire energy is kinetic (Turbine action). The hydraulic design of this type of turbine is easy, but the fatigue which is subjected to the shaft as well as the spoons is complex to study. It should be noted that the type Turgo is a variation of the Pelton turbine, which uses half the impeller jet bucket and axial bearing - tangential.

Kaplan turbine is the one chosen in this project, so it will be explained more deeply later. The rotor of this machine is designed as a propeller, in which the blades can be oriented searching in combination with the dealer to obtain a yield curve virtually flat at different flow rates. There are also turbines with the blades fixed. In this case this is a propeller turbine. Although they are similar to Kaplan turbines are designed to operate with constant flow and jump. The cost per kW installed is high because of the regulatory system and the large size of these turbomachines. These turbines operate at high flow rates and low head gross.

4.4 Information of the location of the hydro plant

At first, due to the proximity to the place where the project author lives, the river chosen to design a hydraulic Plant was the River Dee. After checking in a study that no real chance to build turbines that provide high energy level in this river, we proceeded to the change of river.

River Dee

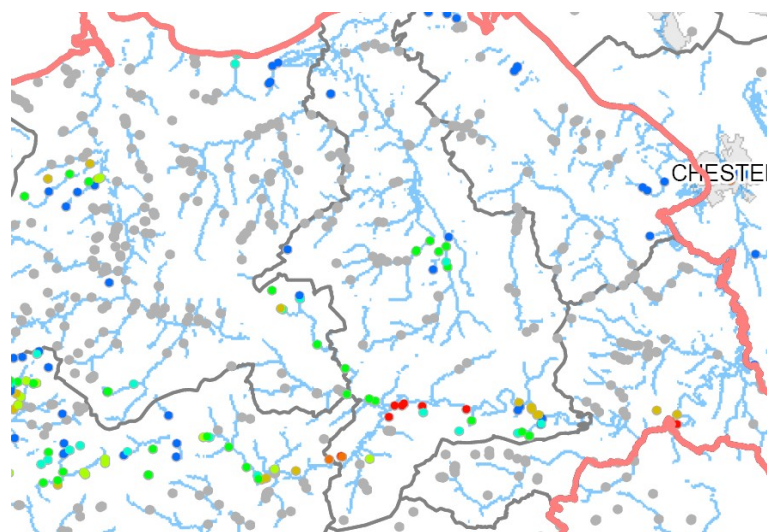


Figure 5, Mapping hydropower opportunities for Denbighshire (Denbighshire Hydro Energy Potential Assessment, 2011)

As it can be seen in the study of the web page, there is no good opportunity to build a hydro plant in river Dee near Wrexham. There are some opportunities near the place the river borns, but just for small plants, as we can see in some examples of the study. These plants would provide powers between 3 and 50 kw, which is too small for this project. Another option was searched, and inspired by heron mill turbine, in river Bela, a similar river was found, and a good place to install a turbine. It was Burrs weir, near Bury, river Irwell.

River Irwell

River Irwell flows through Rawtenstall, Ramsbottom and Bury before joining the Mersey in Manchester. It is one of the rivers that drove the Industrial Revolution and, though getting better, the water quality leaves a lot to be desired. Discharge level in Adelphi weir, in Manchester, is about 17.72 m³/s. The discharge choosen to design the turbine and every component is 15 m³/s, as Bury is nearer to the place the river is born. This discharge is quite high to build a turbine there. The only thing needed to do it is a jump of water. This jumps of water are provided by the weirs that are in that river. One of the most important one is Burrs Weir. This weir is about 18 feet (5m) high. It was made to supply water to Manchester, because of an old mill and because to build a channel. The objective is to modify this weir to build a power house there and take advantage of the big head gross of this place. We can see the big head gross and the flow rate in this pictures.



Figure 6, Burrs weir photo (panoramio, 2012)

The kind of turbine chosen for this project depends on the discharge of the river in that point and the head gross of the weir. A hydropower turbine chart must be used for this:

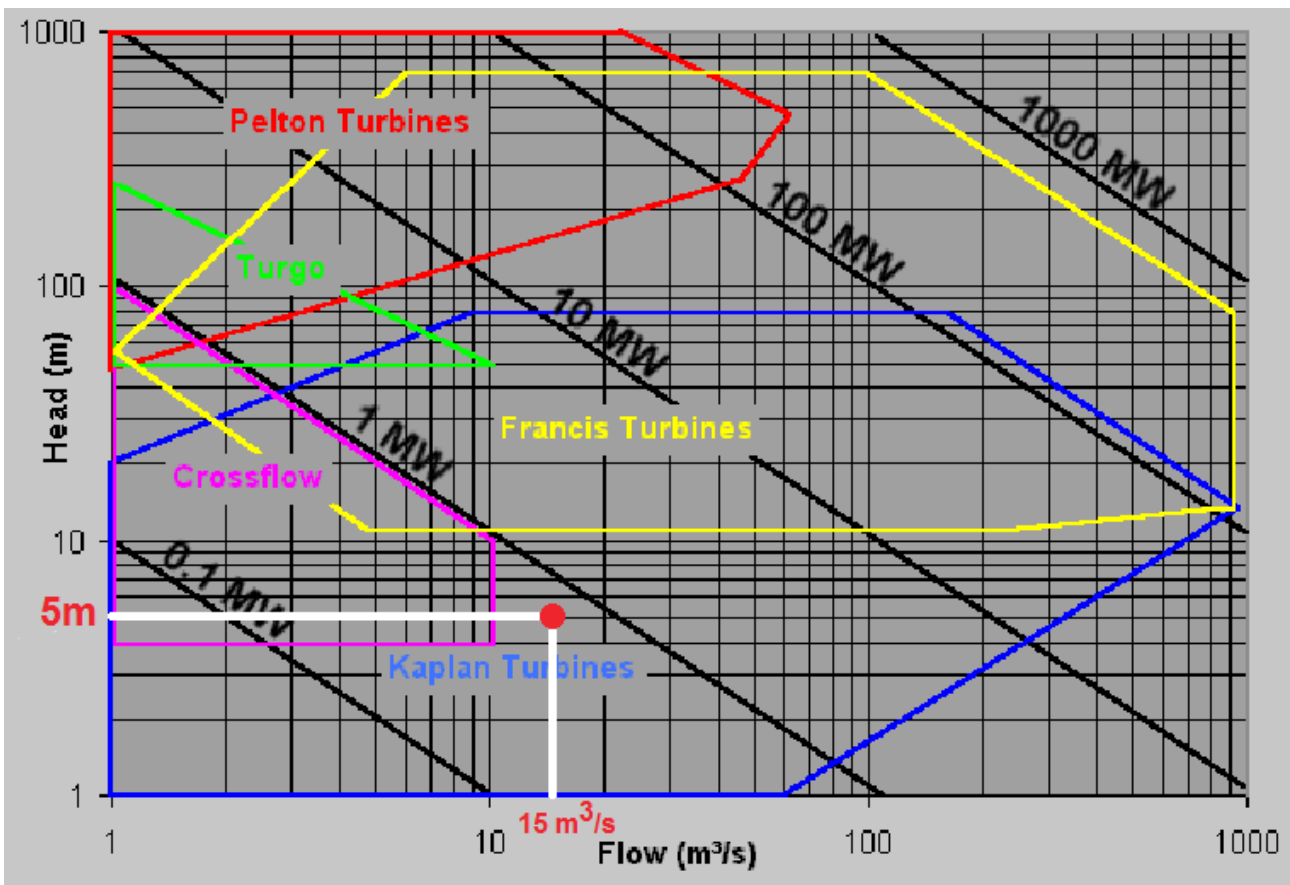


Figure 7, Turbine application Chart (jcmiras, 2012)

As we can see in this chart, the only possibility with this data is using a Kaplan turbine. The characteristics of Burrs Weir is that it has a Head gross of 5m, and the flow rate in that point is more or less 15 m³/s.

4.5 Study case: Kaplan Turbine

The importance of this turbine is its ability to operate small head gross and high flow rate and regulatory capacity in terms of maximum performance. The trend to build faster turbines (depending on specific parameter) for speeds above 450 ns means the use of the Kaplan turbines. The Kaplan turbine is a turbomachine usually irreversible.

4.5.1 Characteristics of Kaplan turbine

Some characteristics of Kaplan turbines are the small number of blades which improves the circulation of water in the presence of large flows. The mass flow through the turbine produces

great tensions in the base of the blades so these must be designed with high strength so its mass is also high, and this motivate in part that the number of blades is normally between 3 and 8. This turbine is the larger than Francis or Pelton turbines per kW installed. The blades on these turbines are quite high, and its length from the centre of rotation tends to be smaller the higher the specific number of revolutions are. This makes the inclination of the blades at the start and half of them is practically parallel to the axis of rotation. The impeller hub support in addition to handle the blades, also handles the regulatory mechanism of the blades so it has a large diameter ratio. This element is a truncated sphere with caps, and exceptionally may be cylindrical.

Inside the cube is the mechanism of regulation of mobile blades of the impeller. Each blade is extended by a shaft, which penetrates into the bucket, perpendicular to the axis of rotation of the impeller. Each blade shaft pivots on two bearings, including a lever drag on L which is what regulates the orientation of the blade, which in turn is secured to the axle of the wheel. The composition of the Kaplan water turbine depends on its own support structure.

4.5.2 Procedures to design a kaplan turbine

Once known the parameters of the head gross, the turbine operates in a way, or some variation. To achieve a defined layout of the Kaplan turbine, the expected theoretical power must be determined, as well as the specific number of revolutions per minute to do the design of the machine. After this procedure, there are a lot of ways to calculate it.

For the design of the strength of every element, there is a multitude of possibilities to do these estimations, however it will always be present techniques that improve the safety and suitability of the machine with the most demanding circumstances. Taking an overview of the turbomachine, energy balance must be done to determine the efficiency of the turbine.

4.5.3 Hydrodynamic calculation of the kaplan turbine

Once known the general characteristics of hydraulic machines, and particularly the Kaplan turbines, the hydraulic dimensioning of every element of the turbine can be made. The first thing that must be calculated is the power of the turbine, and then the design the impeller, distribution elements, and elements of fluid intake and output can be done.

4.6 Hydraulic Calculations

4.6.1 Calculation of channel sections

It must be an assumption done. It is that the water enters the inlet of the channel at a speed of 1.5m/s. The section required in the input channel is:

$$S=Q/V=15/1.5=10\text{m}^2$$

The derivation channel must have 3.2 metres wide and 3.2 metres high ($3.2*3.2 \approx 10$).

In the output channel, the water velocity will be less.

4.6.2 Weir Study

This part of the river has already a weir. However, it must be changed to satisfy the needs of the turbine that is going to be built there. The original weir was orthogonal. The new weir will be diagonal. This makes that water can be derived easier to the turbine. The old weir isn't going to be removed completely as it is historical. It was built in the 19th century. One or two meters wide of the weir is going to be conserved. This can be useful for fish migrations and will also continue providing enjoyment for people who likes canoeing in that zone of the river.

Mechanical calculation of the weir

For the mechanical calculation of the weir, we must know that the maximum height of the weir is 7m given a foundation of 2 meters. External forces that act per unit length are:

P: weight of the dam (2.2 tn/m^3).

H: horizontal thrust due to water pressure.

S: underpressure due to the thrust at the base of the weir. Is supposed to be half the hydrostatic load

and admits a triangular distribution.

Stability is given by the condition that the resultant of the two forces P and F passing through the core central base.

the stability coefficient overturning V is the ratio between the stabilizing moment given by the weight P and the sum of the overturning moment produced by the pressure of water H and the the underpressure S.

New weir

In this section what is it being calculated is the mechanical part of the new weir. The maximum height of the little dam is 5m. There is a side of the weir that is under the ground. It is the footing of the weir, what has to be also considered. The slope sheet or nappe is 0.2 m.

P = weight of the concrete

$\rho_{concrete} = 2200 \text{ kg / m}^3$

$\rho_{water} = 1000 \text{ kg / m}^3$

H = horizontal load because of the water pressure

S = subpressure due the buoyancy

The weir will be stable if the resultant load of P and H pass through the central core of the base of the weir. The stability coefficient V to overturning is the equation between the stabilizer torque due to the weir weight and the torque due to the push of the water and the buoyancy S. To do the calculations, the length of the weir will not be considered. Just the weir section will be considered. In this case the loads are measured in Kg, as the density of concrete and water will be needed.

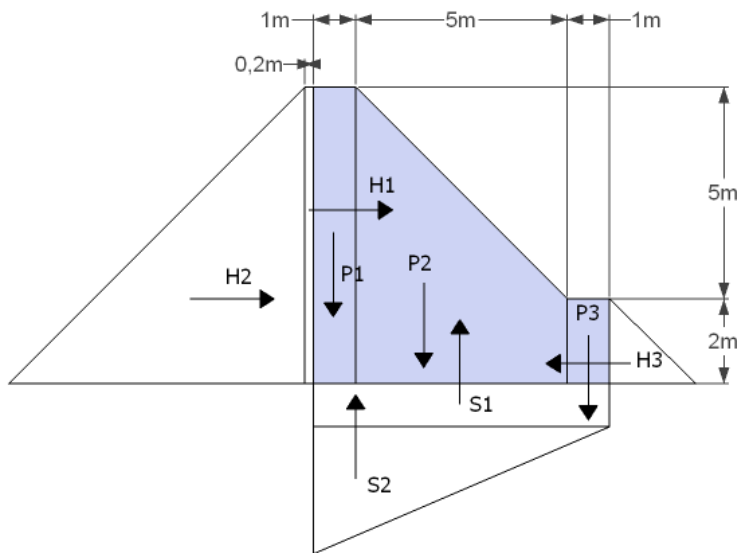


Figure 8, loads in the new weir (Made by project's author)

$$P1 = 1 * 7 * 2200 \text{ Kg/m}^3 = 15400 \text{ kg/m}$$

$$P2 = \frac{1}{2} * 5 * 7 * 2200 = 38500 \text{ kg/m}$$

P3 is included in the calculation of P2. Geometrically it fits perfect.

$$P1 + P2 = 53900 \text{ kg/m}$$

The meter can be removed in this calculations so we have:

$$\Sigma Pi = 53900 \text{ kg}$$

Horizontal loads:

$$H1 = 0.2 * 7 * 1000 \text{ kg/m}^3 = 1400 \text{ kg}$$

$$H2 = \frac{1}{2} * 7 * 7 * 1000 = 24500 \text{ kg}$$

$$H3 = \frac{1}{2} * 2 * 1000 = 2000 \text{ kg}$$

$$\Sigma Hi = H1 + H2 - H3 = 23900 \text{ kg}$$

Subpressure

$$S1 = 1.015 * 7 * 1000 = 7105 \text{ kg}$$

$$S2 = \frac{1}{2} * 3 * 7 * 1000 = 10500 \text{ kg}$$

$$\Sigma Si = 17605 \text{ kg}$$

The vertical resultant of the load will pass with a distance X of the right border of the weir.

$$X = \frac{(15400 * 6.5 + 38500 * 3.5 + 2200 * 0.5 - 7105 * 3.5 - 10500 * 4.6)}{(56100 - 17605)}$$

$$X = 4.21 \text{ m}$$

The horizontal resultant will pass with a distance Y to the inferior border of the weir.

$$Y = \frac{(1400 * 3.5 + 24500 * 2.3 - 200 * 0.6)}{(23900)}$$

$$Y = 2.59 \text{ m}$$

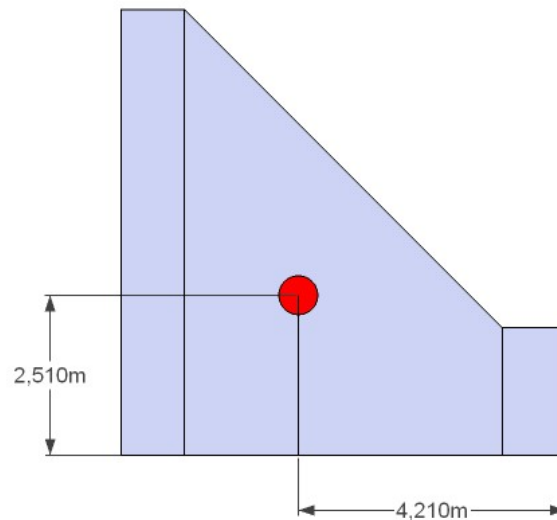


Figure 9, resultant of loads (Made by project's author)

As it can be seen, the point is in the core of the weir so the sizes of this small dam are appropriate for this amount of water.

4.6.3 Hydrodynamic calculation of the kaplan turbine

Once known the general characteristics of hydraulic machines, and particularly the Kaplan turbines, the hydraulic dimensioning of every element of the turbine can be made. The first thing that must be calculated is the power of the turbine, and then the design the impeller, distribution elements, and elements of fluid intake and output can be done.

Calculation of the effective power of the head conditions

First, we start using the data provided by the river conditions in Burrs weir:

$$Q=15\text{m}^3/\text{s}$$

$$H=5\text{m}$$

$$\eta=0.88$$

Theoretical power of the turbine is:

$$P=Q*H*g*d$$

g is the gravity acceleration (9.8 m/s²)

d is the density of the water (1000 kg/m³)

$$P=15*5*9.8*1000=735000w=735kw$$

For an efficiency estimated for a full work regimen of 0.88, the following power on the turbine shaft is obtained:

$$Pe=P*\eta=735000*0.88=646800w=647kw$$

This power is enough to give electricity for more or less 200 houses.

Impeller of the kaplan turbine

The calculation of the diameter of the impeller, must be made knowing the parameters of the blades or the angles of velocities of the water, for example.

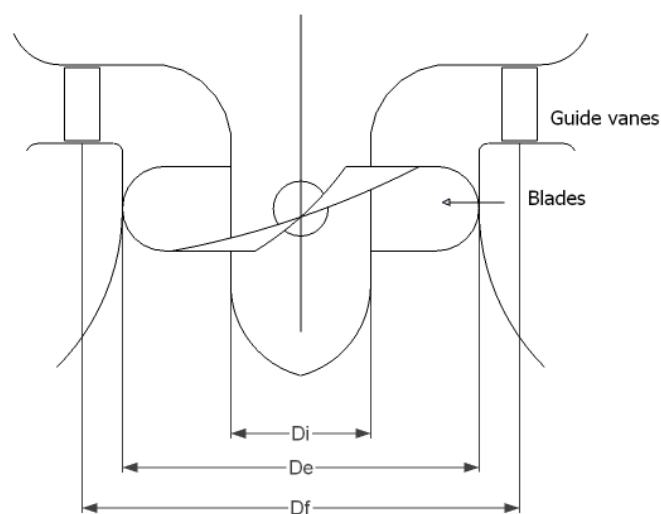


Figure 10, turbine impeller (Made by project's author)

Calculation of the specific speed n_s depending of the rotational speed:

The calculation of this speed is different depending on the source you look at. The best option was making a kind of mix of all of them. The steps to follow are in the web page of jaibona, about the calculation of the rotational speed. this web page. The steps in this web page take you to others like the one of ptrenergy. In the section of fluid machines of this page and with the help you can calculate it easily. The process followed is this one: This must be started with the table about the specific number of revolutions (N_s) depending on the gross head.

N_s	400-500	500-600	600-750	750-900	>900
H_n	60	50	40	20	5

The gross head is 5 metres so the specific number of revolutions should be similar.

$$P_u = g * H_n * Q * \eta * \rho = 646.8 \text{ kw}$$

$$H_n = \text{Gross head} = 5 \text{ m}$$

$$Q = \text{flow rate} = 15 \text{ m}^3/\text{s}$$

$$\eta = \text{efficiency} = 0.88$$

$$\rho = \text{density} = 1000 \text{ kg/m}^3$$

$$N_s = \frac{N * \sqrt{P}}{H_n^{1.25}}$$

N_s = Specific number of revolutions

N = Synchronous speed

$$P = \text{Power}$$

According to the table, $N_s=900$

$$900 = \frac{N * \sqrt{646.8}}{5^{1.25}}$$

$$N=264.6$$

The number of poles for 60 Hz systems is:

$$Pl = \frac{7200}{N}$$

So the number of poles is 27.2

Taking the nearest even number: 28

$$\text{Synchronous speed} = \frac{\text{Frecuency} * 60}{Pl} * 0.5 = \frac{60 * 60}{28} * 0.5 = 257 \text{ rpm}$$

$$N_s = \frac{N * \sqrt{P}}{Hn^{1.25}} = \frac{257 * \sqrt{646.8}}{5^{1.25}} = 874.7 = N_s$$

4.6.4 Turbine parameters:

The first calculations were taken from the e-book of Blas Zamora parra, “Problemas de Máquinas Hidráulicas”, what means “Hydraulic machines exercises”. In this electronic book, there are different exercises or problems about velocity triangles, the power of different turbo machines and the sizing of turbines.

$$c1 = k * \sqrt{2 * g * H} = c1 = 0.66 * \sqrt{2 * 9.81 * 5} = 6.534$$

$$k = \text{constant of reaction turbines} = 0.66$$

$c_2=c_1$, Because it is an axial turbine, so the tangential speed in the inlet and outlet is the same.

$$\text{Runner diameter : } De = \frac{84.5 * (0.79 + 1.602 * Nqe) * \sqrt{Hn}}{60} * n$$

$$Nqe = \frac{2.294}{Hn^{0.486}} = 1.0493$$

$$n = 257 \text{ rpm} = 4.283 \text{ rps}$$

$$De = 1.84$$

$$Di = (0.25 + \frac{0.0951}{Nqe}) * De = 0.627 \text{ m}$$

$$u = ku * \sqrt{2 * g * Hn} = 1.5 * \sqrt{2 * 9.81 * 5} = 14.86$$

$$\omega = \frac{U}{(\frac{De}{2})} = \frac{14.86}{(\frac{1.84}{2})} = 16.15 \text{ rad/s}$$

$$Pu = P * 0.88 = \frac{Q * \rho * U}{(\frac{De}{2})} * c_l * \cos(\alpha_1) - (\frac{De}{2}) * c_l * \sin(\alpha_1) * \cos(\alpha_2)$$

$$\alpha_2 = 90^\circ \text{ so:}$$

$$646800 = P * 0.88 = \frac{15 * 1000 * 14.86}{0.92} * 6.534 * \cos(\alpha_1)$$

$$\cos(\alpha_1) = 0.44410004$$

$$\alpha_1 = 63.634^\circ$$

$\alpha_2 = 90^\circ$ because the exterior part of the blade can be considered as lineal.

4.6.5 Velocity triangles:

The velocity C_{1m} has the same value than C_{2m} , which is the same as C_2 , in the blade exit. This is a simplification in the design that will be useful to find the section of the blade and its diameter.

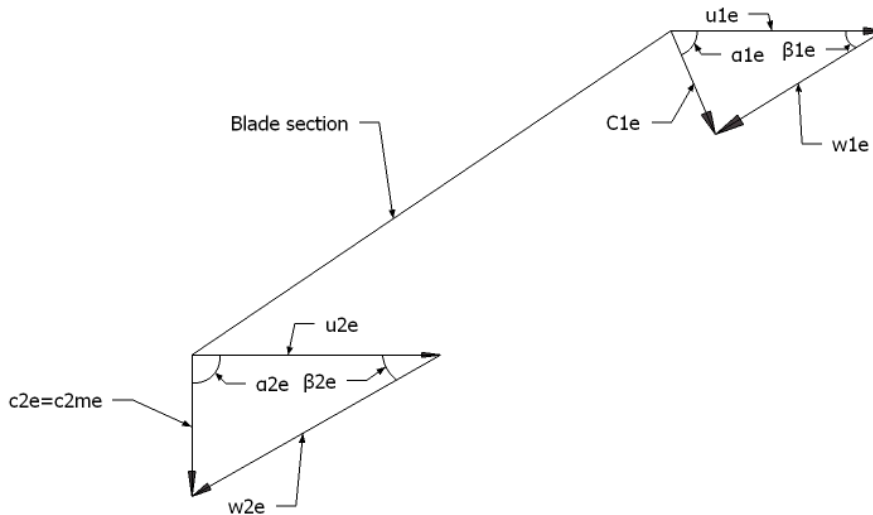


Figure 11, velocity triangles (Made by project's author)

$$\alpha_1 = 63.634^\circ$$

$$u_1 = u_2 = 14.86 \text{ m/s}$$

$$\alpha_{2e} = 90^\circ$$

$$\beta_{1e} ?$$

$$\beta_{2e} ?$$

$$\tan(\beta_1) = \frac{C_{1m}}{U} - C_{1u} = \frac{(C_1 * \sin(\alpha_1))}{(U - C_1 * \cos(\alpha_1))}$$

$$\tan(\beta_1) = \frac{(6.534 * \sin(63.634))}{(14.86 - 6.534 * \cos(63.634))}$$

$$\beta_1 = 26.08$$

$$\tan(\beta_2) = \frac{C_{2m}}{U} = \frac{C_{1m}}{U} = \frac{(6.534 * \sin(63.634))}{14.86} = 0.39396$$

$$\beta_2 = 21.5$$

From the data obtained we can extract some conclusions: The absolute velocity in the inlet has a big tangential component. This is very important to obtain a good transfer of energy from the fluid to the impeller hub. This can be seen in the blade outlet. The velocity has changed and doesn't have tangential component. This means that the fluid creates a force in the blade and drives the impeller.

4.6.6 Number and important parameters of blades:

To obtain the number of blades on the impeller, the specific number of revolutions depending on the power must be calculated first. To do this, we will use the following expression.

$$ns^* = 3.65 * \sqrt{\eta h * \eta q}$$

$$\eta q = \frac{n * \sqrt{Q}}{H^{3/4}}$$

$$\eta q = \frac{264.6 * \sqrt{15}}{5^{3/4}} = 306.48 \text{ rpm}$$

$$\eta h = \frac{((u_{1e} * C_{1ue}) - (u_{2e} * c_{2ue}))}{g} * H$$

$$C_{2ue} = 0$$

$$C_{1ue} = \sqrt{C_{1e}^2 - C_{1me}^2} = \sqrt{6.534^2 - 5.85^2} = 2.905 \text{ m/s}$$

$$Clm = Cl * \sin(\alpha l) = 6.534 * \sin(63.6) = 5.85 \text{ m/s}$$

$$\eta h = 0.881$$

$$ns^* = 3.65 * \sqrt{0.881} * 306.48 = 1050 \text{ rpm}$$

According to Bohl, some main sizes of the blade can be obtained using models of other kaplan turbines, so with this expression, these sizes are:

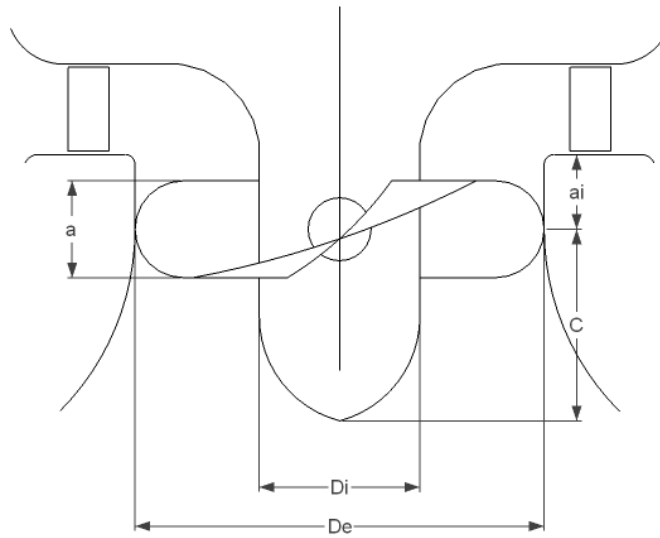


Figure 12, turbine impeller sizes (Made by project's author)

$$C = (6.94 * ns^{-0.403}) * De = (6.94 * 1050^{-0.403}) * 1.84 = 0.7738 \text{ m}$$

$$ai = (0.38 + (5.17 * 10^{-5} * 1050)) * 1.84 = 0.8 \text{ m}$$

$$a = \frac{1}{3}(c + ai) = 0.524 \text{ m}$$

The next equation considers the space free between two blades. The main important point of this equation is giving strength to the system of blades.

$$t = \frac{a}{(\tan(\beta l e))} = 1.0756 \text{ m}$$

There is no superposition of blades in this turbine. It just happen in those turbines that has small flow rates. Superposition of blades would affect to the effectiveness of this turbine. So the number of blades can be obtained using next equation:

$$Z = \frac{\pi * De}{t} = 5.37 \approx 5 \text{ number of blades}$$

With all this data we can make a first impression of how is going to be the layout on the inside of the turbine. As we can see in the lower one, the angle between axis of 2 consecutive blades is 72° .

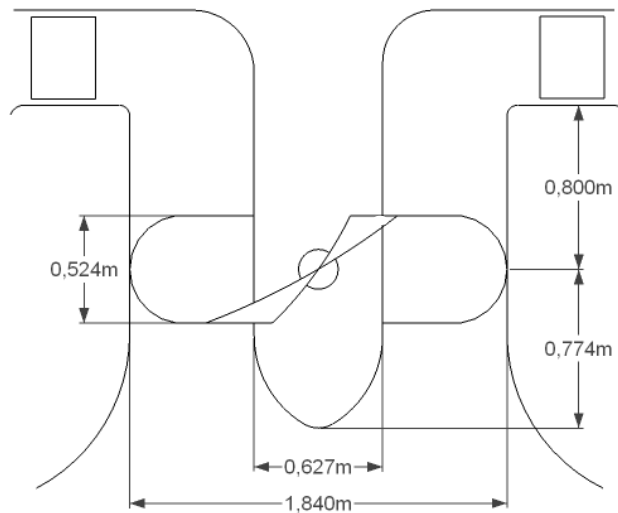


Figure 13, turbine impeller with sizes (Made by project's author)

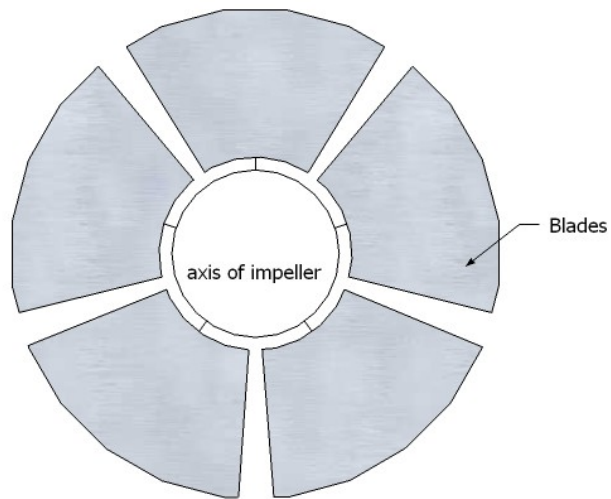


Figure 14, axis of impeller and blades (Made by project's author)

4.6.7 The guide Wheel or the Fink distributor

The function of this part of the turbine is guiding the water to the blades, distributing it in the whole 360° that has the scroll case. To do the calculations of this part, the most important thing is knowing the angle the angle of the fluid when it has contact with the blade, to avoid crashes with the impeller. Once known the surface of access to the impeller, the height and thickness of the vanes, the number of guide vanes can be calculated, to drive the flow of water. The following data is needed to this these calculations.

$$Q=15\text{m}^3/\text{s}$$

$$c\text{lsf}=6.534\text{ m/s}$$

$$ue=14.86\text{ m/s}$$

$$De=1.84\text{ m}$$

$$\rho=1000\text{ Kg/m}^3$$

$$g=9.81\text{ m/s}^2$$

$$\alpha\text{le}=63.6^\circ$$

The calculations to know the number of vanes are these.

$$Asf = \frac{Q * (\tan(\alpha l e))}{ue} = \frac{15 * (\tan(63.6))}{14.86} = 2.0335 \text{ m}^2$$

Number of vanes (Zf)

$$\sin(\alpha l e) = \frac{Zf * a}{2} * \pi * R_{ext}$$

$$a l = \left(\frac{3}{4}\right) * b$$

$$Asp = \frac{Asf}{zf} = b * a l$$

$$Zf = \frac{Asf}{B} * a q = \frac{(\sin(\alpha l e) * 2 * \pi * R_{ext})}{a l}$$

$$\frac{2.033}{Zf} = b * a l = b * \left(\frac{3}{4}\right) * b = \frac{3}{4} b^2$$

$$0.896 = \frac{Zf * \left(\frac{3}{4}\right) * b}{(2 * \pi * 0.92)}$$

$$b = 0.39 \text{ m}$$

$$a l = 0.294 \text{ m}$$

$$Zf = \frac{Asf}{(b * a l)} = \frac{2.0335}{(0.39 * 0.294)} = 17.7 \approx 18 \text{ guide vanes}$$

Some assumptions about the angles of the guide vanes must be done to calculate the loads acting on

them. Later, with that loads, strength calculations will be done.

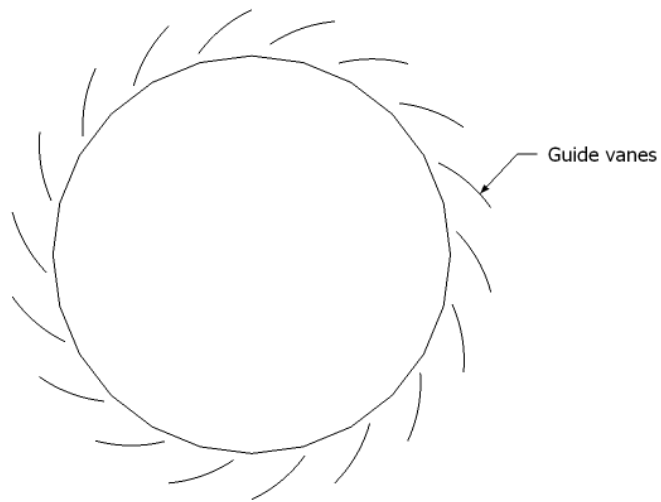


Figure 15, guide vanes (Made by project's author)

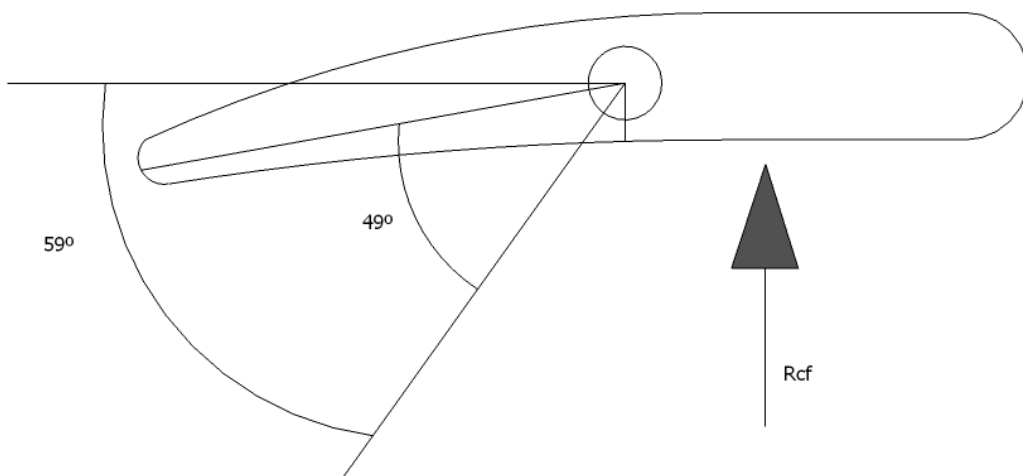


Figure 16, guide vane (Made by project's author)

The assumption of this angles must be done to calculate the loads acting on the vane. In the lower figure, we can see a vane. The water flow direction is from right to left.

$$Df = De + al = 1.84 + 0.294 = 2.134\text{m}$$

$$ec = \pi * Df = 6.7 \text{ m}$$

$$\text{length of the vane is: } lu = \frac{ec}{zf} = \frac{6.7}{18} = 0.37 \text{ m}$$

20% of superposition must be assumed when the distributor is closed:

$$l = lu * 1.2 = 0.4625 \text{ m}$$

With all this data we can add sizes to the inner layout drawn before.

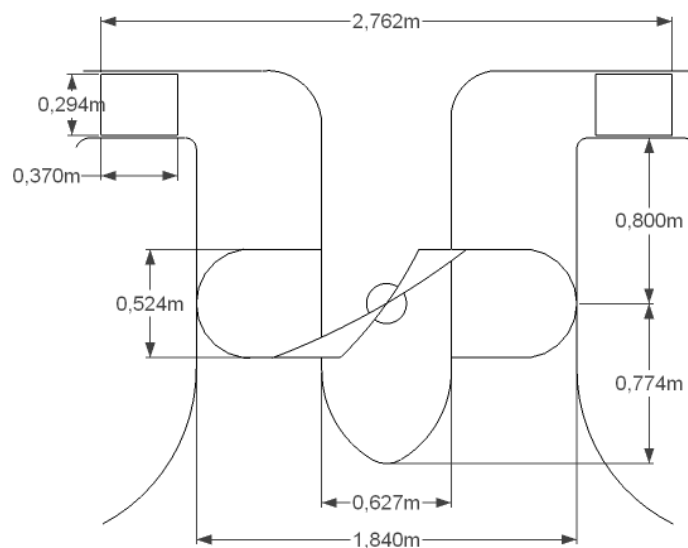


Figure 17, impeller with every size (Made by project's author)

The loads that act on the guide vanes can be calculated now. There are two cases: When the distributor is closed and when is open:

-When the distributor is closed:

$$Ap = l * b = 0.180375 \text{ m}^2$$

The hydrostatic pressure in a closed system is:

$$Prf = \rho * g * h = 49000 \text{ pa}$$

So the forces acting on the vane are:

$$F = Prf * Ap = 8838.375 \text{ N} = 8.838 \text{ KN}$$

-When the distributor is open:

In this situation, dynamic pressure is acting due to the movement of the fluid. The vane has changed also his angle so the reaction on it will be calculated.

$$c1 * A1 = c2 * A2$$

$$C2 = C1sf * \sin(\alpha fink) = 6.534 * \sin(59^\circ) = 5.6 \text{ m/s}$$

The area of the distributor exit between 2 vanes is:

$$A_{sp} = \frac{A_{sf}}{Z_f} = \frac{2.0335}{18} = 0.113 \text{ m}^2$$

The area inlet is:

$$A_{ep} = \frac{A_{ef}}{Z_{ef}} = \frac{(\pi (De+l) * b)}{Z_f} = 0.1567$$

$$C1 = \frac{C2 * A2}{A1} = \frac{5.6 * 0.113}{0.1567} = 4.037 \text{ m/s}$$

With The Velocities we can calculate the loads:

$$\vec{C}2 = -C2 * \cos(49^\circ) - C2 = (-3.674 \vec{i} - 5.6 \vec{j}) \text{ m/s}$$

$$\vec{C1} = -\cos(59^\circ) * C1 - \sin(59^\circ) = (-2.08 \vec{i} - 3.46 \vec{j}) \text{ m/s}$$

The negative symbols means that the fluid moves in the opposite direction to the reference system. The loads will be also negative.

$$R_x = -\left(\frac{Q}{Z_f}\right) * \rho * (C2x - C1x) = -\left(\left(\frac{15}{18}\right) * 1000 * (-2.08 + 3.674)\right) = -1328 \text{ N} = -1.328 \text{ KN}$$

$$R_y = -\left(\frac{Q}{Z_f}\right) * \rho * (C1y - C2y) = -\left(\left(\frac{15}{18}\right) * 1000 * (-3.46 + 5.6)\right) = -1783 \text{ N} = -1.783 \text{ KN}$$

Once known the loads, we can calculate the diameter of the axis of every vane and also the thickness of everyone. This will be made latter, in another section of the project.

4.6.8 The scroll case

Is a chamber in which the water flows before passing through the guide vanes. The section of this chamber decreases gradually. With this disposition, the water velocity does not change and there are no losses of energy. To calculate the sizes of the chamber, the different diameters of it will be calculated first. The data needed is:

$$Q = 15 \text{ m}^3/\text{s}$$

$$H = 5 \text{ m}$$

$$v = \text{dynamic viscosity of water} = 1.307 * 10^{-6} \text{ m}^2/\text{s}$$

$$R_{fink} = \frac{Df}{2} = \frac{2.134}{2} = 1.067 \text{ m}$$

The velocity in this chamber is:

$$c1s = 0.18 + (0.28 * \sqrt{(2 * g * Hn)}) = 2.95 \text{ m/s}$$

$$Q = S * c * l_s$$

$$S = \text{area of the circular section} = 5.08 \text{ m}^2$$

The diameter of the first section of the scrollcase will be

$$D = 2 * \sqrt{\left(\frac{S}{\pi}\right)} = 2 * \sqrt{\left(\frac{5.08}{\pi}\right)} = 2.54 \text{ m}$$

The diameters of the other sections must be calculated:

$$x = \frac{Q}{Q_{in}} = 1 - \left(\frac{\varphi}{360^\circ}\right)$$

$$\frac{D_c}{D_{in}} = x^{(2/5)}$$

$$D_c = D_{in} (1 - (\varphi - 360^\circ))^{(2/5)}$$

$$0^\circ \rightarrow D_c = 2.54 \text{ m}$$

$$90^\circ \rightarrow D_c = 2.264 \text{ m}$$

$$180^\circ \rightarrow D_c = 1.925 \text{ m}$$

$$270^\circ \rightarrow D_c = 1.46 \text{ m}$$

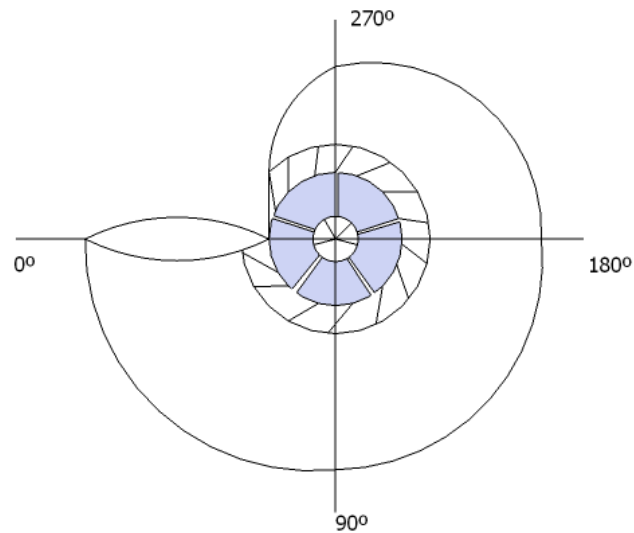


Figure 18, scroll case (Made by project's author)

4.6.9 Cavitation

Definition

Cavitation is the formation of vapour pockets inside the liquid, specially in the nearest parts in which the blades are. After this formation, they collapse or implode, causing damages on the blades. Cavitation can appear in liquids in movement but also in stopped ones. The sudden decrease in the pressure, what causes cavitation, is produced due to the movement of the blade and the liquid. The pressure energy is transformed into kinetic energy. When the small bubbles collapse, high frequency vibrations are produced. This affect the resistance of the surrounded materials.

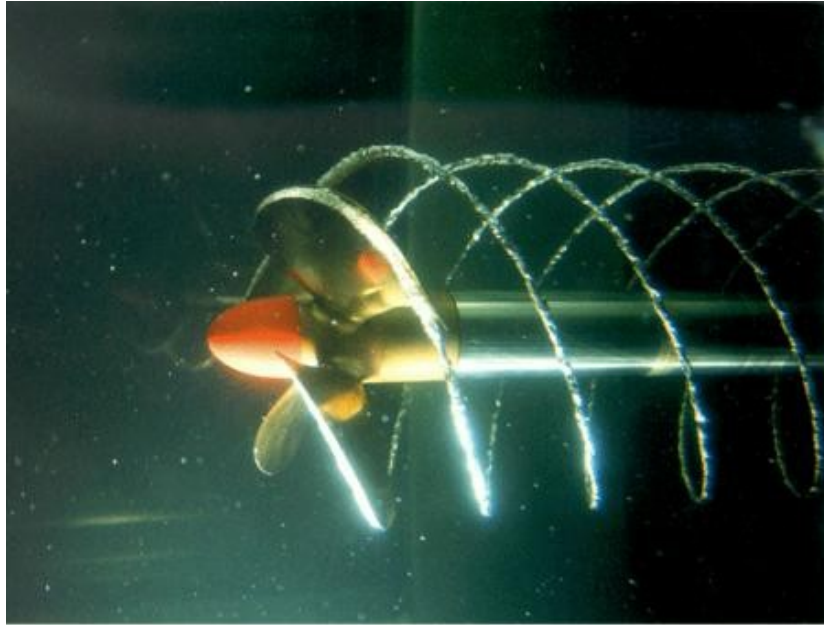


Figure 19, cavitation example (reporteciencial, 2012)

Kinds of cavitation

There are a lot of kinds of cavitation, depending on the way it is produced, the develop of it or the macroscopic way of work: Vapour cavitation, gas cavitation, emerging cavitation, developed cavitation, supercavitation, separated cavitation, bubble cavitation, inlet cavitation, sheet cavitation, streak cavitation, vortex cavitation, vortex shedding cavitation, gap cavitation and torch cavitation. They are some examples. There are a lot of kinds, as it can be seen. That is why it must be taken into consideration in the realization of an hydraulic project. Its appearance is very common.

Cavitation consequences in hydraulic machines

The way of appearance of the cavitation is making immediate loads. They appear and disappear very quickly and can produce the bearing failure and the eccentric of the axis. Noises and vibrations appear with the cavitation, depending on the kind of cavitation. The continuous collapse of bubbles with high implosion velocities, generate this high frequency vibrations. If this frequency reach the mechanical resonance frequency, it can be catastrophic for many parts of the turbine. The pitting is one of the worst effects of the cavitation. Pores are appearing with cavitation in the blades until they break the total structure of it, as we can see in the image.



Figure 20, cavitation failure(ingesaerospace-mechanicalengineering, 2012)

Cavitation Characteristics

The best way to deal with cavitation is defining an expression of the cavitation coefficient depending on the hydraulic parameters we know about this turbine. The cavitation is produced in the low pressure points. This pressure depends on the high in which we are working, so the part of the turbine that can suffer more cavitation is the draft tube.

Ways to prevent cavitation

Cavitation can not be removed. The only way to fight against it is controlling it and keeping it into admissible values. To maintain it into these values, some parameters and its design has to be considered. For example, the edges of the blades must be rounded, avoiding sharp ones. The surface of the blade must have low roughness.

Cavitation coefficient and draft tube:

The most important thing to calculate in this part is the maximum height of aspiration, in order to avoid cavitation. The cavitation coefficient must be known first, as with this coefficient the transition zone of this phenomenon will be placed. The sizes of the draft tube can be calculated once

known these two parameters. The data needed is:

$$H_n = 5 \text{ m}$$

$$D_e = 1.84 \text{ m}$$

$$n_s = 871.4$$

$$c_l = 6.534 \text{ m/s}$$

$$u_l = 14.86 \text{ m/s}$$

$$C_{lu} = 2.91 \text{ m/s}$$

$$\alpha_l = 63.6^\circ$$

$$C_e = 2.8 \text{ m/s}$$

$$\rho = 1000 \text{ kg/m}^3$$

$$g = 9.81 \text{ m/s}^2$$

The saturation vapour pressure for 25°C is 3166 Pa. The temperature is high enough for the conditions of the turbine. It is supposed that the water temperature will never be higher than this. According to F. de Siervo, the Thoma Coefficients are:

$$\text{Hydraulic application coefficient } \sigma_s = 0.0413 * \left(\frac{n_s}{100}\right)^{1.672} = 1.55$$

$$\text{Point of critic cavitation coefficient } \sigma_c = 0.0348 * \left(\frac{n_s}{100}\right)^{1.283} = 0.56$$

With these coefficients the maximum height can be calculated in order to avoid cavitation due to pressure. The reference is the sea level, as the altitude of Bury is small. That is why the pressure

chosen is the sea level one.

$$H = -(\sigma c * H) + \frac{(P_{amb} - P_s)}{\rho g}$$

$$H = -(0.56 * 5) + \frac{(101300 - 3166)}{9810} = 7.214 \text{ m}$$

If we have a height higher than this between the blades and the draft tube exit, cavitation can appear. Considering $H_s = 1$ because it must be lower than 7.214, and this value fits our turbine and the river after the turbine, we have:

$$P_{amb} = (H_s + (\sigma c * H) \rho g) + P_s$$

$$P_{amb} = (1 + (0.567 * 5) 9810) + 3166 = 52556.4 \text{ Pa}$$

This ambient pressure is normal in an altitude of 5000m more or less. If this turbine was in that altitude, it would have cavitation problems. This is not the case because as it was said before, Bury has a lower altitude. The dimensions of the draft tube depend on the diameter of the impeller. These dimensions can't be exactly calculated, so in this case the calculations are done using approximate constants.

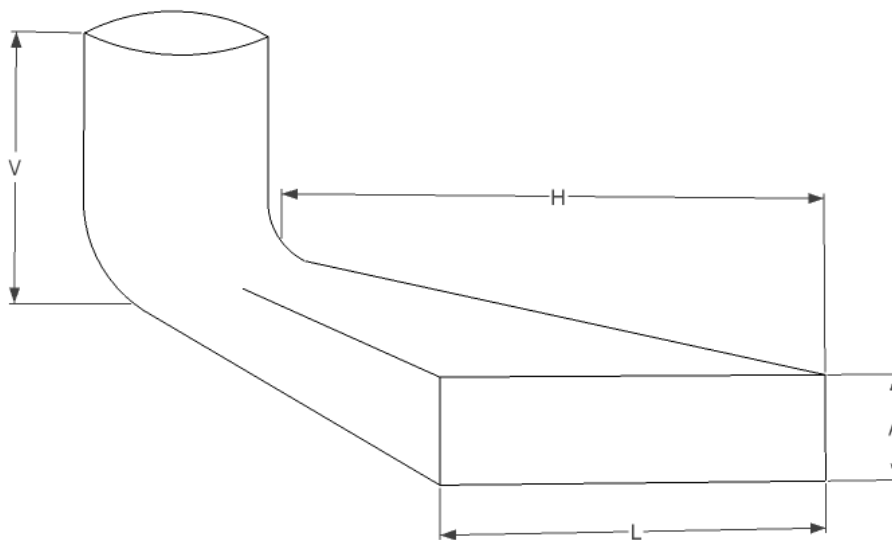


Figure 21, Draft tube (Made by project's author)

$$A = 1.25 * D_e = 1.25 * 1.84 = 2.3 \text{ m}$$

$$L = 3.1 * De = 3.1 * 1.84 = 5.7 \text{ m}$$

$$V = 1.75 * De = 3.22 \text{ m}$$

$$H = 2.7 * De = 4.968 \text{ m}$$

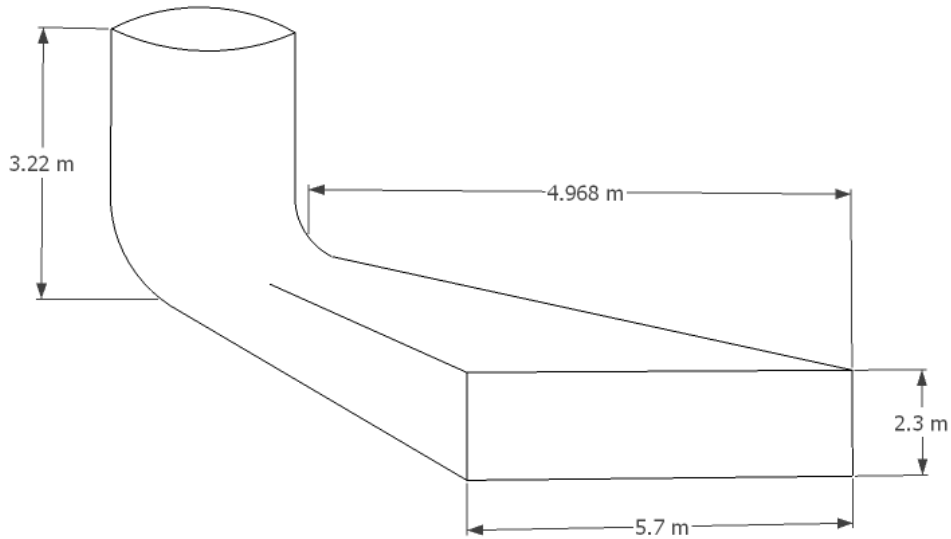


Figure 22, draft tube sizes (Made by project's author)

The layout of the important parts of the turbine with real sizes is like this

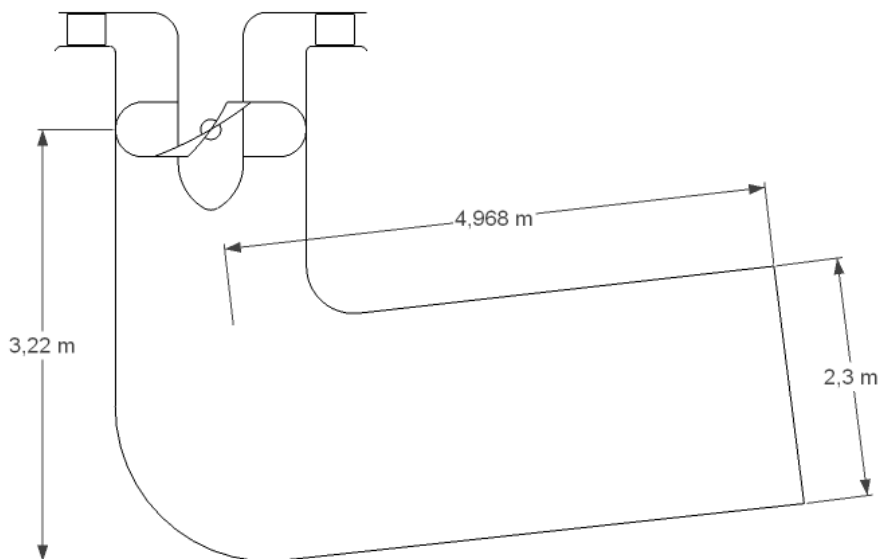


Figure 23, Draft tube with sizes (Made by project's author)

Once known the dimensions of the draft tube, the layout of the turbine, with the draft tube and the weir can be done.

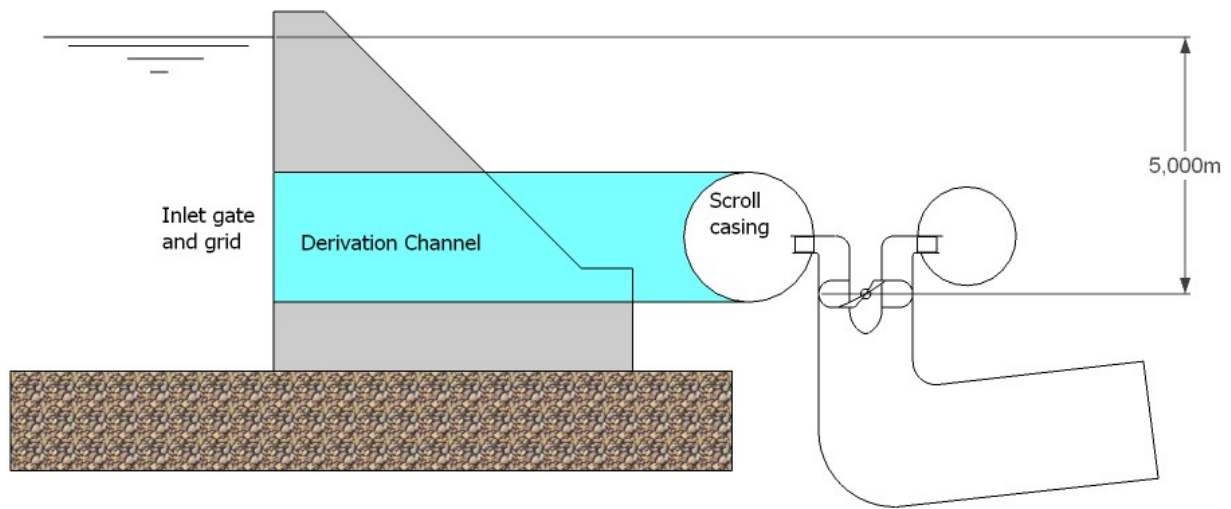


Figure 24, layout (Made by project's author)

4.7 Resistive calculation of the elements of the turbine

4.7.1 Dimensional sizing of the blades. Calculation of the loads on the blade

Once known the main sizes of some parts of the turbine, the next step is sizing others taking into consideration the strength of the material used and the loads acting on it. Knowing these loads that act on the blades is one of the most important things to do the design of some parts of the turbine. These elements are the blades, the impeller hub or the axis of power transmission.

To calculate the loads and torques due to the circulation of the fluid, this data must be taken into consideration:

$$\rho = 1000 \text{ kg/m}^3$$

$$Hn = 5\text{m}$$

$$g = 9.81 \text{ m/s}^2$$

$$r_i = \frac{D_i}{2} = \frac{0.627}{2} = 0.3135 \text{ m}$$

$$r_{ext} = \frac{D_e}{2} = \frac{1.84}{2} = 0.92 \text{ m}$$

$$\omega = 16.15 \text{ rad/s}$$

$$Z = 5 \text{ blades}$$

$$C_{le} = 6.534 \text{ m/s}$$

$$C_{2u} = 0 \text{ m/s}$$

$$\alpha_l = 63.6^\circ$$

$$\eta_h = 0.881$$

The easiest way to calculate the loads is consider the blade as a circular sector. It is not the real shape of the blade, but some simplifications must be done to be able to calculate the loads easily.

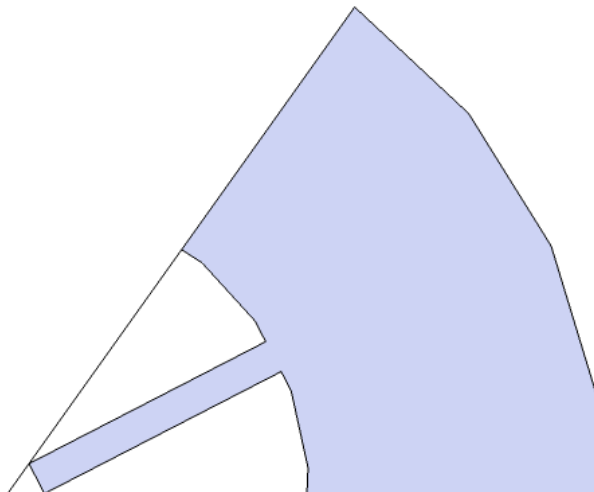


Figure 25, blade shape simplification (Made by project's author)

$$Clm = Cl_e \sin(\alpha_l) = 5.85 \text{ m/s}$$

$$C2 = Clm = 5.85 \text{ m/s}$$

$$u_l = \omega * r = 14.86 \text{ m/s}$$

$$Clu = \frac{(\eta h * g * Hn)}{(16.5 * 0.92)} = 2.844 \text{ m/s}$$

Reaction grade in function of the radius of the impeller:

$$\sigma(r) = \frac{((\omega * r * \eta h * g * Hn) \frac{(\omega * r)}{g} - (\frac{\sqrt{((\frac{\eta h * g * Hn}{(\omega * r)})^2 + Clm^2)} - Clm^2)}{2g}))}{(\eta h * Hn)}$$

$$\sigma(r) = \frac{(4.405 - \frac{((\frac{6.8644}{r^2}) + 34.2225) - 5.85}{19.6})}{4.405}$$

$$Fa = \frac{2 * \pi * \rho * g * Hn}{2} * \int \sigma(r) * r * dr$$

$$Fa = 61675.2 * \left[\frac{(579655 * x^2 + 68644)}{(863380 * x)} \right]_{0.3135}^{0.92} = 61675.2 (0.7041 - 0.4641) = 14803 \text{ N}$$

$$Ma = \left(\frac{2 * \pi * \rho * g * Hn}{2} \right) * \int \sigma(r) * r^2 * dr$$

$$Ma = 61675.2 * \left[-\frac{(137288 * \log(x) - 579655 * x^2)}{1726760} \right]_{0.3135}^{0.92} = 61675.2 (0.287 - 0.073) = 13195.7 \text{ N * m}$$

$$Ma = 13195.7 \text{ N * m}$$

Another load and torque must be calculated. The one above it was the vertical one. This is the horizontal.

$$\Delta Cu = Cu1 - Cu2 = \frac{\eta h * g * Hn}{(\omega * r)} = \frac{0.881 * 9.81 * 5}{(16.15 * r)}$$

$$Fu = \frac{2 * \pi * \rho * g * Clm}{Z} * \int \Delta Cu * r * dr = 7204.3 * \int \Delta Cu * r * dr$$

$$Fu = 7204.3 * \left[\frac{669 * X}{250} \right]_{0.3135}^{0.92} = 7204.3 (2.46192 - 0.84) = 11684.8 \text{ N}$$

$$Mu = \frac{2 * \pi * \rho * g * Clm}{Z} * \int \Delta Cu * r^2 * dr = 7204.3 * \int \Delta Cu * r^2 * dr = 9081.6 \text{ N * m}$$

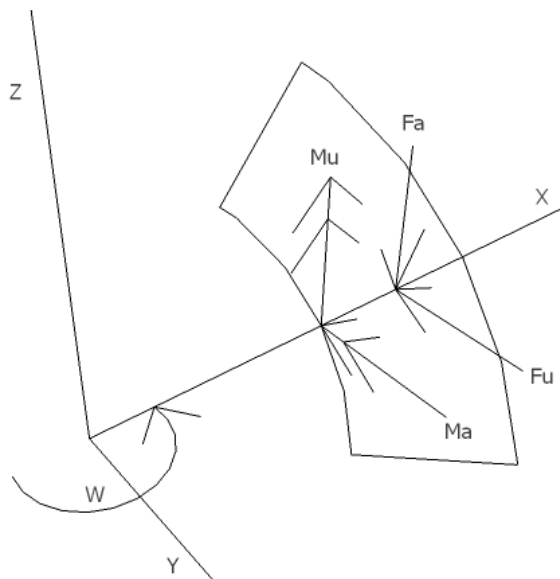


Figure 26, loads on blade (Made by project's author)

4.7.2 Calculation of the stress on the blade and Selection of the material used for the blade

Once known the loads and torques acting on the blade, an analysis of the stress suffered by the blade must be done. The first thing that must be done is setting the material used depending on the

loads. With this, the size of the axis of the blade can be known, and also the thickness of the blade profile. The data used is:

$$r_{ext} = 0.92 \text{ m}$$

$$r_i = 0.3135 \text{ m}$$

$$\varphi_{blade} = 52^\circ$$

$$F_a = 14803 \text{ N}$$

$$M_a = 13195.7 \text{ N} * \text{m}$$

$$F_u = 11684.8 \text{ N}$$

$$M_u = 9081.6 \text{ N} * \text{m}$$

The properties requested are big stress resistance, great resilience and good behaviour to oxidation. Some materials that can fit these characteristics are bronze and aluminium, but these materials cause a loss in the efficiency, due to that water can slip in them. Molten chrome steel is a good material but it is oxidized easily.

The best material and more commonly used to make turbine blades is the stainless steel ASTM A743 CAG NM. The main characteristics of this steel is the high content of nickel and chromium. It is easy to work with and good has good solderability properties. These solderability properties are advantages in case of impact, corrosion or cavitation. The mechanical properties are:

$$\text{minimum yield stress} = 555 \text{ Mpa}$$

$$\text{ultimate stress} = 755 \text{ Mpa}$$

$$\text{Minimum elongation (50 mm)} = 15 \%$$

$$\text{Minimum contraction} = 50 \%$$

$$\text{Density} = 7695 \frac{\text{Kg}}{\text{m}^3}$$

$$\text{Elastic modulus (20}^\circ\text{)} = 199 \text{ Gpa}$$

We can define now the stresses.

$$S_y = 555 * 10^6 \text{ Pa}$$

Considering a safety factor of $n=1.5$:

$$S' y = \frac{S_y}{n} = 370 * 10^6 \text{ Pa}$$

$$\text{The maximum Shear stress is } \frac{S_y}{(2 * n)} = 185 * 10^6 \text{ Pa}$$

If we combine The two moments of the blade to calculate its diameter:

$$Mr = \sqrt{(Ma^2 + Mu^2)} = \sqrt{(13195.7^2 + 9081.6^2)} = 16018.8 \text{ N * m}$$

$$\sigma f = \frac{Mr * e}{I} = \frac{32 * Mr}{(\pi * d^3)}$$

$$S' y \geq \sigma co = \sqrt{(\sigma^2 + 3 * \tau^3)}$$

$$\tau = 0$$

$$\sigma f = \frac{32 * Mr}{(\pi * d^3)}$$

$$185 * 10^6 = \frac{32 * 16018.8}{(\pi * d^3)}$$

$$d^3 = 8.8198 * 10^{-4}$$

$$d = 0.0959 \text{ m}$$

The shear stress must be calculated to see if the diameter is correct:

$$Fr = \sqrt{(Fd^2 + Fu^2)} = \sqrt{(14803^2 + 11684.8^2)} = 18859 \text{ N}$$

$$\tau = \frac{Fr * m}{(b * I)} = \frac{(4 * Fr * (\frac{d}{2})^2)}{(3 * \pi * (\frac{d}{2})^4)}$$

Von misses:

$$S' yr \geq \tau$$

$$185 * 10^6 = \frac{(4 * 18859 * (\frac{d}{2})^2)}{(3 * \pi * (\frac{d}{2})^4)} = \frac{18859}{(\pi * d^2 * 48)}$$

$$d^2 = 6.76 * 10^{-7}$$

$$d = 0.0008 \text{ m}$$

With this calculation we can see that the diameter calculated before is correct.

Now we round the diameter of the axis to 0.1m. This makes it more real because this has to fit in the hub impeller.

The thickness of the blade is calculated now. The simplification about the shape must be established. The blade is a flat circular sector and the section of the base is rectangular. Calculation of the length of the section:

$$b = \frac{2 * \pi * r l * \varphi}{360^\circ} = \frac{2 * \pi * 0.12 * 70^\circ}{360^\circ} = 0.1466 \text{ m}$$

$$\sigma_f = \frac{M r * e}{I} = \frac{\left(\frac{M r * e}{2}\right)}{\left(\frac{1}{12}\right) * b * e^3} = \frac{\left(\frac{16018.8}{2}\right)}{\left(\frac{0.1466 * e^2}{12}\right)}$$

Von misses:

$$S' yr \geq \sigma co$$

$$183 * 10^6 = \frac{\left(\frac{16018.8}{2}\right)}{\left(\frac{0.1466 * e^2}{12}\right)}$$

$$e^2 = 3.544 * 10^{-3}$$

$$e = 0.059 \text{ m} = 5.9 \text{ cm}$$

The whole blade can be drawn in pro-engineer following the data calculated above.

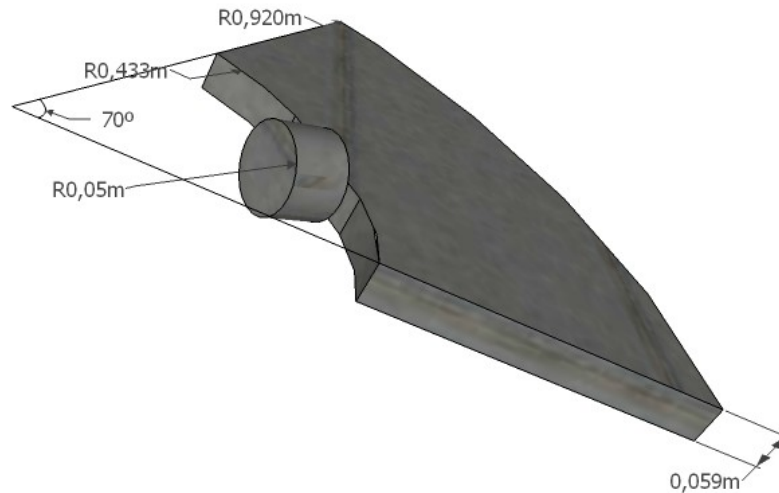


Figure 27, blade with sizes (Made by project's author)

4.7.3 Calculation of the stress on the guide vane

The design of these elements is based in the fact that the axis bears the maximum load in the bigger size of the vane. The maximum load is made when the Fink distributor is closed due to the water pressure. The material considered is the same as the blades: Steel ASTM A743 CAG NM. There is no cavitation in this point. The Characteristics of the material are:

$$S_y = 555 * 10^6 Pa$$

Considering a safety factor of $n=1.5$:

$$S' y = \frac{S_y}{n} = 370 * 10^6 Pa$$

The maximum Shear stress is $\frac{S_y}{(2 * n)} = 185 * 10^6 Pa$

The length (l) of the vane is 0.39m and the height (b) is 0.294. The loads over the vane are:

$$R_x = 1.328 KN$$

$$R_y = 1.783 KN$$

$$Fh = 8.838 \text{ KN}$$

The distribution of the load through the vane is:

$$qh = \frac{Fh}{b} = \frac{(8838 \text{ N})}{(0.294 \text{ m})} = 30061 \text{ N/m}$$

The endpoints of the axis are backed. So the reactions are:

$$R1 = \frac{Fh}{2} = 4419 \text{ N}$$

$$R2 = \frac{Fh}{2} = 4419 \text{ N}$$

$$\text{The momentum is} = R1 * x - \frac{qh}{2} * X^2$$

$$Mr = 4419 * 0.195 - \frac{30061}{2} * 0.195^2 = 290.17 \text{ N * m}$$

The torque is:

$$Fr = \sqrt{(Fx^2 + Fy^2)} = \sqrt{(1328^2 + 1783^2)} = 2223.2 \text{ N}$$

$$Mt = \frac{Fr * l}{2} = 433.5 \text{ N * m}$$

The stress due to the momentum is:

$$\sigma_f = \frac{Mr * e}{I} = \frac{32 * Mr}{(\pi * d^3)}$$

The tangential stress due to the torque is:

$$\tau t = \frac{\left(\frac{Mt * df}{2}\right)}{I_o}$$

Von Mises: To calculate the minimum diameter:

$$S' y \geq \sigma co = \sqrt{(\sigma^2 + 3 * \tau^3)}$$

$$\sigma co = \sqrt{\left(\frac{32 * Mr}{(\pi * d^3)} + 3 \left(\frac{\left(\frac{Mat * d}{2}\right)^2}{\left(\frac{\pi * d^2}{4}\right)}\right)\right)}$$

$$185 * 10^6 = \sqrt{\left(\frac{32 * 290.17}{(\pi * d^3)} + 3 \left(\frac{\left(\frac{433.5 * d}{2}\right)^2}{\left(\frac{\pi * d^2}{4}\right)}\right)\right)}$$

Solving this complicate equation, we have that the diameter is $d = 0.0172$ m. So the diameter chosen is $d = 0.02$ m = 2cm.

5-RESULTS AND DISCUSSION

In this part, the resistive calculation using computer aid is done. It could be included in the design process. However, the software testing is part of the results, because we will see if the theoretical calculations were correct. In addition, some corrections can be done with this, so its part of the discussion.

5.1 Resistive Calculation using Computer aid

The calculations done to determine the shape and strength of the turbine, are based in calculus theories and model tests. These calculations are effective but there are some variables needed that cannot be solved with this method. Nowadays, the majority of the improvements in turbomachinery are obtained with computer calculations. This saves money because there is no need to build models to test every machine. Testing machines with a computer can also help us in our design finding mistakes in the design or failure causes.

In this project, computer aid is used to improve the initial design, test if it can stand the loads and make an analysis of the results obtained. The program used to test some of the parts of the turbine is pro-engineer. This program allows you to draw the part tested, put the restrictions in the appropriate place and the loads. The program itself, based in the finite elements theory, gives you an outcome showing you the result of some variables like the most stressed point of the calculated part, the value of this stress or the deformation of the part.

Verification of the resistance of the blade

The behaviour of the blades exposed to the loads is one of the more interesting thing to calculate with the computer in order to show and check that the calculations done before are correct. The software also provides the possibility to see if the deformation of the part is admissible or not. The software used was pro-engineer. In this case, the first thing done is defining the material used in our blade and setting the real values of this material. The characteristics of the steel used were written in the software as we can see in the next Figure.

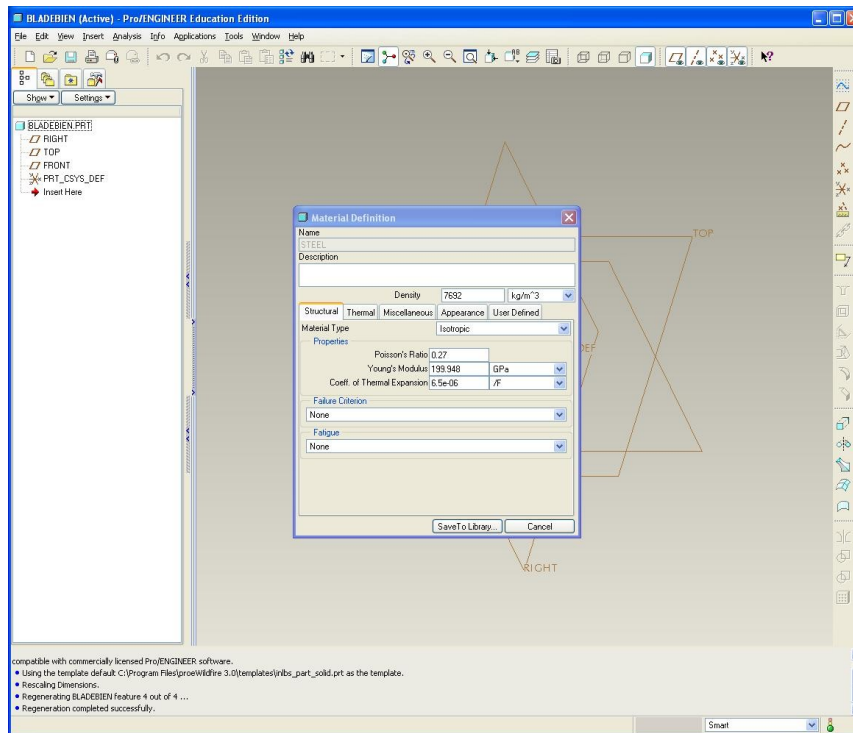


Figure 28, pro-engineer material (Made by project's author)

The density, Poisson's ratio and Young modulus were changed from the normal steel to adapt it to the steel ASTM A743 used for the blade. The next step done was drawing the blade. As it was said before, the shape used is not the real one. It was simplified to make the drawing easier. This assumption is made to allow the program do all calculations correctly. After this, the constraints and loads were setted in their correspondent place. The constrain on the blade axis is due to the fact that it is embedded into the impeller hub. To set the loads, another simplification were done. Due to the impossibilitiy to set a single load in the centre of the blade with the value of 18859 Newtons, the area of the blade was calculated to set a pressure in the surface with the same value as the load. The area of the blade is:

$$A = 70^\circ * \pi \frac{(0.92^2 - 0.4865^2)}{360^\circ} = 0.3725 m^2$$

$$P = \frac{F}{A} = \frac{18859}{0.3725} = 50628.2 Pa$$

This value is exactly the one that can be seen in the software.

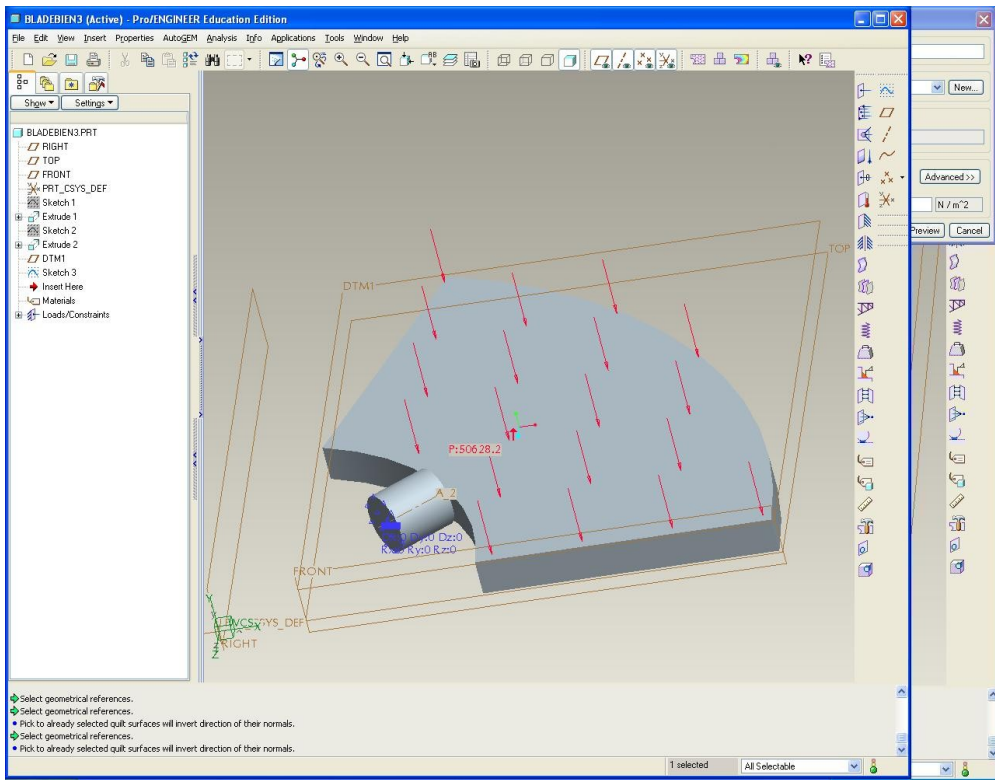


Figure 29, loads on blade (Made by project's author)

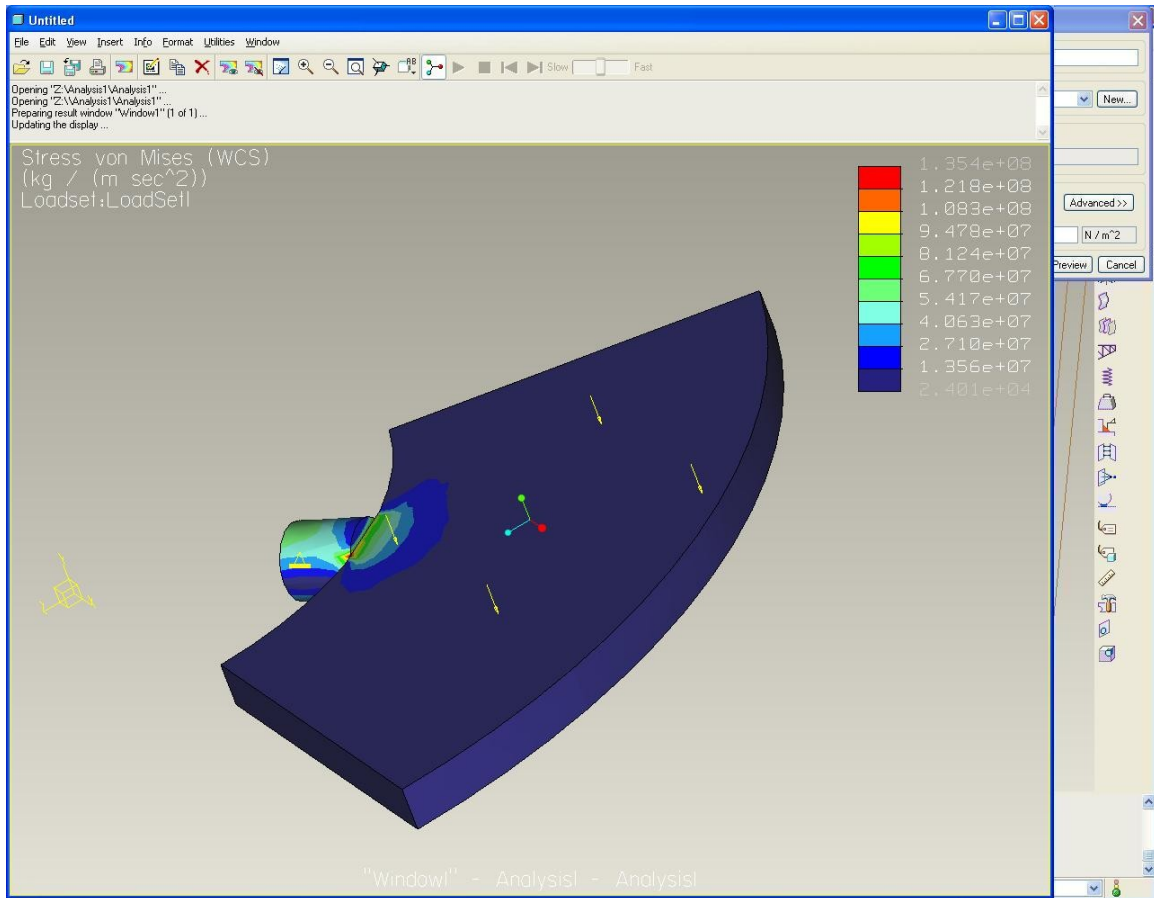


Figure 30, pro-engineer stress result (Made by project's author)

In the last Figure, the results of the simulation can be seen. In this case it is the stress Von Mises test. The most stressed part is the blade and its axis junction. This is due to the sharp edge in which they are together. It can be rounded to improve the behaviour of the blade and avoid problems as the appearance of cracks. Anyway, the maximum value of the Von Mises stress is 135400000 Pa, which is less than the shear stress admissible, 185000000 Pa, which means that the blade is well designed because it works perfectly.

In the detailed Figure below this we can see better the junction of blade and axis.

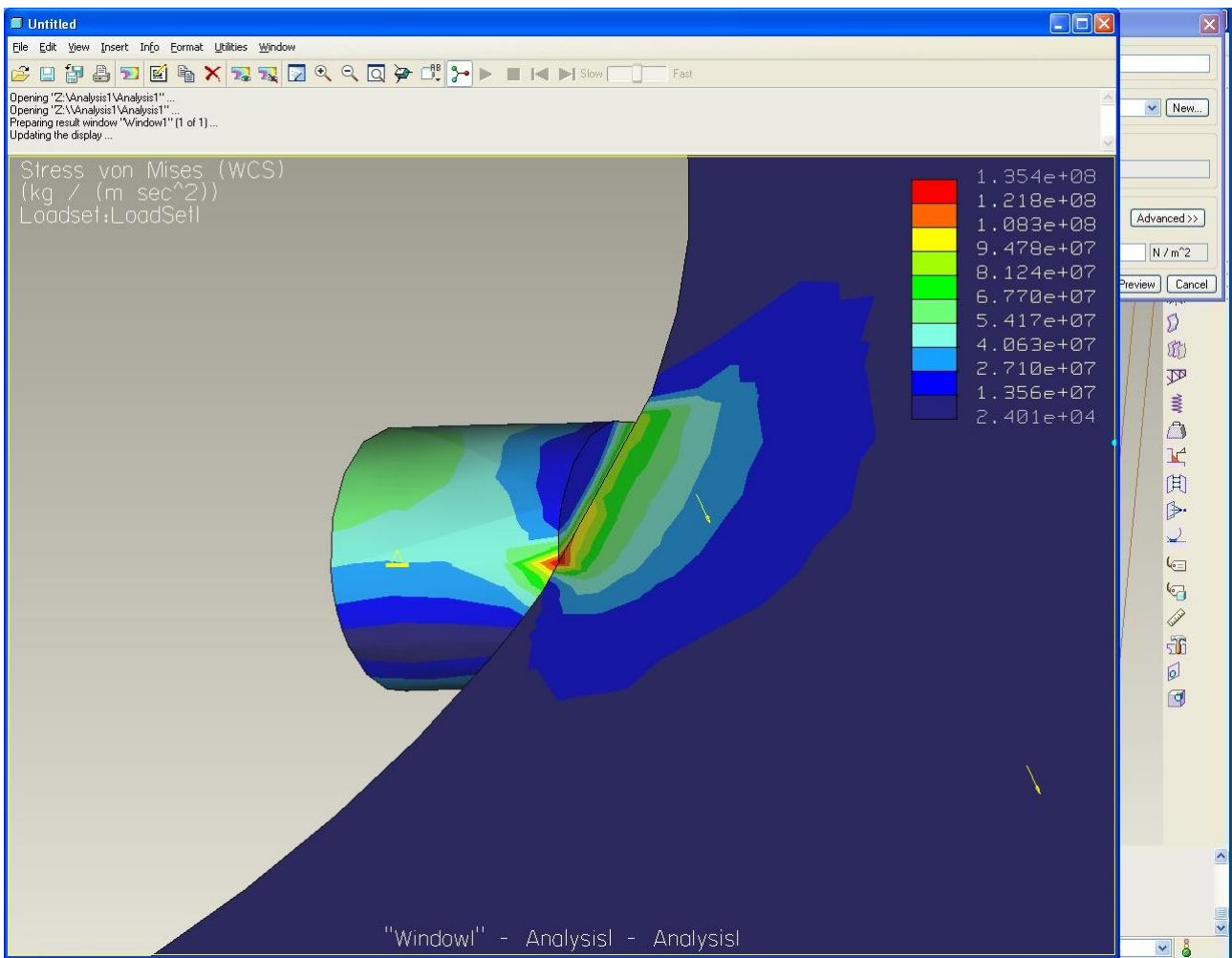


Figure 31, pro-engineer stress result on axis (Made by project's author)

Another result can be seen if we choose the displacement outcome. In the figure below this, we can see that the maximum displacement is $6.142 \cdot 10^{-4} = 0.0006 \text{ m} = 0.6 \text{ mm}$. This displacement is very

small, what means that the blade works perfectly also taking into consideration the maximum displacement admitted for the blade.

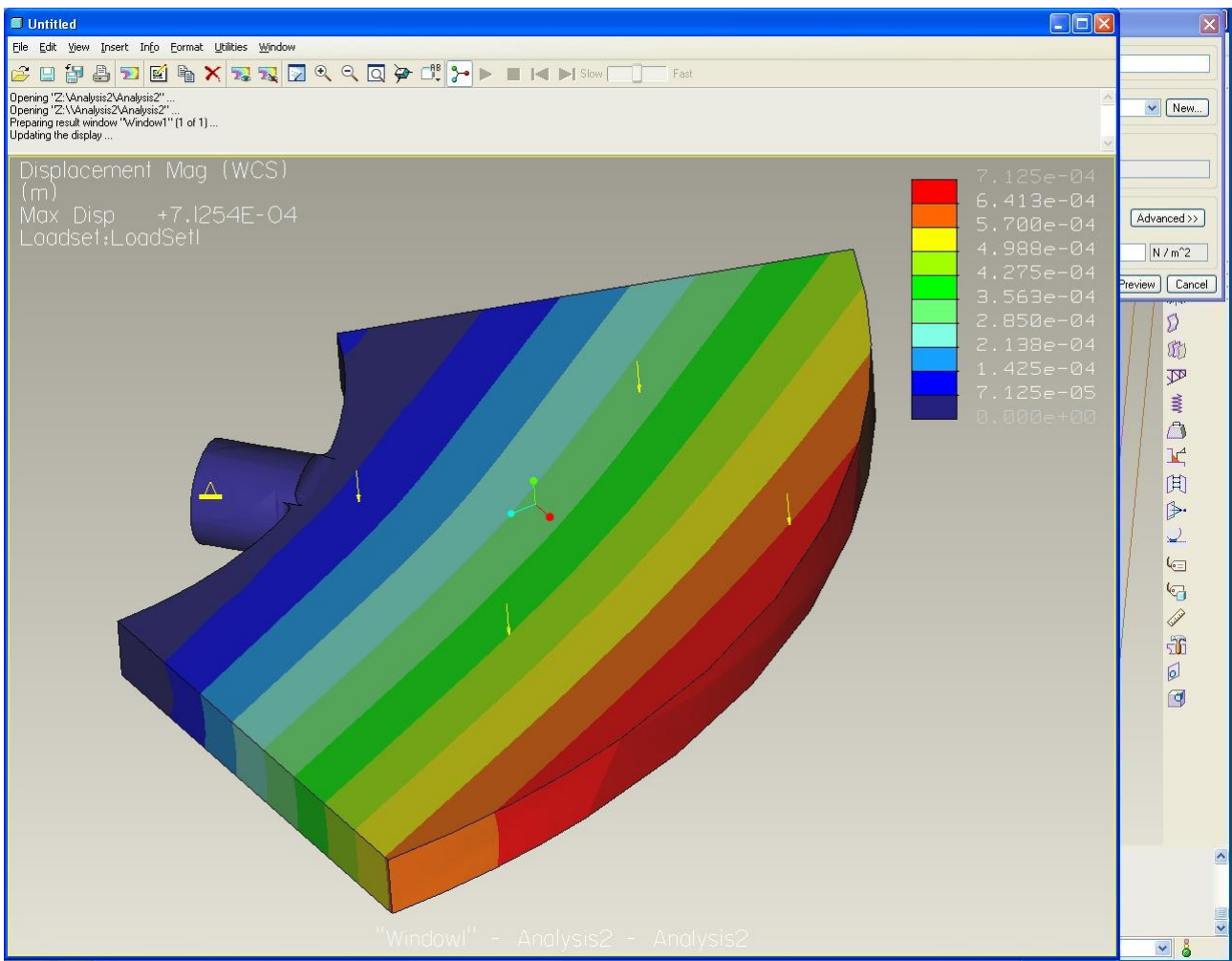


Figure 32, blade displacement (Made by project's author)

The Von Mises stress test and the displacement one says that there will not be failure of the blade. However, if we leave the junction between axis and blade like this, a crack can appear with time. The way to avoid it is rounding the edges. The rounding will affect every edge of the blade, to avoid also the cavitation that sharp edges produce. The maximum stress in the blade will be decreased, what means that the qualities of the blade will be improved. We can see it in the next figure.

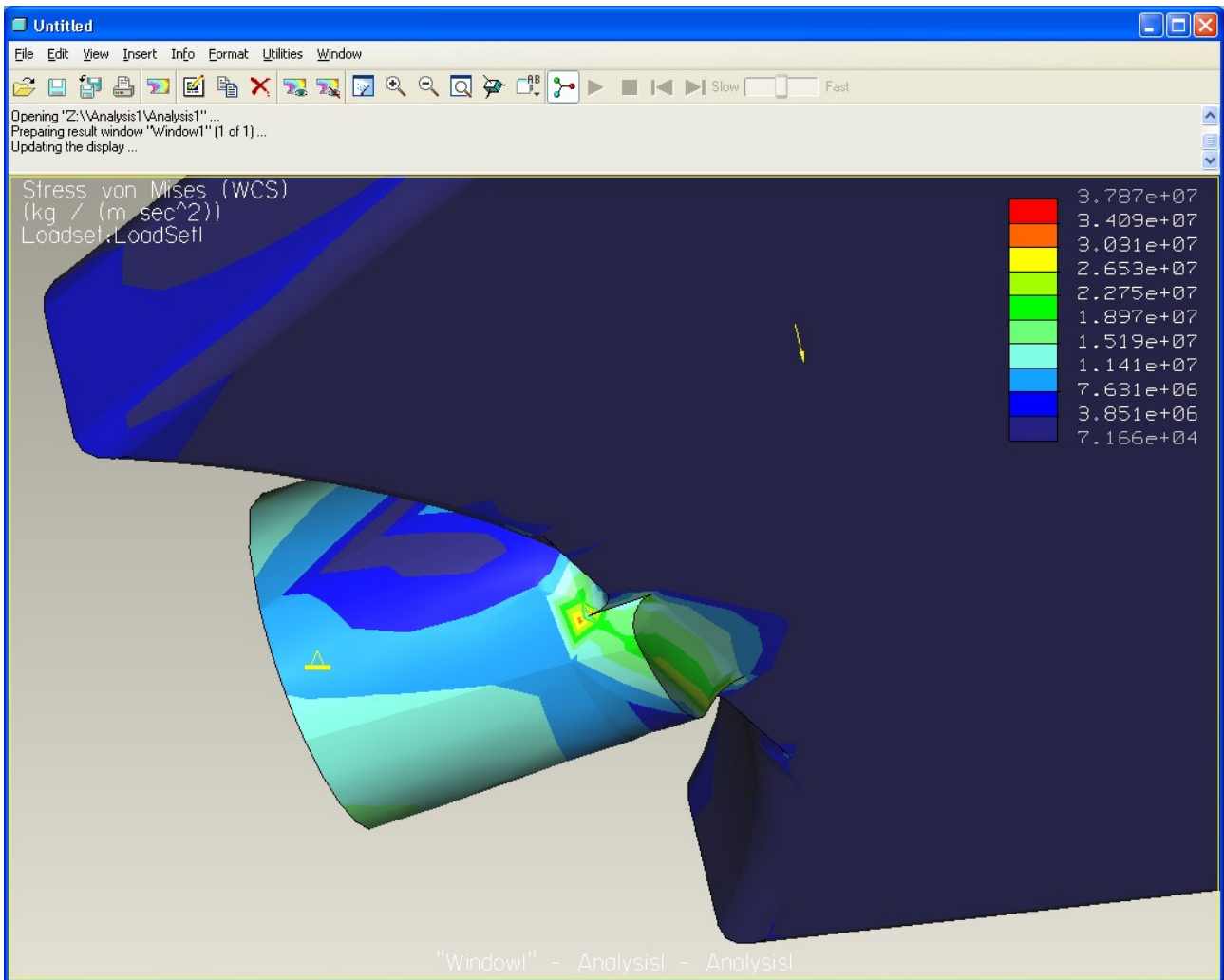


Figure 33, blade with rounded edges (Made by project's author)

The maximum value of the Von Misses stress is 37870000 Pa, which is even less than what we had before, so it is less than the shear stress admissible, 185000000 Pa.

Verification of the resistance of the guide vane

The same process is done to test the behaviour of the guide vane. So as it was said, the first step was drawing it and set the displacements and loads.

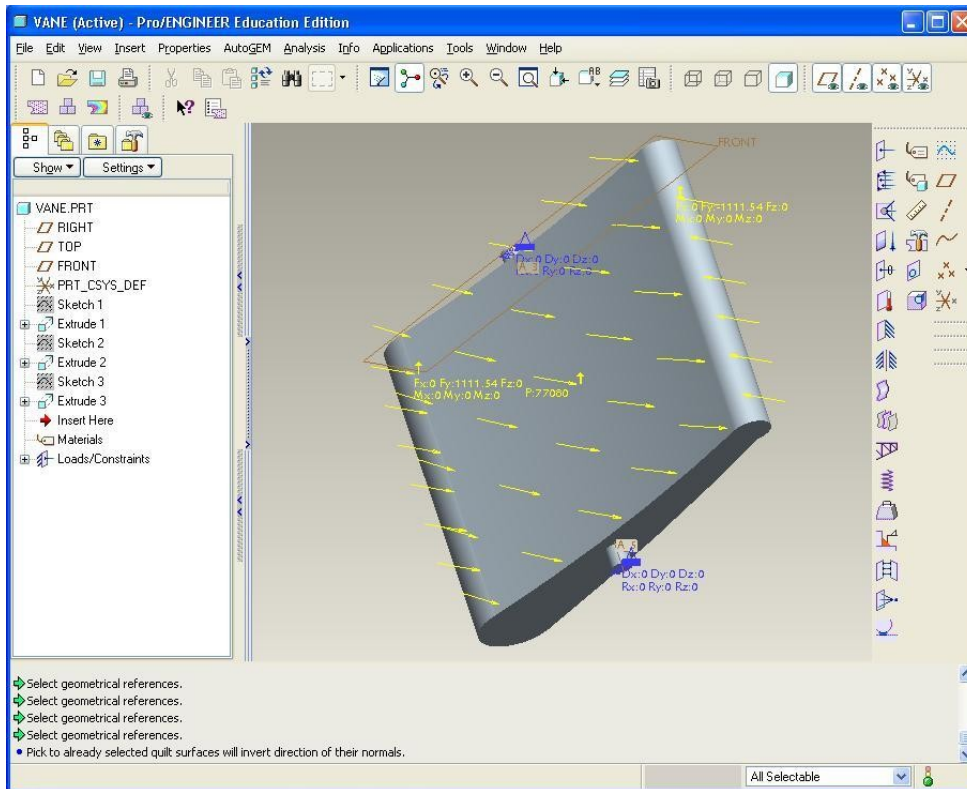


Figure 34, guide vane with loads (Made by project's author)

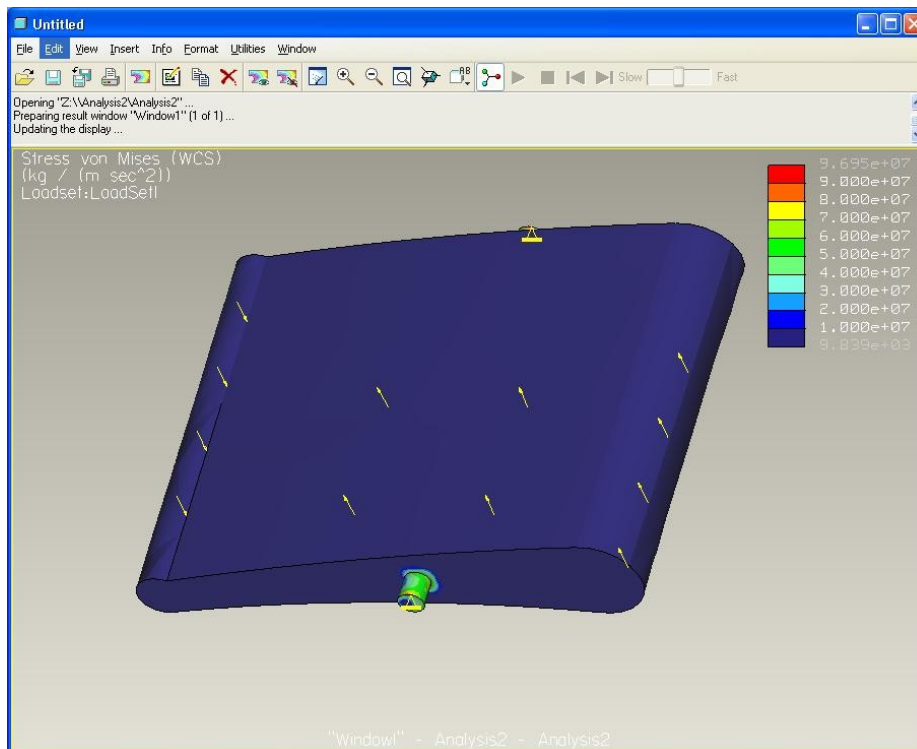


Figure 35, guide vane stress result (Made by project's author)

The most stressed part is the blade and its axis junction, again. The maximum value of the Von Misses stress is 96950000 Pa, which is less than the shear stress admissible, 185000000 Pa. The

vane is correctly designed. But we are going to round the edges to see the difference.

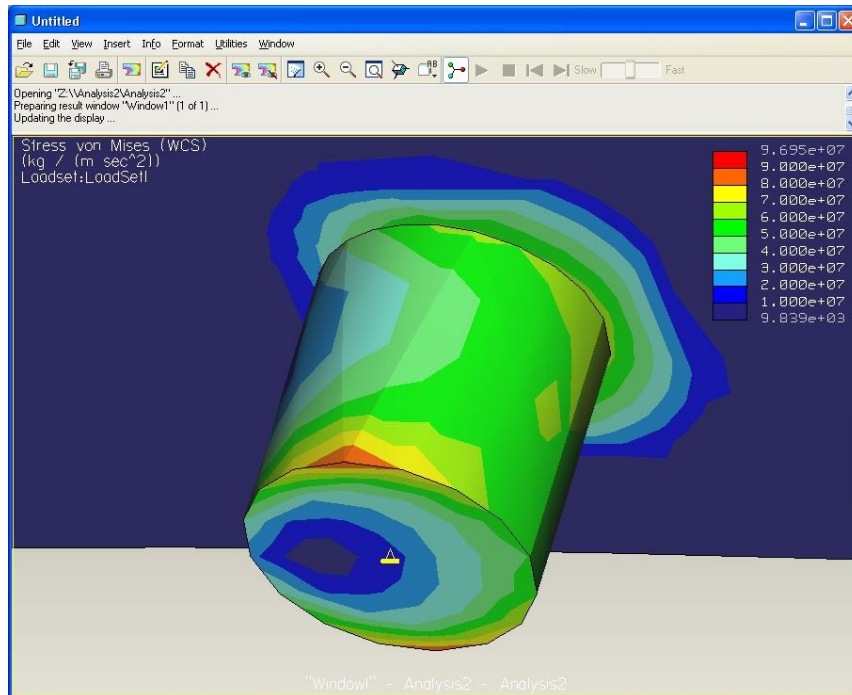


Figure 36, guide vane axis (Made by project's author)

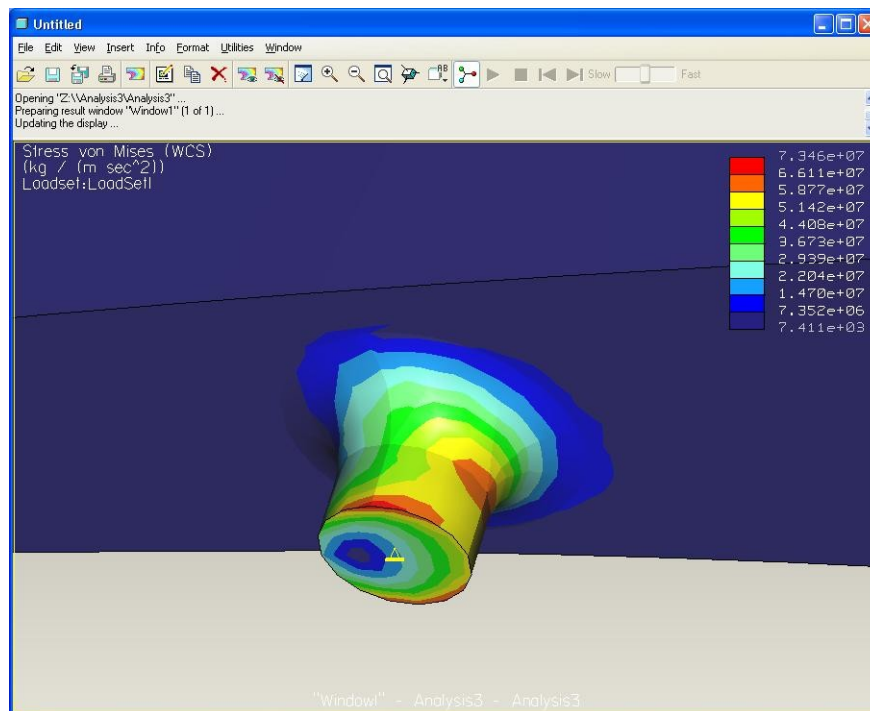


Figure 37, guide vane axis with rounded edge (Made by project's author)

The maximum value of the Von Mises stress is 79460000 Pa, which is even less than what we had before, without the round edges, so again, the characteristics and resistance of the guide vane improved.

6- CONCLUSIONS

This project served his author to review some modules he studied in his degree and to learn new things. Learning the process that involves the complete realization of the project was specially important as it is something that is not learned in any module. How to deal with the proposal, searching and finding the way to solve the questions raised, choosing the best option in each case and deadlines were the most challenging issues in the process of solving the project.

Initially, the project idea was much more extensive than what it was achieved finally. What it was wanted to do is a simulation with a fluid software, and with that, knowing results of stress in blades and flow issues. After the realization that it was almost impossible, due to the length of the project, the lack of time and the lack of a good software, it had to be done in other way. However, it did not affect the final result of the project. The “practical” method was replaced by a more theoretical one. The stress of the blades and guide vanes could be known and cavitation and the flow of water could also be solved with the fundamentals of physics.

The main purpose of the project was achieved. The most important parts of a turbine were designed. They are the ones that are directly in contact with the water. This design of the parts of the turbine is based in calculations that normally fits similar projects than this one, but with a bigger amount of water and a higher head gross. It was proven that this design is very simple, so cheap. This raises the possibility to build these kind of small hydroelectric power plants in rivers like this one, and shows the importance to use renewable energies with an important hypothetical percentage of the energy demand covered.

The review of literature part is the most time absorbent one, but the most interesting. Knowing how turbines work was one of the most enjoyable parts. Unluckily, the turbine that suited the conditions of the river in that point, the kaplan one, is the less studied one. So it was difficult to find good sources to use in this case, but, at the same time, motivational as it was a success to find the way to solve every problem that the design of the turbine had.

During the development of the design of the turbine, some problems were found. For example, there are some integrals and equations very difficult to solve. The way to calculate it was using some web pages that solved that kind of operations. In general, the design process was successful. The design

of the more important parts were done, calculating their sizes and shape.

The last part of the project consisted in the resistive calculation of the most stressed parts of the turbine and the testing of this calculation using computer aid. The most important thing here was the interpretation of the computer results. It could be seen that the design was correct, but it also revealed that some improvements could be done, like the rounding of edges to avoid critic points in which cracks could appear with time.

To summary of the project is that the realization of the project was successful. Even knowing that the initial idea was so ambitious that could not be possible to do, the second option was correct and more simple.

7- RECOMMENDATIONS FOR FURTHER WORK

The realization of the initial idea of this project is not possible to do in the amount of time used. Seven months, having other modules is not enough time. In addition, the software used is a little bit simple for a real project. The complete design of this hydroelectric plant must be done by a complete team of engineers. The mechanical engineer is the one who is responsible of the mechanical parts of the turbine. This is the part that was developed in this project. The electrical engineer is the one who is responsible of the electrical part of the turbine. It is the generation of electricity. He is the one that is in charge of the design of the control systems and the generator of the turbine. An industrial engineer is the responsible of the project. He is in charge of the other members of the team that are designing the project. He is also the one who makes all the legal part of the project, the organization of the assembly and construction steps.

To sum up, this project included part of the mechanical design of the hydropower plant. The complete project must be done by a professional team of engineers, including different engineers to solve every problem that this project have. There is also need of computer aid, that big companies can afford but maybe not an university. There is need of software to design the electrical circuits, the flow of water throughout the turbine, a drawing program to do every simple part of the machine with the dimensions and a 3D program, like the one used in this project, pro-engineer.

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9- REFERENCE OF THE FIGURES

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Figure 19- [Cavitation example] n.d. [image online] Available at:

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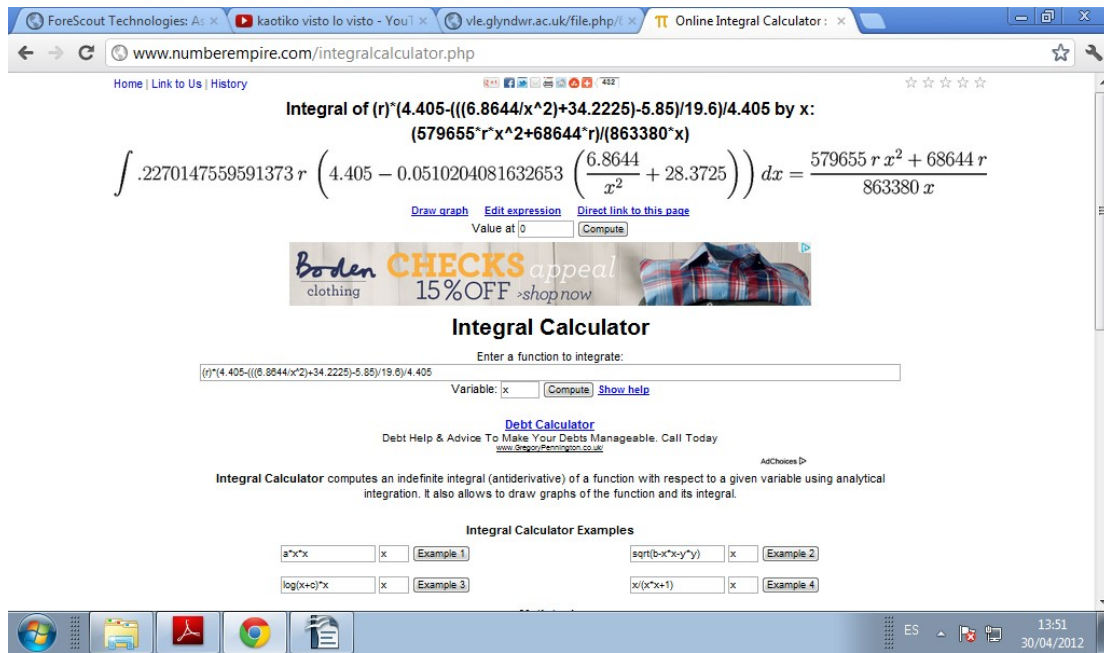
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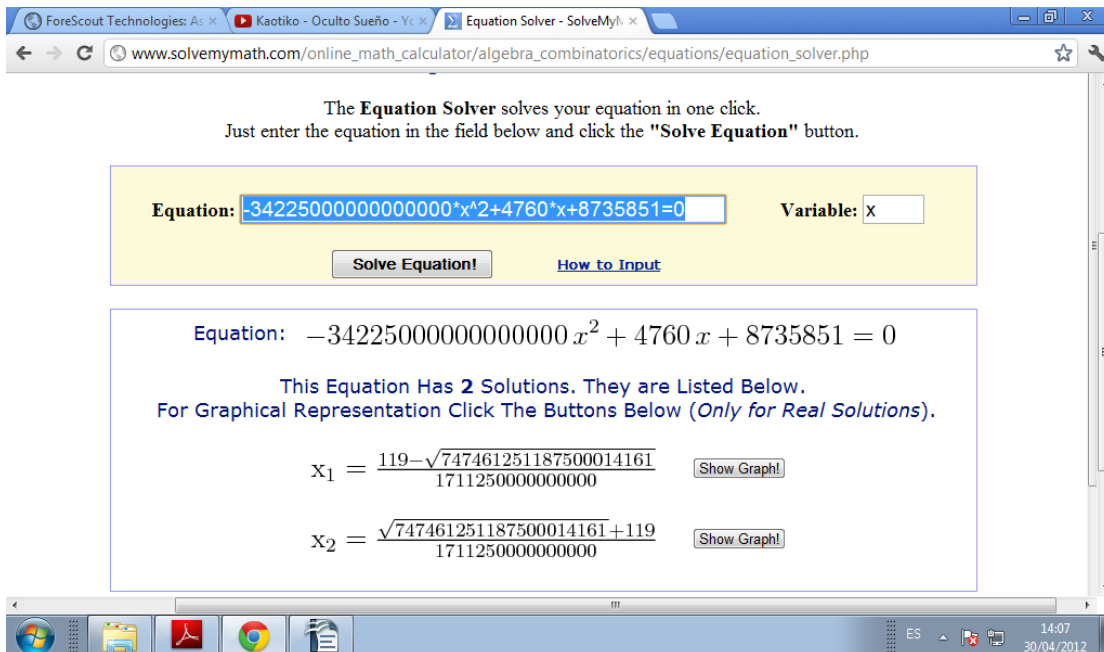
[Electronically accessed 25th January, 2011]

Figures from 8 to 18, and from 21 to 37- [Made by project's author]

10-APPENDICES



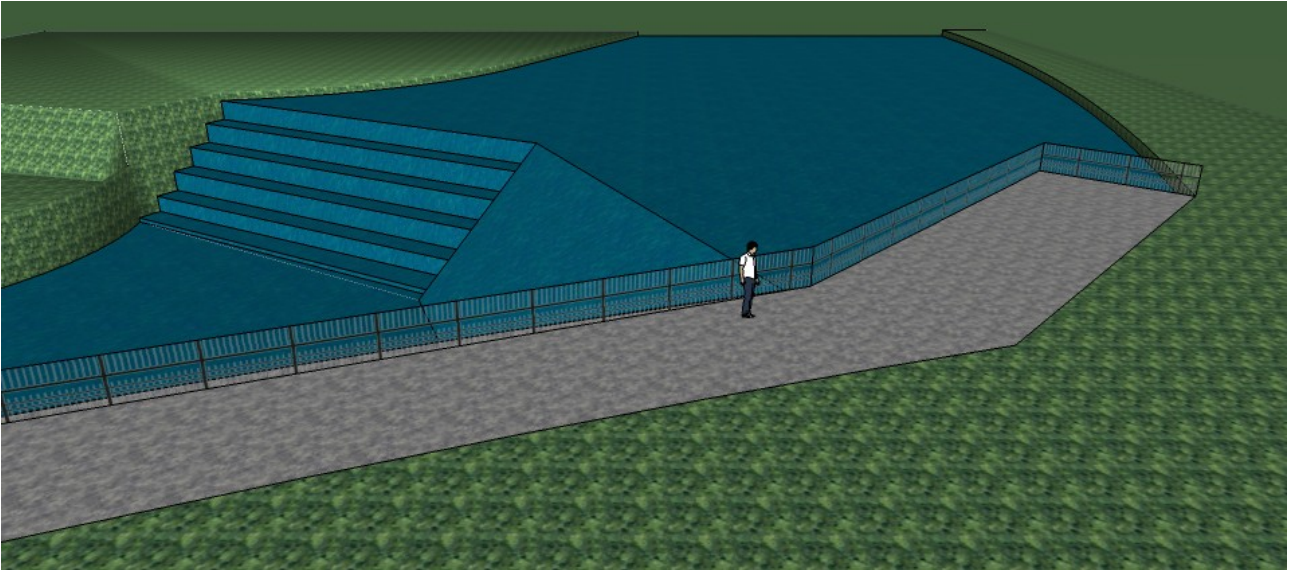
Figure, Integrals Calculator



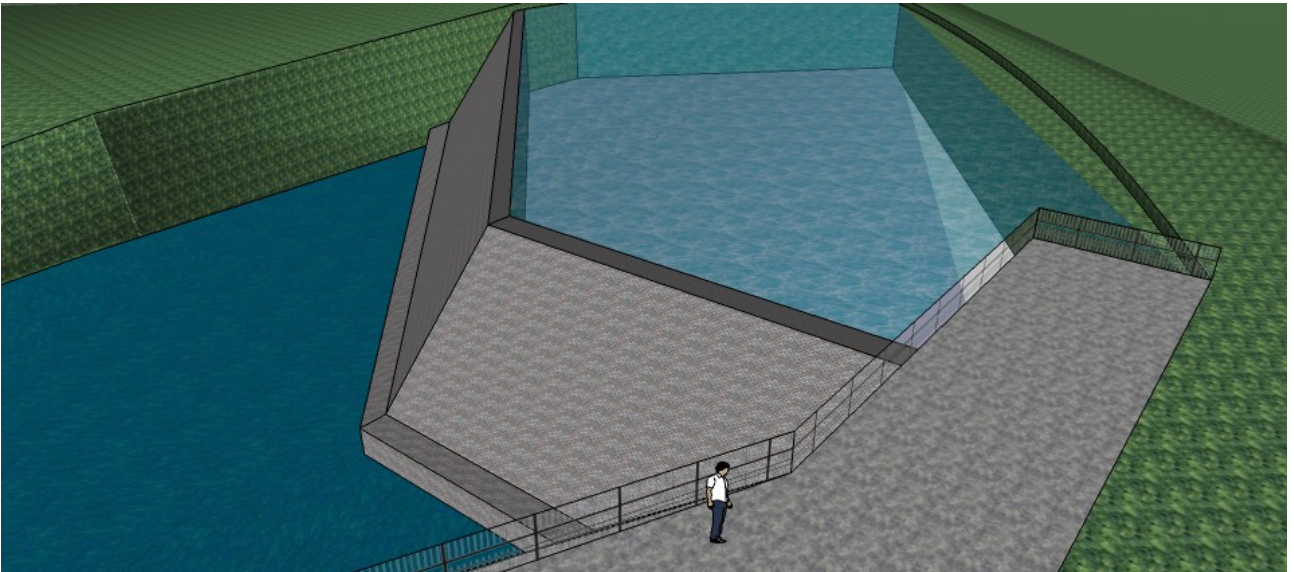
Figure, Equation Calculator

Grado	Cont. de C, %	Dureza HRC después del revenido durante 2 h, para diferentes temperaturas (°C)									Tratamiento térmico
		205	260	315	370	425	480	540	595	650	
Acero al carbono templado en agua											
1030	0.30	50	45	43	39	31	28	25	22	95	Normalizado a 900°C temple en agua 830-845.°C promedio punto de rocío t,16 °C
1040	0.40	51	48	46	42	37	30	27	22	94	
1050	0.50	52	50	46	44	40	37	31	29	22	
1060	0.60	56	55	50	42	38	37	35	33	26	Normalizado 885 °C temple agua 830-855 °C
1080	0.80	57	55	50	43	41	40	39	38	32	
1095	0.95	58	57	52	47	43	42	41	40	33	Promedio punto de rocío,7 °C
1137	0.40	44	42	40	37	33	30	27	31	91	Normalizado 900 °C temple en agua desde (830-855 °C);promedio punto de rocío,13°C
1141	0.40	49	46	43	41	38	34	28	23	94	
1144.	0.40	55	50	47	45	39	32	29	25	97	
Acero aleado templado en agua											
1330	0.30	47	44	42	38	35	32	26	22	16	Normalizado a 900 °C templado en agua desde 800-815 °C; promedio punto de rocío,16 °C
2330	0.30	47	44	42	38	35	32	26	22	16	
3130	0.30	47	44	42	38	35	32	26	22	16	
4130	0.30	47	45	43	42	38	34	32	26	22	Normalizado a 885.°C templado en agua desde 800-855.°C Promedio punto de rocío,16 °C
5130	0.30	47	45	43	42	38	34	32	26	22	
8630	0.30	47	45	43	42	38	34	32	26	22	
Acero aleado templado en aceite											
1340	0.40	57	53	50	46	44	41	38	35	31	Normalizado a 870 °C Templado en aceite desde (830-845) °C ; Promedio punto de rocío,16 °C
3140	0.40	55	52	49	47	41	37	33	30	26	
4140	0.40	57	53	50	47	45	41	36	33	29	
4340	0.40	55	52	50	48	45	42	39	34	31	Normalizado a 870 °C Templado en aceite desde (830-845) °C Promedio punto de rocío,13 °C
4640	0.40	52	51	50	47	42	40	37	31	27	
8740	0.40	57	53	50	47	44	41	38	35	22	
4150	0.50	56	55	53	51	47	46	43	39	35	Normalizado a 870 °C Templado en aceite desde (830-870) °C Promedio punto de rocío,13 °C
5150	0.50	57	55	52	49	35	39	34	31	28	
6150	0.50	58	57	53	50	46	42	40	36	31	
8650	0.50	55	54	52	49	45	41	37	32	28	Normalizado a 870 ° Templado en aceite desde (815-845) °C Promedio punto de rocío,13 °C
8750	0.50	56	55	52	51	46	44	39	34	32	
9850	0.50	54	53	51	48	45	41	36	33	30	

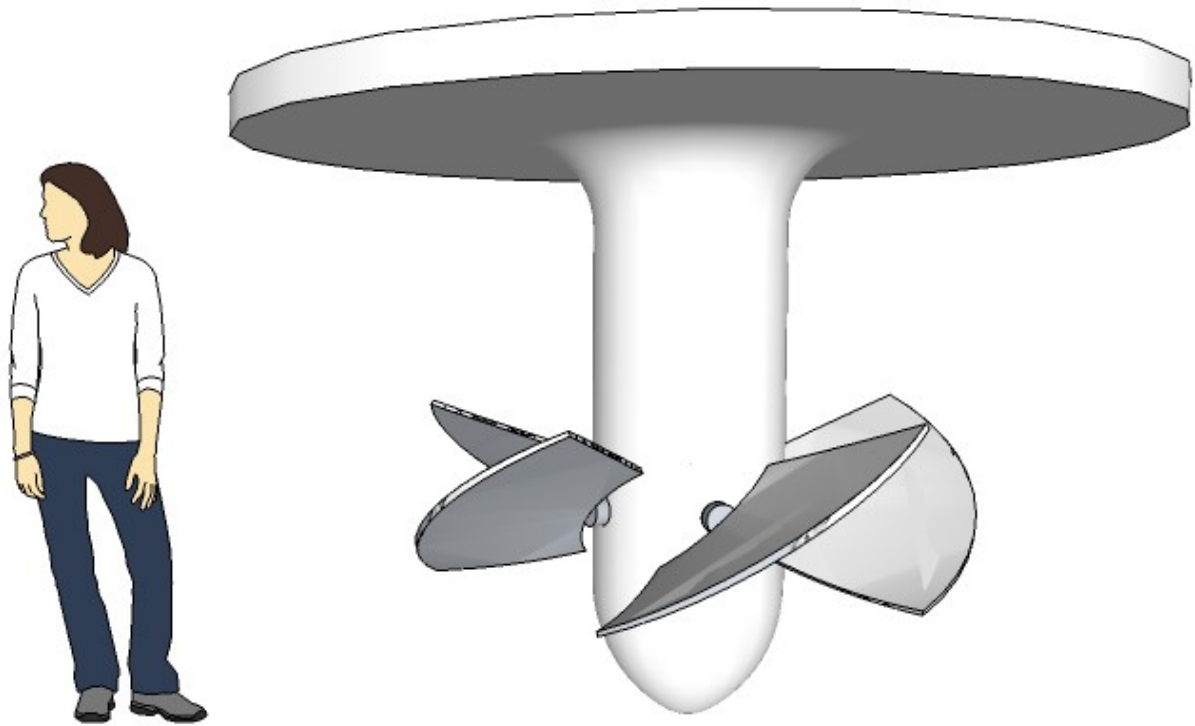
Figure, Table of different Steel Characteristics



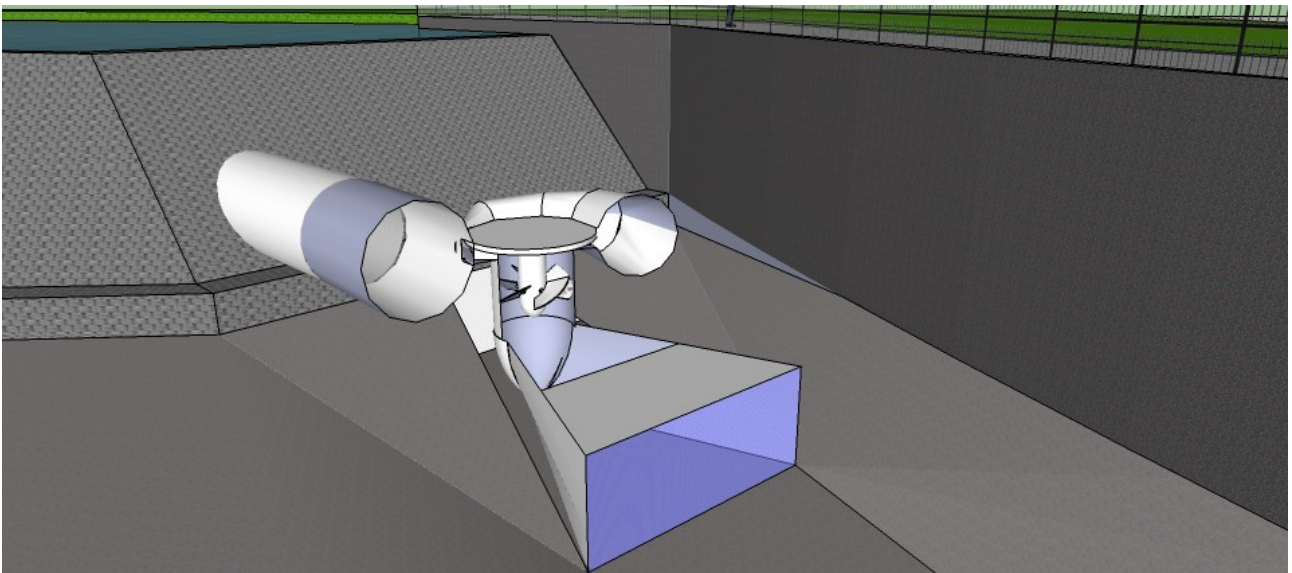
Figure, Old Weir



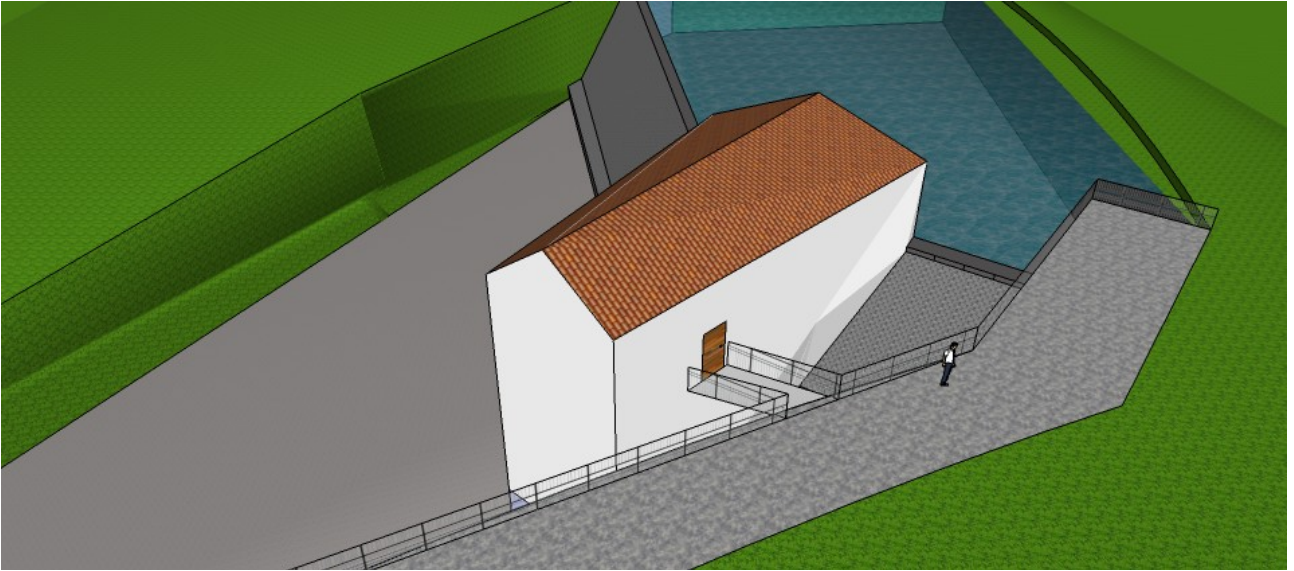
Figure, New Weir



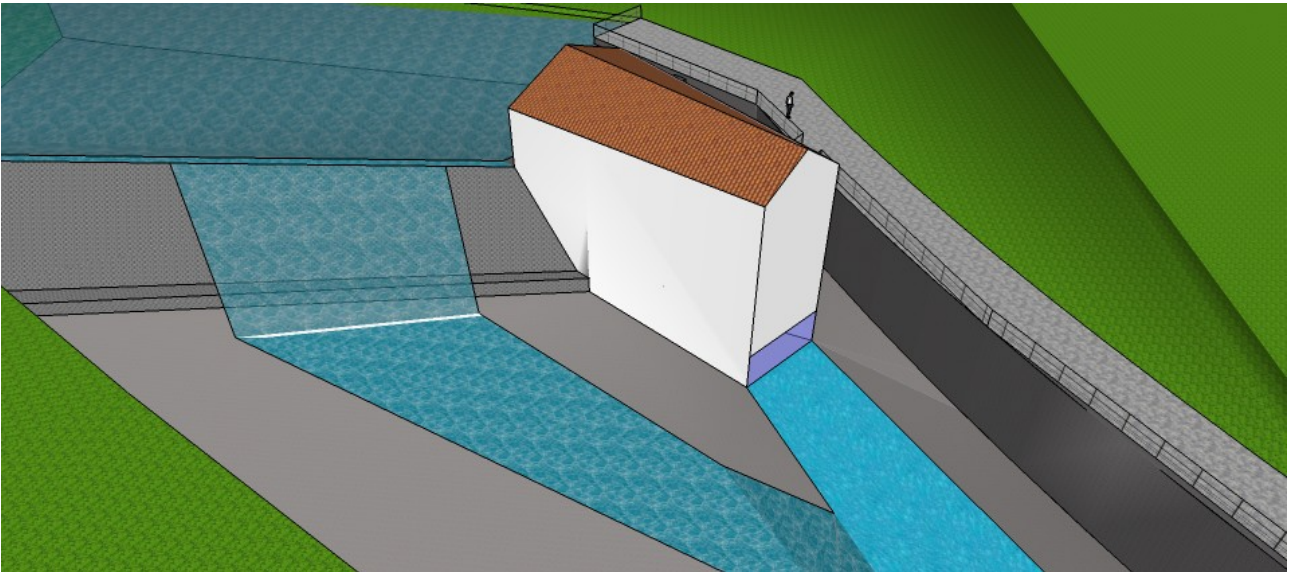
Figure, Turbine Size Estimation



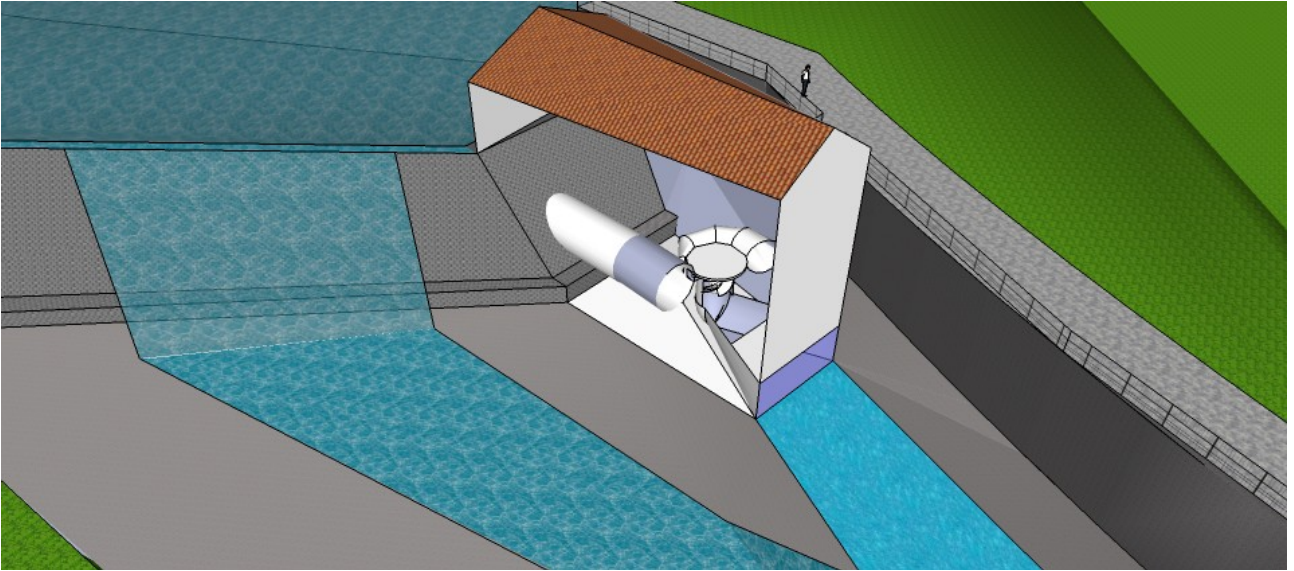
Figure, Turbine With the Scroll case and Draft Tube



Figure, Power House Access



Figure, Power House



Figure, Power House and Turbine