

Kaplan Turbine

**From
Remote HydroLight**

**Developed by
Anders Austegard
Owen Schumacher**

Kaplan turbine from Remote HydroLight

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0 Forward by Owen Schumacher, President, Remote HydroLight

The successful development of the Kaplan turbine was a major achievement for Remote HydroLight. Conditions in Afghanistan do not make the research and development of a completely new design of water turbine easy. We appreciated the patience and funding from the USAID/ASMED (Afghanistan Small and Medium Enterprise Development) team because the process took longer than expected. A gold medal was earned by Anders Austegard who did all the research, engineering design, managed field testing, re-design, drawings, and training to the local workshops. From the start to the finish Anders showed professionalism and ingenuity to make this unique turbine work in rough conditions and to be built by local Afghan workshops. Anders faced many challenges during the field testing phase; however, each turbine weakness discovered was replaced by a creative new design solution that later on proved to be the correct answer. Technology was used to find the right balance between reliability, efficiency, build-ability, and cost. I believe Anders found this balance for the Kaplan turbine. We also want to thank the villagers along the Istalif River who operated the proto-type Kaplan turbine and used the energy produced so the testing would be realistic. The high silt and sand in the Istalif River allowed RHL to test the Kaplan turbine in the most severe conditions possible. The RHL workers started out with some doubt about the suitability and reliability of this new turbine, however, after seeing and working with the development process they now know their hard work has paid off. They can be proud of the level of technology this new turbine brings to the small hydropower industry. They can be proud that this new Kaplan turbine opens new opportunities to generate electricity from low head sites all over Afghanistan.

0.1 Thanks by Anders Austegard

The biggest thanks is to the donor USAID/ASMED, that made this development possible. Also thanks to my coworker and leader of Remote HydroLight, Owen Schumacher, to the Norwegian University of Technology, Department of Energy and Process Engineering, Hydropower Lab, and to SINTEF Energy Research, that gave me leave of work to do the projects.

1 Introduction

1.1 Background

The K-350 Kaplan turbine was designed to fill a need for sites having low heads such as 2m to 6m. The current Cross Flow turbine does not capture the full energy of a site because below the rotor the water drops to the tailrace level. This loss below the rotor is not very significant for higher heads (about 5% for a 10m head plant). The Kaplan turbine captures the entire head of the site from the fore bay water level to the tailrace water level. On some sites the Kaplan turbine can produce 30 - 40% more power than a Cross Flow turbine mounted in the same site. This extra energy if given a value can easily pay for the extra initial cost of a Kaplan turbine over a Cross Flow turbine. USAID funded the development of this turbine and the training of 10 local workshops to build the Kaplan turbine. These workshops have built the turbine in their own shops as part of the training process.

The size of the Kaplan turbine was chosen to fit potential low head sites in Afghanistan. The rotor became 350mm in diameter and with the ability to adjust the blades the maximum flow can be reduced to about 50%. The minimum flow of the turbine at 2m head is about 125 L/s, the maximum flow of the turbine at 6m head is about 400 L/s. The Kaplan Turbine must run full so that no air can enter into the entrance pipe (penstock) or the exit pipe (draft tube) which has to be submerged at all times. For this reason, it should not be installed in sites that have potential for low flow during fall or winter seasons. It should be installed in sites where large irrigation canals are utilized or along a large steady flow river. The flow of the Cross Flow turbine can be adjusted to near zero and still get the plant to produce some electricity. This is not the case for the Kaplan Turbine which needs to be full of water for correct operation.

The Cross Flow turbine can easily be made wider by the local workshops for higher flow sites. This change in only one dimension (the width) allows the other dimensions to stay the same. This is not the case for the Kaplan Turbine because a larger rotor changes everything inside (all 3 dimensions). For sites that need more output, multiple Kaplan turbines can be installed in parallel. In the future it may be possible to develop a larger Kaplan turbine if needed by the industry.

1.2 Press Release from RHL about the Kaplan turbine, 02 Oct 2010

A joint project between ASMED (Afghanistan Small and Medium Enterprise Development) and RHL (Remote HydroLight) has produced a locally made Kaplan water turbine. This water turbine is made for low head sites (1.5m to 6m) that are found in irrigation canals, along slow moving rivers, and locations where long canals are not feasible. The Kaplan turbine utilizes the full head (vertical distance from upper canal water level to turbine exit water level) of the particular site and this allows for more energy output than the crossflow turbine also being built in Afghanistan. The Kaplan turbine can be explained as a propeller mounted inside of a pipe that extracts the energy from the water as it moves through the pipe.

First RHL researched the Kaplan turbine technology. A special design was conceived that would allow the turbine to be made in local workshops, have high efficiency, flow adjustment, and be simple to install. A prototype was made and installed at a site along the Istalif River near Kabul. After much testing, re-design, and re-testing; a final design was

made. A final design Kaplan turbine was sent to the Waterpower Laboratory of the Norwegian University of Science and Technology, Trondheim, Norway. This laboratory will test the performance of the Afghan built Kaplan turbine. Previously this laboratory tested a RHL crossflow water turbine built in Afghanistan that achieved a very high efficiency.

The purpose of the ASMED project was to introduce a new type of turbine that would allow more small hydropower sites to be developed so villages can have reliable electricity. An important part of the project is to train private workshops how to make the Kaplan turbine. It is planned that each workshop receiving training will build their own Kaplan turbine step by step during the training process. The workshops manufacturing small scale hydropower equipment are staffed by tradesmen who learn by doing (hands on) rather than in a classroom. RHL will also focus on quality control during the training process so that the turbine is very reliable.

The partnership between ASMED, RHL, and the Norwegian test laboratory is an example of how new technology can be developed and transferred for Afghanistan's benefit. By developing the Kaplan turbine in Afghanistan, locally available materials (steel, castings, rubber, etc.) were used from the beginning of the design process. A special mention should be made about the prototype testing at Istalif. The first design of the lower bearing assembly seemed to work fine when the water was clean, however, during the spring season much silt and sand in the water caused the bearing to fail. If the test was done in a laboratory with clean water, the problem with muddy water may not have been realized until it was too late. Real world testing in Afghanistan will assure that the Kaplan turbine will be reliable in all kinds of situations that are common in remote villages.

ASMED is funded by USAID and implemented by DAI (Development Alternatives International).

1.3 Rational for local construction of turbines and village participation

The RHL Kaplan turbine was designed to be built in local Afghan workshops that are already making the popular Cross Flow turbine. Every effort was made to use local available materials so the manufacturing is sustainable in Afghanistan. Some items such as the stainless steel bolts, nuts, and bearings will be supplied from Pakistan, however, this is sustainable because traders already bring steel, pulleys, belts, pipe, and electric equipment for the hydropower industry from Pakistan.

All rotating or moving equipment eventually needs repairing or replacing (even the reliable Toyota Corolla so popular in Afghanistan). Imported equipment may be more reliable than some local made product, however, when it fails, we usually find that no one can find or make the replacement part. For this reason RHL strongly supports the local hydropower industry in building the equipment in country. Price is also important due to the low economic position of remote villages. We wanted to make a product that can be repaired at a reasonable cost quickly, not wait for an expensive air shipment of an even more expensive component and then not having a trained person to install it. Expecting a village to even locate the foreign supplier of some failed equipment is a stretch. Sustainability means that the local industry can build, repair, and finance these small hydropower plants without foreign involvement or monies.

Equally important is the involvement of the village. It has proven to be very beneficial for the village to contribute labor (without salary) and local materials (stone, sand, gravel, wood, etc.) so that they take ownership and responsibility. Remote locations, travel insecurity, and low economic status of villages do not lend itself to a service industry that will maintain the hydropower plants. Instead the village chooses a person to operate and manage the plant. They usually get paid from the electricity charge levied on each family. The operator is usually a local farmer who can not read or write. Service and maintenance has to be very simple otherwise it will not get done. These considerations were taken into account for the design of the Kaplan turbine.

Remote HydroLight has done the research and development of this turbine and the high efficiency and reliability experienced proves that it is suitable for the Afghan environment. We would be very pleased if other countries would adopt this work so they do not have to do the difficult development work all over again. For this reason we have published the drawings and instructions for the benefit of all. We would caution those that attempt to build this Kaplan turbine without training or experience. Each part needs to be made correctly and installed correctly for the turbine to perform properly. We would recommend that only those with experience in hydropower technology should attempt to build this turbine.

1.4 Comparison with the Cross Flow water turbine

For Afghanistan the Cross Flow water turbine has been a huge success. The design developed and used by IAM (International Assistance Mission) and Remote HydroLight has been widely adopted by the majority of local workshops in Afghanistan. Over 3000 of these turbines have been installed throughout Afghanistan, some have been operating over 13 years. This locally manufactured turbine has been tested in the Waterpower Laboratory of the Norwegian University of Science and Technology, Trondheim, Norway. The efficiency was surprisingly high and its simplicity to build and reliability has resulted in it being the overwhelming choice of most customers.

The Cross Flow turbine has two disadvantages that the Kaplan turbine doesn't have. These disadvantages are especially negative in low head sites and where the tail race water level varies (such as during high flow or floods).

- The Cross Flow turbine does not capture the energy of the water between the rotor and tailrace. After the water jet passes through the rotor it drops into the tailrace. For higher head sites this is insignificant, however, if the head is only 3m, the energy lost can be 20% or higher.
- Related to the above; the high water level at flood stage can be 1m or more higher than the water level during low flow. The Cross Flow turbine must be mounted above the high water level so it will work throughout the year. When the low water level occurs, the distance between the rotor and tail race can increase to 1m or more. This potential loss can be 30 ÷ 40 % of the capacity of the plant. The high water level may only happen for 1 month out of the year, however, it determines the location of the Cross Flow turbine and for 11 months the full potential energy of the site is not captured.

The Kaplan turbine has two strong advantages that the Cross Flow turbine doesn't have.

- The entire head of the site (from fore bay level to tail race level) is able to be captured

by the Kaplan turbine. This means that more power can be produced with the same

amount of water as the Cross Flow turbine.

- Related to the above; the Kaplan turbine has a draft tube below the rotor that must always be below the tail race water level. If the tail race water level goes up (such as when floods occur), the Kaplan turbine can still operate properly because there is allowance due to the draft tube. When the water level goes down the actual head increases allowing the Kaplan turbine to produce more energy.

An example can illustrate this: the river or canal has a design flow of .262 m³/s and the turbine empties into the river which has 0.8m difference between high flow (flood) and low flow (winter) level. The Cross Flow must be positioned about 1m above the low flow level so that it doesn't get under water during a flood. The table below shows that a Kaplan K-350 turbine would get 1.8 kW extra power over a similar sized Cross Flow turbine during much of the year.

Table 1 Comparison of Kaplan and Cross Flow turbine

Turbine	Kaplan K-350	Cross Flow HKT	Difference
Turbine size	Rotor dia. .354m	Rotor dia. .34m, bo 0.6m	
Turbine setting	Position 3	Flow flow, valve open	
Net head (m)	3m	2m	1m
Flow m ³ /s	.262	.262	
RPM	630	166	
Electrical power output (kW)	4.8	3.0	1.8
Efficiency based on net head	62%	58%	
Efficiency based water to water	62%	39%	

If the Kaplan costs \$1500 more than the Cross Flow turbine, it would still be a good decision to use it because the extra cost per kW is economical ($\$1500/1.8 \text{ kW} = \$833/\text{kW}$). For higher head sites, the difference in kW becomes larger, however, the difference in percent efficiency becomes lower. This example shows that the K-350 Kaplan turbine is very similar in size to the popular HKT bo 645mm turbine.

Benefits of the Kaplan turbine:

- uses the full head of a site (water to water)
- can produce 30% - 50% more power than a Cross Flow turbine
- has higher operating RPM which helps reduce belt slippage on the alternator pulley
- has higher efficiency than Cross Flow turbine at optimal flow
- shape of Kaplan is more compact than the Cross Flow turbine (especially for very large sizes)
- water force on the blades is constant, blade force on Cross Flow rotor is cyclic (off and on)
- water creatures (fish) can pass through a Kaplan turbine more easily
- the alternator is mounted about 1.2m above the floor so it will not get flooded
- one or all four rotor blades can be replaced if required
- installation of Kaplan turbine is easier than the Cross Flow turbine

Benefits of the Cross Flow turbine:

- Lower cost to manufacture; the Kaplan has tighter tolerances, is more difficult to build, it needs to be sealed due to being pressurized, requires more parts and machining operations

- Simpler to manufacture with less parts to assemble
- Has been proven to work reliably in very rough conditions
- Can be used up to 50m head, the K-350 Kaplan is approved for 1.5m ÷ 6m head
- Flow can be regulated from 100% (full) to zero, the Kaplan can operate down to 50% flow
- Takes sand (or silt with larger particle sizes) better than the Kaplan turbine. In the Kaplan turbine sand wear out the passage between the blades and the rotor pipe which can reduce efficiency considerable. However, one get places with low head mainly where the river is flowing slowly; there one does not have so much sand in the water.
- Larger sizes can easily be made by changing only the width (bo) of the turbine, a larger Kaplan turbine would need larger blades and everything inside changed (3 dimensional change)

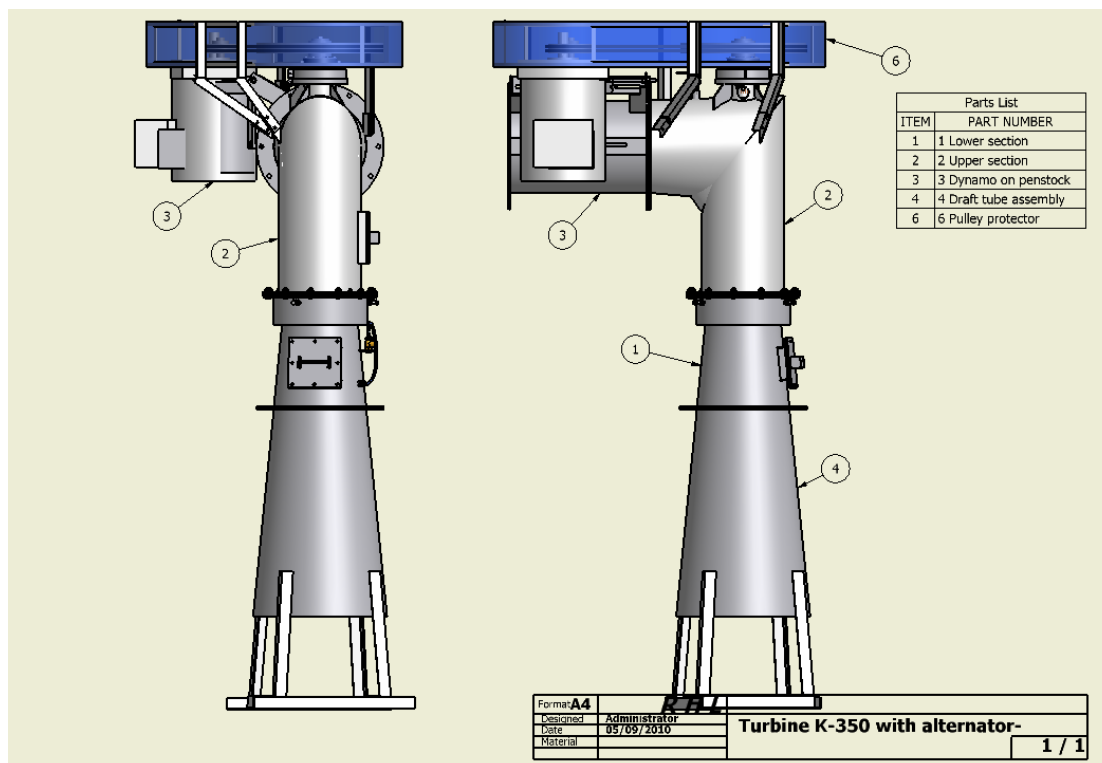


Figure 1. Turbine with main parts identified

Figure 1 and Figure 2 show the completed Kaplan turbine with major parts identified. By having the alternator mounted to the penstock it eliminates installation errors and mistakes. It also raises the alternator off the wet floor and protects it from floods. Water enters the turbine and then bends 90° with the help of internal guide vanes to reduce head losses. The 90° bend was chosen to allow the K-350 to fit into sites as low as 1.5m head. Prior to the water reaching the rotor another set of guide vanes turns the water to optimize the force on the rotor blades. The bottom opening of the draft tube must always be below the tail race water level so the full benefit of the weight of water below the rotor causing a suction force is realized. The water force and suction force on the rotor blades is transferred to the large pulley with a shaft. Standard v-belts and pulleys are used to transfer the power to the Chinese 1500 RPM alternator.

Two inspection doors are provided to allow pitch adjustment (flow adjustment) of the rotor blades and for removal of foreign objects (tree branches). Four marked positions are provided with 1 being for the lowest flow and 4 for highest flow. It is possible to set the

blades between position 2 and 3 (2.5 position) if fine adjustment is necessary. When calculating the blade profile the optimal efficiency was designed to be at position 3.

If the turbine needs repair, the village operator separates item 1 (lower section) from the cemented in draft tube by removing the flange bolts. Item 1 and 2 need to be kept together and not be separated. Then item 2 (upper section) should be separated from the penstock by removing the flange bolts. This unit (items 1 and 2) weighing 160 kg should be brought to a qualified workshop that has experience in manufacturing the Kaplan turbine to be inspected. After repair, the village operator should be able to re-install the turbine correctly and restart the plant.

1.5 Field testing of the Kaplan turbine at Istalif River

Due to long term relationships along the Istalif River from previous hydropower activity, Remote HydroLight was able to convince a village of about 20 families to install the proto-type Kaplan turbine in a 7m head site. The proto-type was started up in Jan 2010 and is currently operating except when it was returned to RHL's workshop for modifications. The April to July run off for the years 2010 and 2011 in the Istalif River had very high amounts of silt and sand. A measurement was taken that showed about 1000 kg/hour of silt and sand was passing through the turbine at one point. It took time to come up with new designs to protect the bearings, seals, and rotating parts from silt, sand, and small rock damage. The high sand content of the Istalif River water was invaluable and caused RHL some sleepless nights, but, it allowed repeated testing of each improvement that was made. Since Jan 2010 the proto-type Kaplan turbine has been operating 24/7 which the village really appreciates. Total hours operated as of Aug 2012 is estimated to be 18,000 hours. They have learned to consume the power with pail mounted 1200W water heaters. Some even purchased refrigerators and electric hot pots. The prototype turbine also was used by RHL for performance testing as described in section 3.5.



Figure 2 Photo of completed Kaplan turbine with short draft tube

2 Installation of the Kaplan turbine

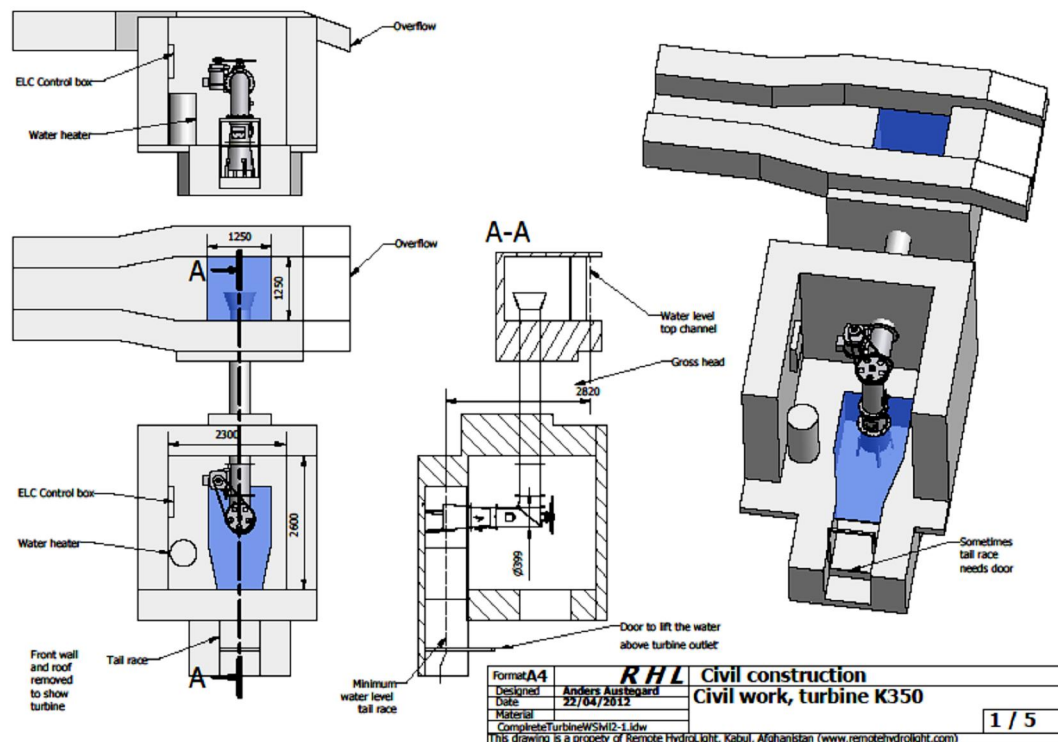


Figure 3. Plant with turbine.

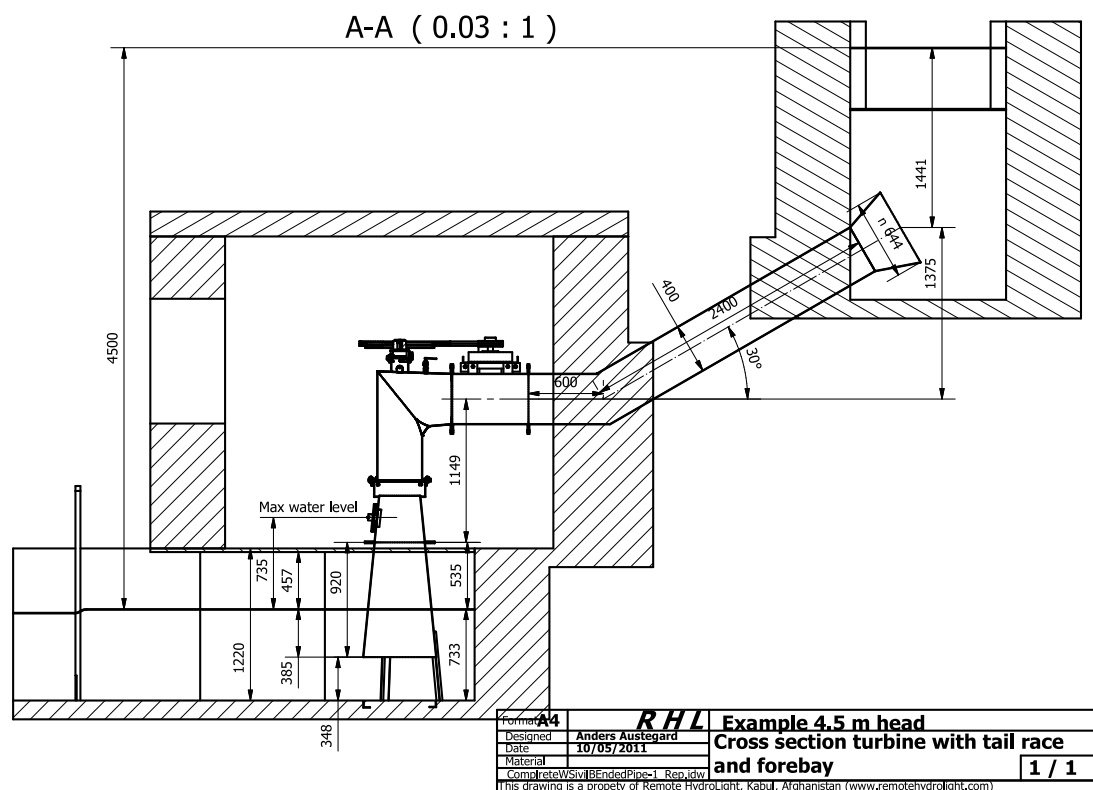


Figure 4. Cross section of turbine for a site with 4.5 m head



Figure 5. Kaplan turbine being installed, note water level in tail race

Figure 3 shows how the Kaplan turbine can be installed at a site. The overflow is shown after the fore bay which helps push floating matter (ice, snow, leaves, branches, etc.) away from the trash rack. The size of the power house can be small (2.6m X 2.3m) because the turbine and alternator is positioned vertical. If the ELC and water heater are located in another building, a power house is not needed, only a rain shield above the turbine/alternator assembly is required.

Figure 4 is a cross section of a Kaplan turbine installed in a 4.5m head site. The penstock 30° bend is mounted in the power house cement wall to allow it to hold the weight of the turbine, alternator, and water. The feet of the draft tube are also cemented into the floor. It is also possible to put a floor in the power house just below the draft tube upper flange. The draft tube upper flange needs to be opened if the turbine is removed for repair. Figure 4 shows the water level about half way up the draft tube. If the water level lowers 385mm, air will enter the bottom of the draft tube and the suction from the weight of water below the rotor to the water level will be lost. If the water level of the draft tube goes up 735mm it will allow water and dirt to enter the lower bearing through the air inlet and lower bearing holder. If this happens the turbine needs to be disassembled and cleaned. Usually most power houses have a floor below the draft tube flange so this should not happen. For special situations, it is possible to make a longer draft tube if needed for changing tail race water levels, however, the distance from the rotor to the bottom of the draft tube opening should never be over 2m due to the possibility of cavitation damage to the rotor blades.

Figure 4 shows the penstock opening being 1441mm (1.441m) below the fore bay water level. The opening of the penstock is recommended to be at least 800mm below the fore bay water level. For lower heads the penstock must be straight and for heads 2.5m or below it must be bent down 20°. The shaft seal uses a labyrinth shape controlled flow design. The

water level must be above the top bearing otherwise air will enter the labyrinth seal. This requirement restricts the minimum head to 1.5m. At 1.5m head the turbine only produces about 1.6 kW, which results in a high cost/kW which may not be cost effective. A 1.25m X 1.25m trash rack that has 10mm round rods with 15mm spacing between the rods is adequate for the Kaplan flows. If positioned flat, chunks of ice, leaves, and other material can self clean by flowing over the trash rack and into over flow. If the electrical load from the village lowers the RPM of the Kaplan turbine, the flow into the turbine is reduced and the excess water must go to an over flow. The Cross Flow turbine has more constant flow even when its RPM is reduced. This makes the over flow more important for the Kaplan turbine.

Figure 5 shows a turbine being installed. For low head sites it is important to use the full head available. The tail race that leads to the river or another irrigation canal should be dug out prior to positioning the draft tube. This will bring the water level of the river or irrigation canal into the power house. First make sure the high water level of the site is below the draft tube flange to be conservative. If the low water level is below the bottom opening of the draft tube, a water door may be needed to lift the water above the bottom opening so air doesn't enter. This could also be done with sand bags during the time the river is at low flow. The cement floor below the turbine should be flat until it leaves the power house. If it is lower below the turbine it will collect sand. If a water door is used to keep the tail race water level above the draft tube opening, a small opening is needed at the bottom so the sand gets removed. This can be done by wedging a rock between the floor and the bottom of the door. This leakage allows the sand going through the turbine to get carried away to the river and not build up in front of the door.

3 Measure of head, flow power

The blade can be turned to adjust the flow, where it has 4 positions. Position 1 gives lowest flow and position 4 gives highest flow. The flow is tested at NTNU for position 1 and 2 for the Kaplan turbine (Remi Andr ). Position 3 and 4 was not tested because of lack of facilities. That lack limited the flow through the turbine. Position 3 and 4 will be tested later, hopefully at spring 2012.

3.1 How the test is done

Figure 6 shows the test stand at NTNU. The test has been done autumn 2011 for the lowest flow. That is blade position 1 and 2. It is described by Remi Andr . It got an insecurity of 2%.

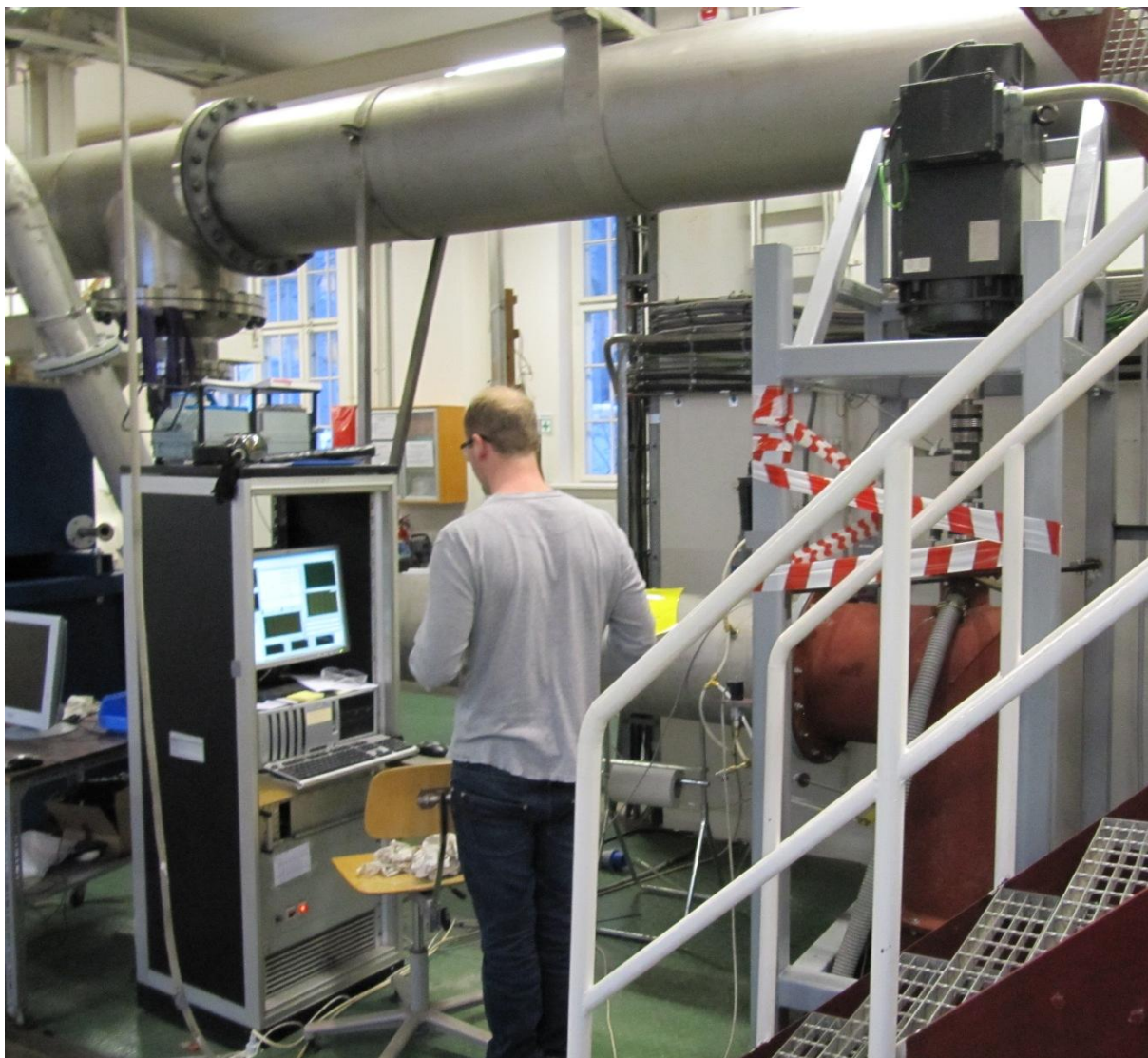


Figure 6. Test stand at NTNU

3.2 Variable, dimensionless numbers

To reduce the number of variables it is first done a dimension analysis.

The formula for drag on any equipment, and for pressure drop through a system can be written (<http://en.wikipedia.org/wiki/ Drag equation>):

$$\Delta p = c \rho v^2 / 2$$

Where Δp is pressure drop through the system, u is a characteristic speed, ρ is density and c is a constant.

For the turbine as a whole one can write:

$$\Delta p = \rho g \Delta h = c \rho v^2 / 2 \Rightarrow v = \sqrt{2 g \Delta h / c} = k_1 \sqrt{\Delta h}, \quad k_1 = \sqrt{2 g / c}$$

Generally c is a function of Reynolds number ($Re = \rho v r / \mu$) and change if one get cavitation (water pressure below evaporating pressure of water). But generally one can assume that c (and then also k_1) is a constant. So if $\Delta h = h_N$: Net head one can set (A_c = Cross section area, v = Velocity)

$$Q = A_c v = A_c k_1 \sqrt{h} = k_2 \sqrt{h}$$

$$\omega = r_o v = r_o k_1 \sqrt{h} = k_3 \sqrt{h}$$

This can be used when analyzing data so one can use $Q/\sqrt{h}$ and $RPM/\sqrt{h}$ as parameters so one reduce the set with one variable.

Then most properties are a function of $RPM/h^{0.5}$, so one can write:

$$\eta = \eta \left(\frac{RPM}{\sqrt{h}} \right), Q = \sqrt{h} * f_1 \left(\frac{RPM}{\sqrt{h}} \right), P = Q h g \eta = h^{1.5} * f_2 \left(\frac{RPM}{\sqrt{h}} \right) \quad (1)$$

Where η is efficiency, and Q flow (L/s), P power (kW) and h head (m).

In Appendix 1 is a more through full analysis of dimensionless variables is done..

3.3 Performance measurement at NTNU

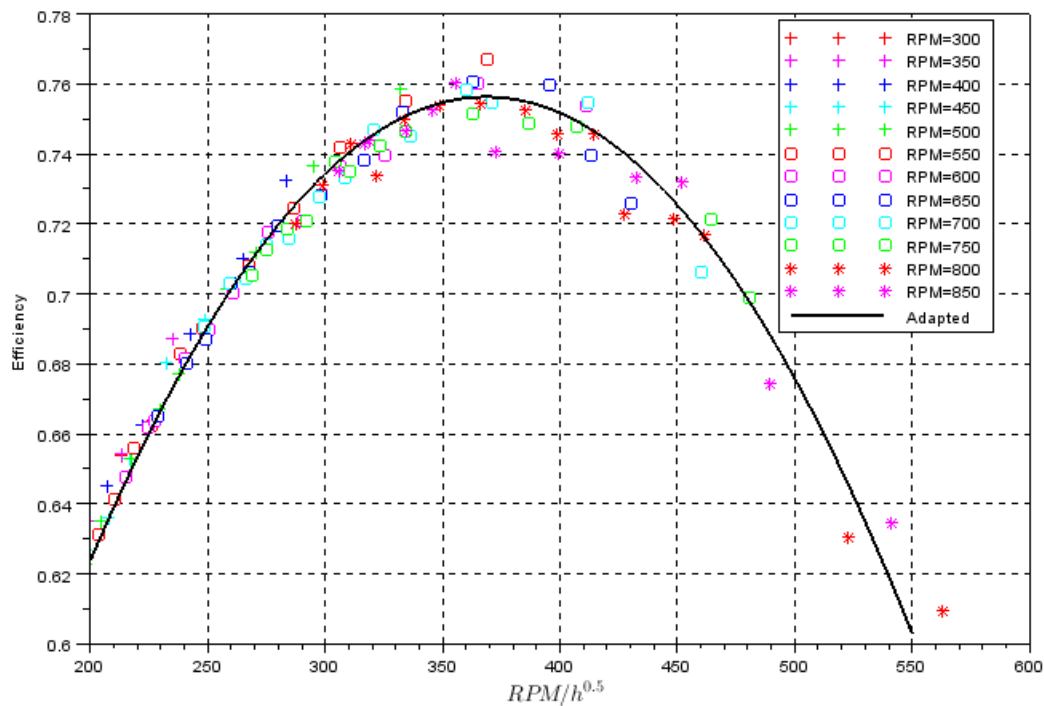


Figure 7. Efficiency as function of $RPM/h^{0.5}$ at blade position 1. Solid line shows adapted value. (Max 75.6% at $RPM/h^{0.5} = 368$).

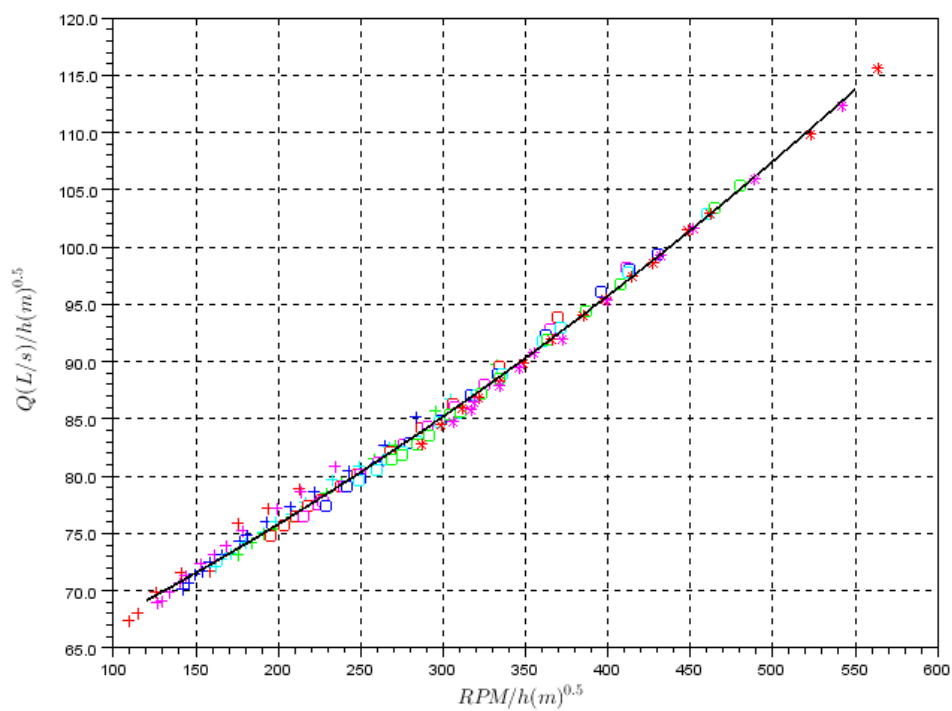


Figure 8. Flow as function of $RPM/h^{0.5}$ at blade position 1. Same symbols as in Figure 7

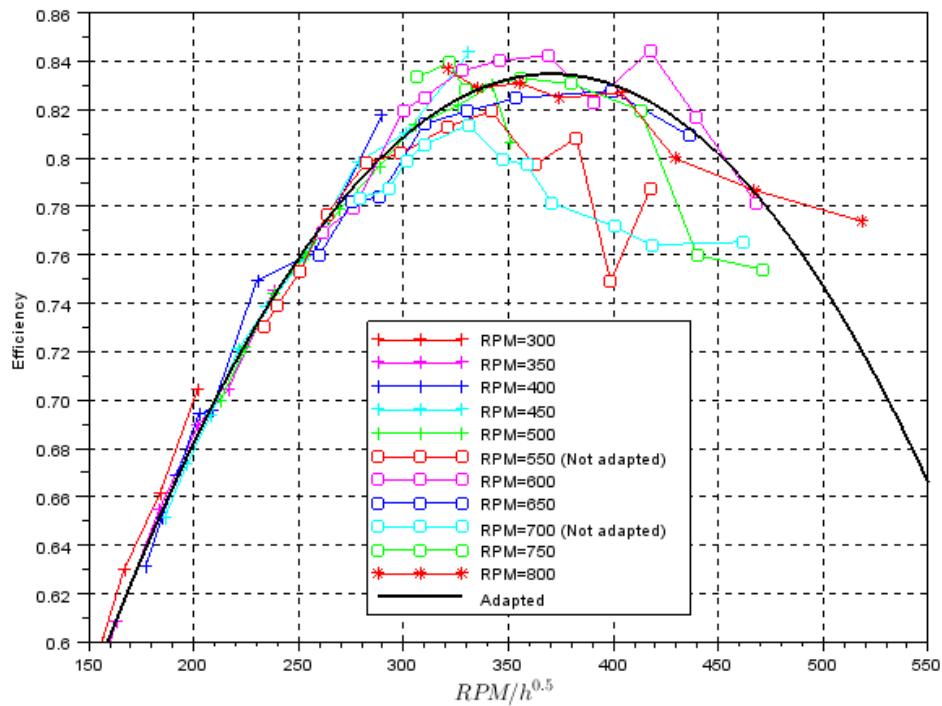


Figure 9. Efficiency as a function of $RPM/h^{0.5}$ at blade position 2. Solid line shows adapted values Some measurement are bad and not included in the adoption (Max: 83.5% at $RPM/\sqrt{h} = 371$)

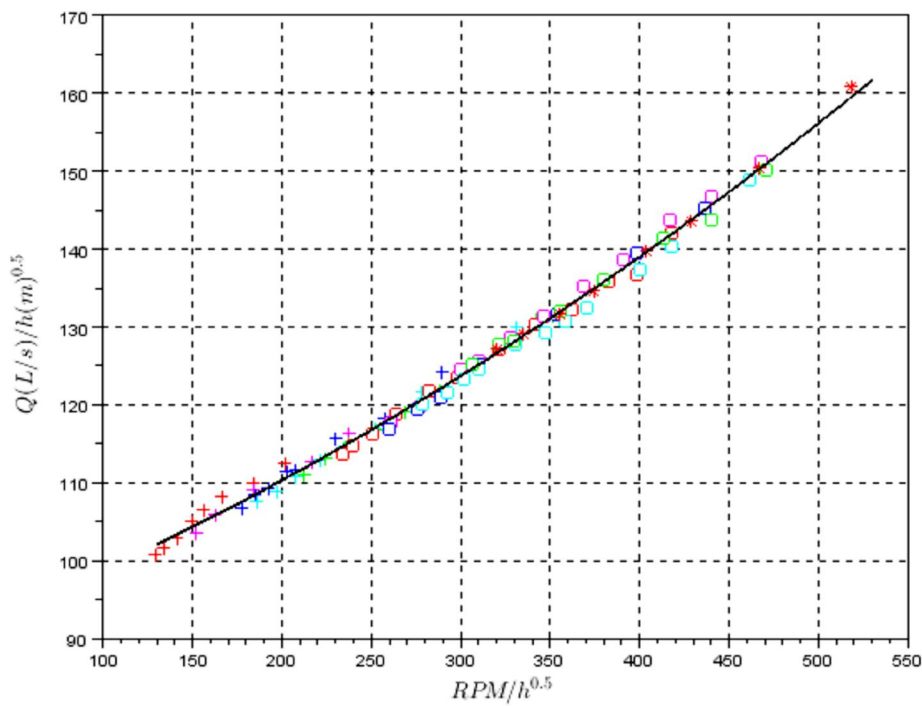


Figure 10. Flow as function of $RPM/h^{0.5}$ for position 2. Same symbols as in Figure 9

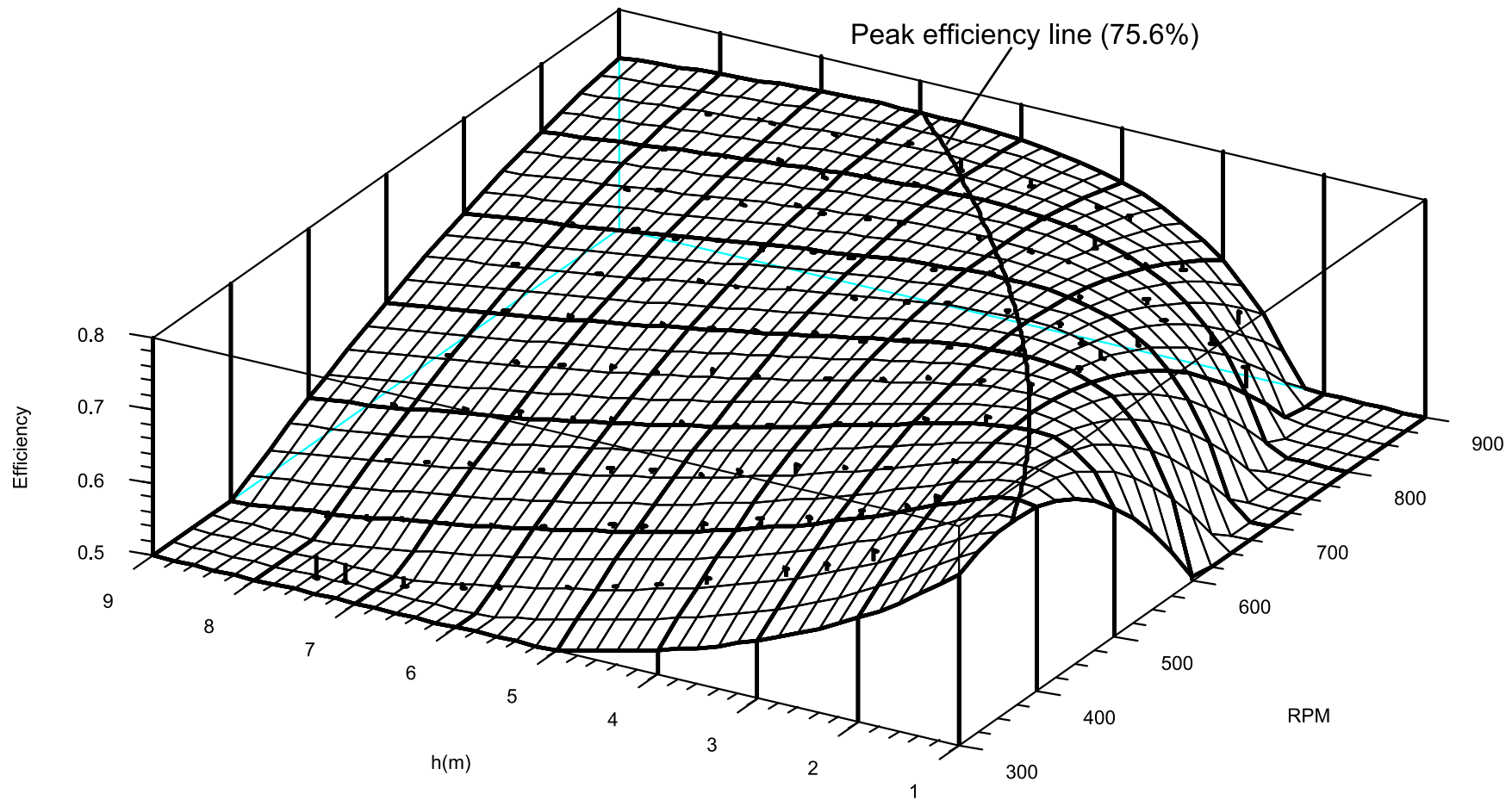


Figure 11. Measured efficiency at blade position 1. For each measured point is a vertical line. One end has a horizontal line and shows the measured point, the other end touches the 3D-Grid which is the adapted value, which is the solid line in Figure 7.

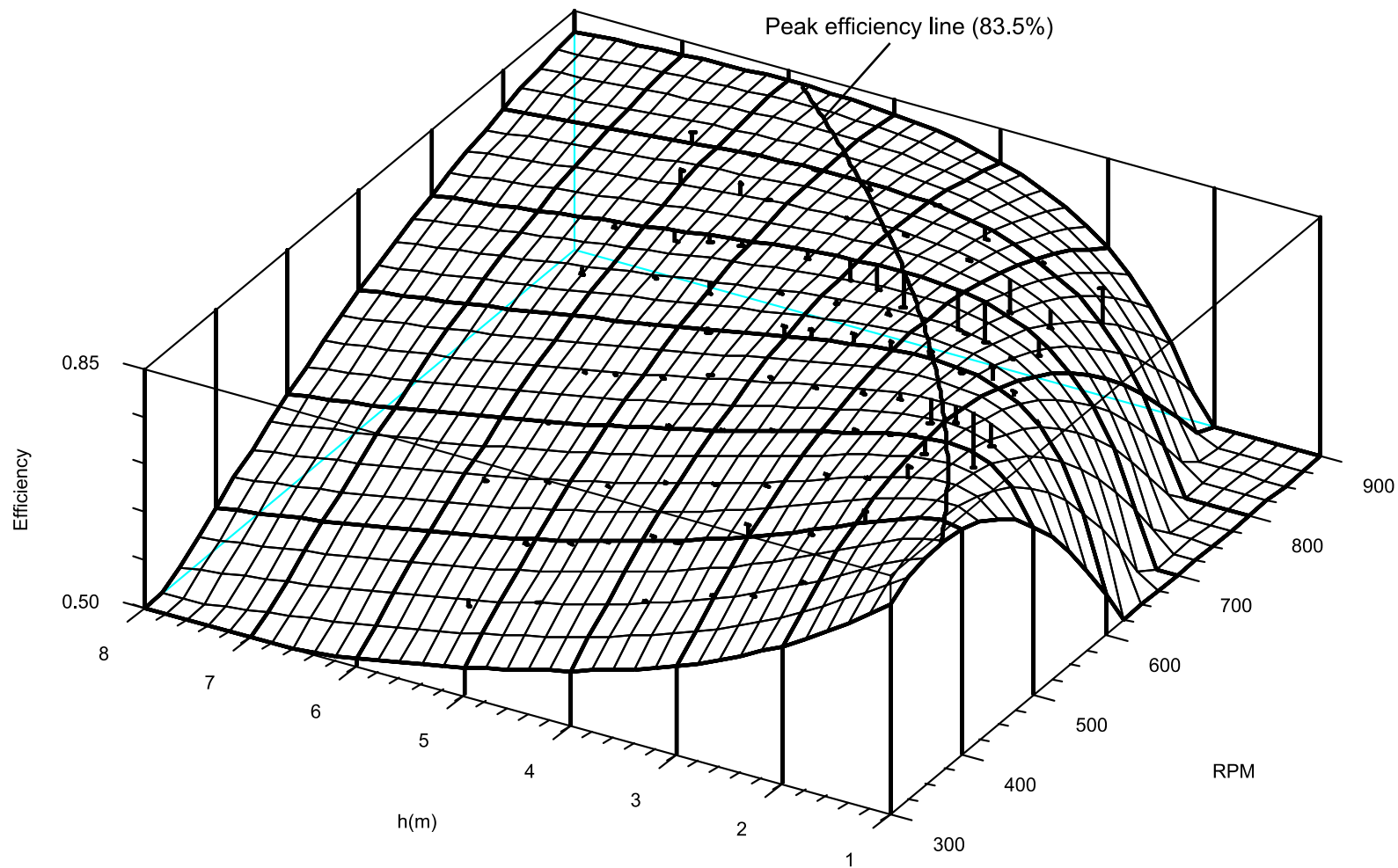


Figure 12. Measured efficiency at blade position 2. See Figure 11 for explanation.

3.4 Results from the analysis

3.4.1 Blade position 1:

The efficiency for blade position 1 is shown in Figure 7 and Figure 11. The measurements for different heads are quite close together and the data can be fitted to a curve. This curve has the formula:

$$\eta = 0.123 + 3.44x - 4.66x^2 = -4.66(x + 0.034)(x - 0.773)$$
$$x = \frac{RPM}{1000(\text{Rev} \times \text{min}^{-1} \text{m}^{-1/2}) * \sqrt{h}} \quad (4)$$

The difference between this formula and efficiency is shown in Figure 11. The surface shows the adapted formula. The lines show the difference between the measured efficiency (a small horizontal line) and the adapted formula (the other end of the vertical line).

The flow ($q/h^{0.5}$) is shown in Figure 8. A curve is made that fits the data with the formula for x defined as shown above.

$$\frac{q}{\sqrt{h}} = (60.53 + 64.68x + 58.37x^2) \text{L/sm}^{1/2} \quad (5)$$

The curve for efficiency has a peak value at:

$$x = 0.368, RPM = 368\sqrt{h}, \eta = 0.756, q = 92\text{L/sm}^{0.5}\sqrt{h}.$$

This results in an efficiency of 75.6%

3.4.2 Blade position 2:

The efficiency for blade position 2 is shown in Figure 9 and Figure 12. There was a large variance for the 550 RPM and 700 RPM data points. When not including these two series the adapted efficiency becomes:

$$\eta = 0.115 + 3.884x - 5.24x^2 = -5.24(x + 0.029)(x - 0.770) \quad (6)$$

x is defined in equation(4). Efficiency η has a max value 0.835 at $x = 0.371$.

In Figure 9 many points are outside the graph, and in Figure 12 it is shown where these points are. The adapted curve in equation (6) is shown as a surface. It can be seen that at RPM = 550, RPM=700 and RPM = 750 many measurements resulted in lower efficiency than the surface, but at the RPM points between this is not the case. This can either be because of error in the measurement or because the flow was unstable. The series with RPM=550 and RPM = 700 was excluded when adapting the formula. Figure 10 shows the flow for all the experiments for blade position 2. The points are located along the line from the formula:

$$\frac{q}{\sqrt{h}} = (89.2 + 86.9x + 93.70x^2) \text{L/sm}^{1/2} \quad (7)$$

The curve for efficiency has a peak value at:

$$x = 0.371, RPM = 371\sqrt{h}, \eta = 0.835, q = 134L/sm^{0.5}\sqrt{h}.$$

3.4.3 Optimum RPM

During early simulation a $RPM/h^{0.5} = 346$ was used. That is fairly close to the results from NTNU with $RPM/h^{0.5} = 368$ and 371 .

Generally there is a benefit to operate the turbine at a high RPM. Then one get power if the turbine is overloaded and the over speed of the alternator reduces. Then a $RPM/h^{0.5} = 370$ is chosen.

When the turbine slows due to overloading, the power output can increase some due to higher efficiency at the lower speed. Over speed of the alternator with no load can also be reduced by selecting a higher turbine speed for the belt drive.



Figure 13. Testing of turbine at Istalief, Afghansitan

3.5 Measure at Istalif

So far NTNU have only measured with blade position 1 and 2, for that reason the test at Istalif is shown to get the flow at position 3.

Remote HydroLight has installed one turbine at Istalif and measured the performance at that turbine. It was described in section 1.5.

Figure 13 shows the turbine at Istalif used for testing performance of the turbine. This turbine was used both for testing performance and in the development of the turbine.

The following was measured:

Flow:

First the flow was measured with a propeller meter in the channel, then the maximum velocity was measured with a float in the channel, with flow: $Q = KVA$. Where velocity V is measured with a floating stick, A is the average cross section area of the channel. Variable K is a factor that related the average velocity of the channel to the maximum velocity. The measurement with the propeller meter was used to calculate k which received the value 0.85. Due to calibration of K being done with a laboratory propeller meter, systematic error is estimated to be 10%.

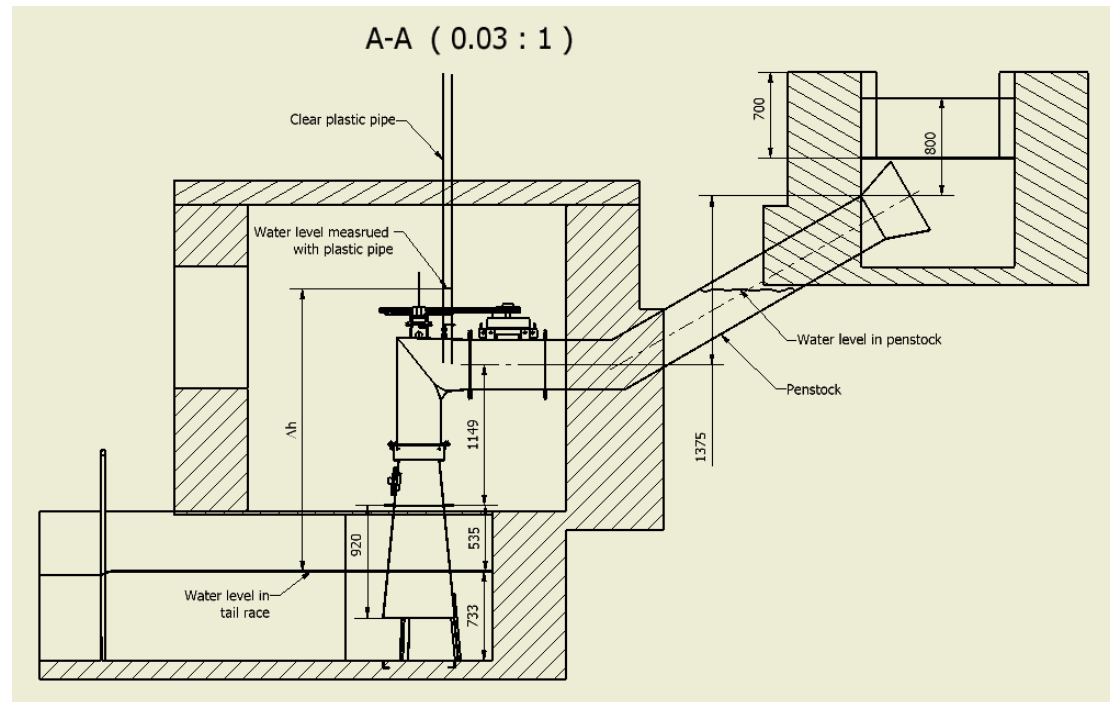


Figure 14 Measure of net head at Istalif

Head:

The net head was measured with a clear plastic pipe in the front of the turbine as shown in Figure 14. A plastic pipe is used where the water level in the pipe is measured and the water level in the tailrace is measured. The height difference between water in the pipe and water below (Δh) is measured. When running the experiments the water was in the penstock as shown in Figure 14. The flow (Q) in the penstock and cross section area of the penstock (A_c) is used to calculate velocity head and added so total net head become:

$$h_N = \Delta h + v^2 / (2g), v = Q / A_c$$

Typical systematic error: 5 cm.

Power:

Power was not measured from the turbine directly, however, the power out of the alternator was measured. This gives the efficiency of the total system, which include the belt (95% efficiency) and alternator (ranging between 70% to 87%).

RPM:

A RPM meter was used, that gave an resulting accuracy of RPM of 1%.

3.5.1 Results of the measurement at Istalif..

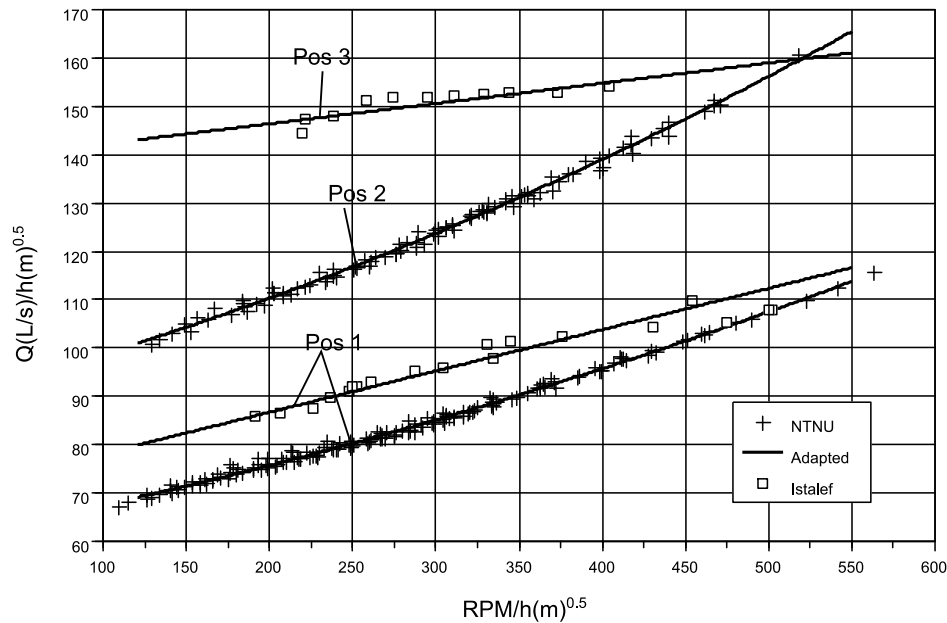


Figure 15. Measurement at Istalif and NTNU

Figure 15 shows the flow data at Istalif compared with NTNU. It can be expected that measurement at NTNU is much more accurate than the measurement at Istalif.

At RPM of $370 \cdot h^{0.5}$ one get for $Q/h^{0.5}$ ($L/sm^{0.5}$):

Table 2 Summary of $Q/h^{0.5}$ ($L/sm^{0.5}$) and RPM for optimal point

	NTNU	Istalif	Use
RPM/ $h^{0.5}$	370	370	370
Pos 1	92.5	101.5	92
Pos 2	134.2	No test	134
Pos 3	No Test	153.5	153
Pos 4	No test	No test	170

3.6 Loss in pipe

A 16 inch (ID=406mm) locally made penstock was used. Normally the penstock is 3 m long and has a 30 degree bend and a funnel with end diameter 0.65m as shown in Figure 4 and Figure 14. At a flow of 300 L/s the head loss is 4 cm because of wall friction, 4 cm from the funnel at the end and 5 cm at the bend. Even if this is very low a smaller penstock is not recommended since the flange on the turbine is 16 inch.

Miller calculated the friction in a sharp pipe bend. That is shown in Appendix 3. It also shows the calculation of pressure drop in the pipe.

For the given pipe the head loss is:

$$\Delta h = k_p q^2 \quad (10)$$

For a typical Kaplan turbine pipe of: 3m long 160 diameter pipe, 30° bend, and 0.65 m opening. $k_p = 1.53 \text{ m}/(\text{m}^3/\text{s})^2 = 1.53 \times 10^{-6} \text{ m}/(\text{L}/\text{s})^2$. Varying $\pm 1\%$ when flow changes from $0.1 \text{ m}^3/\text{s}$ to $0.4 \text{ m}^3/\text{s}$

Because generally the same pipe is used on all Kaplan sites, pipe loss is included in the equation to make the calculation simpler.

For a turbine with $A = Q/\sqrt{h_N}$ one get:

$$h_G = h_N + \Delta h = \frac{q^2}{A^2} + k_p q^2 = (k_p + 1/A^2) q^2 \quad (11)$$

$$\Rightarrow q = \frac{\sqrt{h_G}}{\sqrt{1/A^2 + k_p}}$$

3.6.1 Example of calculation, 6m net head, blade position 2:

Optimum at $\text{RPM}/\sqrt{h} = 371 \rightarrow \text{RPM} = 371 \times \sqrt{6} = 909$,

$q = 134 \text{ L}/\text{sm}^{0.5} \sqrt{h} = 328 \text{ L}/\text{s} = 0.328 \text{ m}^3/\text{s}$

Pressure fall in pipe: $\Delta h = k_p q^2 = 1.53 \times 0.328^2 = 0.165 \text{ m}$.

This mean that net head $h_n = 6 \text{ m}$, gross head $h_g = 6 \text{ m} + 0.165 \text{ m} = 6.165 \text{ m}$

Efficiency turbine: $\eta_t = 0.835$

Efficiency pipe: $= h_n/h_g = 6/6.165 = 0.973$

The components of this pressure loss is:

Loss in 3m straight pipe:	5.1 cm
Loss in 30° bend	6.4 cm
Loss at end, D=65 cm	5.0 cm
Total	16.5 cm (0.165m)

3.7 Loss in belt

V-Belts are used to transfer power from the turbine pulley to the alternator pulley. Since the belts are elastic they also slip and give power loss.

Belt manufacturers state that standard V-belts have a 95-97% efficiency. A belt efficiency of 95% was used in the calculations.

3.8 Loss in alternator

The Kaijieli Chinese made alternator is used in Afghansitan. They are a brush-type, diode regulated alternator.

The alternator has 2 main losses, resistance in the windings and loss when the core is magnetized. In addition does one need power to magnetize the core. At 50 Hz, 220V one then can write power loss:

$$\Delta P = P_{inp} - P_{El} = A(P_{El} / PF)^2 + B, \eta = P_{El} / P_{inp}$$

A is a constant that decides loss in winding resistance since current I is proportional to electric power, P_{El} ($P_{EL} = IU(PF)$). PF is power factor

Measurements have been done on 7.5 kW, 12 kW and 20 kW generators and got the following values:

Table 3. Loss coefficients for the alternators

Dynamo	7.5 kW single phase	12 kW single phase and three phase	20 kW three phase
A (kW ⁻¹)	0.0427	0.0085	0.0032
B (kW)	0.30	0.73	1.03

An error of 5% is assumed in the measurements.

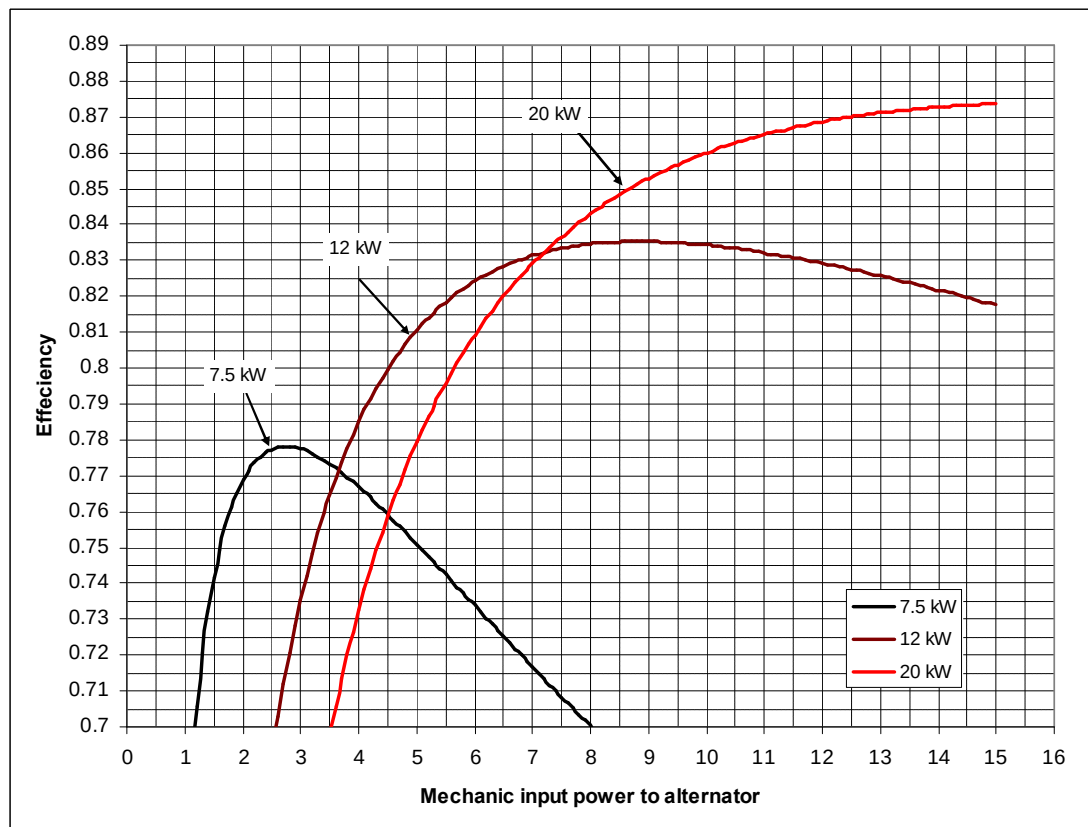


Figure 16. Measured efficiency for Kaijieli brush type alternator at power factor of 0.8 for a 7.5kW, 12kW and 20kW sizes.

In the calculations of Table 4 it is assumed that a 7.5 kW or 12 kW (but not 20 kW) alternators (the ones with highest efficiency) is used.

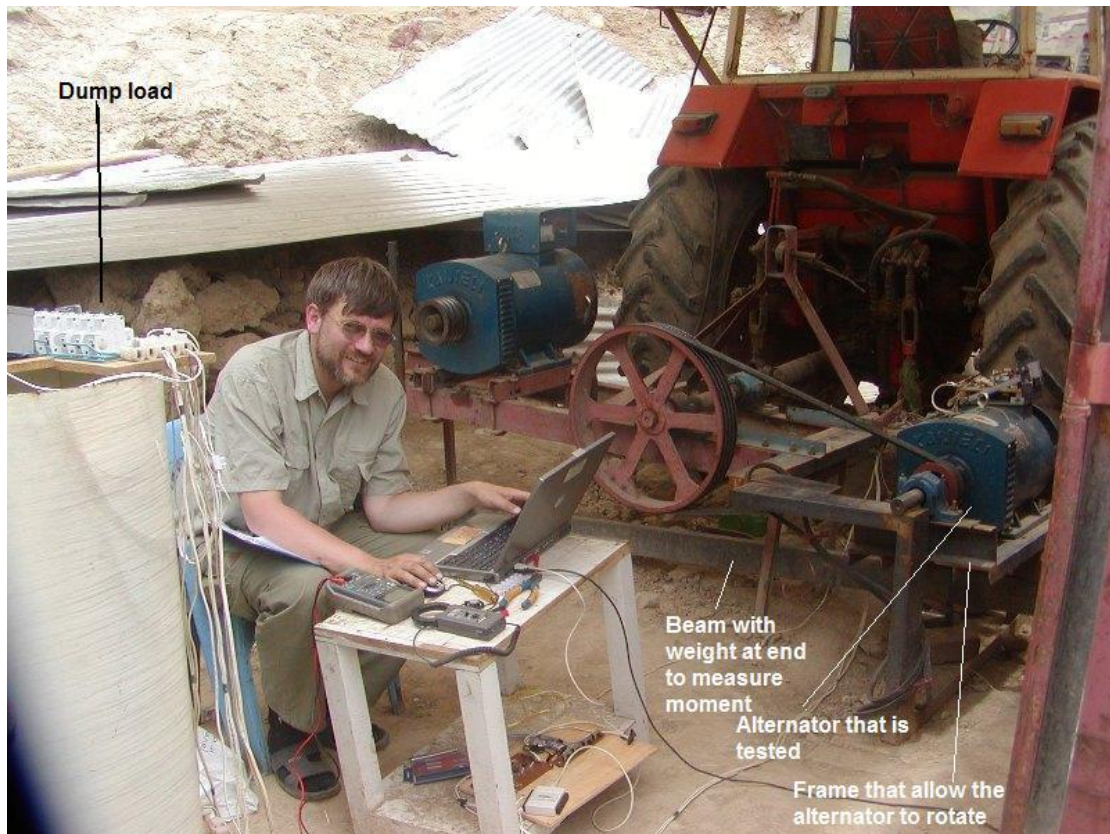


Figure 17 Test stand for measure of efficiency of alternator

3.9 Resulting table over flow and electric effect

Table 4. Resulting flow and power

	Pos 1		Pos 2		Pos 3 ^B		Pos 4 ^B			Pulley size (Inch)	
Gross head(m) ^A	Flow (L/s)	Electric power (kW)	Flow (L/s)	Electric power (kW)	Flow (L/s)	Electric power (kW)	Flow (L/s)	Electric power (kW)	RPM optimal	Turbine	Alter-nator
1.5	112	0.8	162	1.3	184	1.5	204	1.5	445	22	6
2	129	1.3	187	2.1	213	2.4	235	2.3	514	22	8
2.5	145	1.9	209	2.9	238	3.3	263	3.2	575	22	8
3	158	2.4	229	4.0	260	4.6	288	4.5	630	20	8
3.5	171	3.0	247	5.2	281	5.9	311	5.8	680	20	10
4	183	3.9	264	6.4	301	7.2	333	7.1	727	20	10
4.5	194	4.8	280	7.6	319	8.6	353	8.5	771	20	10
5	204	5.6	296	8.9	336	10.0	372	9.9	813	20	10
5.5	214	6.5	310	10.2	353	11.5	390	11.3	853	20	12
6	224	7.4	324	11.6	368	12.9	407	12.8	891	20	12
h(m) ^C	91ãh	5.2hq	132 ãh	6.0hq	150ãh	6.1hq	166ãh	5.5hq	364ãh		
Flow measurement source	Measured at NTNU				Measured at Istalif		Estimated				
Turbine efficiency used ^D	72%		80%		80%		72%				
	Measured NTNU				Estimated		Estimated				

^A: Gross head, water to water, assuming 3 m pipe with 30 degree angle and funnel at the opening end

^B: Note that pos. 3 and 4 data points may have some error.

^C: For 3 m head, power is slightly higher at higher head and lower at lower head because the efficiency of the alternator increases at higher power

^D: These are conservative values that can be sued by Afghan hydropower industry. (Actual peak efficiency measured by NTNU at optimum operating point was 83.9%)

This table includes loss in pipe, turbine, belt and alternator to get effect. It is based on gross head, the head from water to water. Here also the efficiency is reduced 3% for the turbine as a margin. For the alternator a power factor of 0.8 is assumed. Example of calculation of value is shown in Appendix 4.

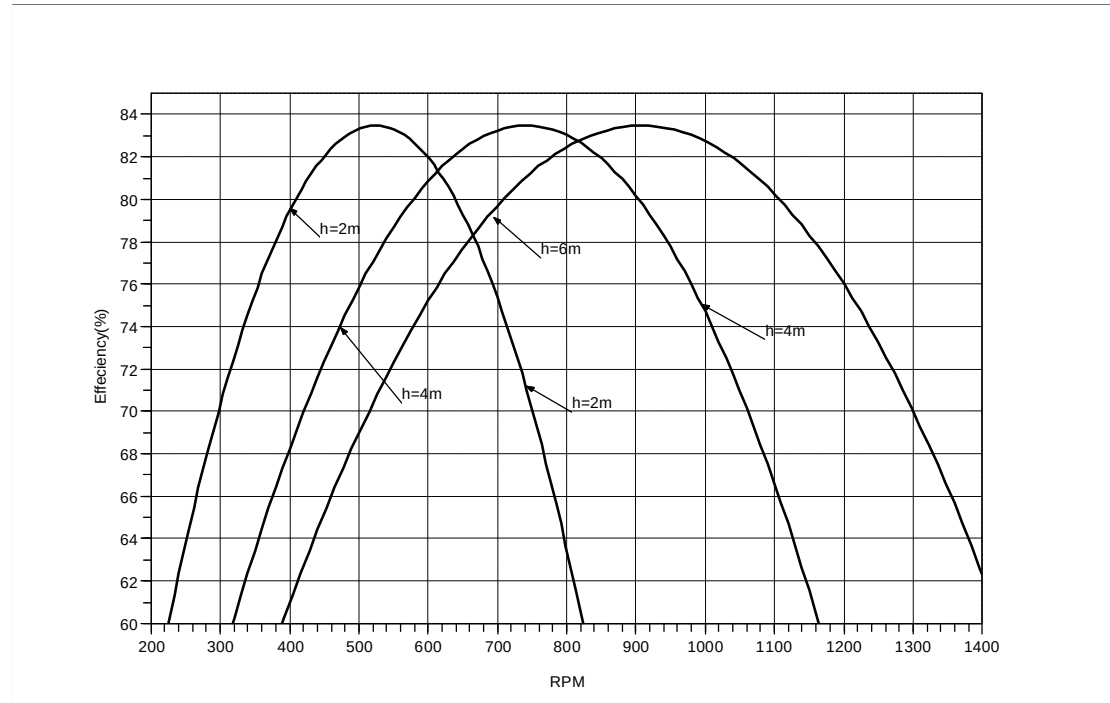


Figure 18. Efficiency for turbine as function of RPM at head of 2m, 4m and 6m

3.10 Dimensionless numbers:

Before we divided on square root of h ($\tilde{h}$). But the constants still have dimensions. To get a better understanding of the system one can use dimensionless numbers as an extension to section 3.2.

The rotor have a diameter of 356 mm, or outer radius $r_o=0.178$ m, and an inner hub with radius $r_i=0.1$ m.

Then one can use free stream velocity $v' = \sqrt{2gh}$ that is the velocity when all head energy is changed to velocity energy. h is here net head. Variables that is divided on v' is called reduced quantities.

With A_c = Cross section of the turbine where the blades is:

$$A_c = \pi(r_o^2 - r_i^2) = 0.0681\text{m}^2, Q = v_z A_c$$

v_z is downward velocity where the blades are.

By substituting:

$$RPM = 60 * \frac{\omega}{2\pi}, h = \frac{v'^2}{2g}$$

One get:

$$\frac{RPM}{\sqrt{h}} = k_1 * \frac{\omega r_o}{v'}, k_1 = \frac{60\sqrt{2g}}{2\pi r_o} = 237.6 \frac{\text{rev}}{\text{min} * \text{m}^{0.5}}, v' = \sqrt{2gh}$$

$$\frac{Q}{\sqrt{h}} = k_2 \frac{v_z}{v'}, k_2 = A_c \sqrt{2g} = 0.3016 \text{ m}^{2.5}/\text{s}$$
(2)

Then one can calculate specific speed (EHSA, http://en.wikipedia.org/wiki/Specific_speed):

$$n_{QE} = \frac{n\sqrt{Q}}{(gh)^{3/4}} = k_3 \frac{\omega r_o}{u'} * \sqrt{\frac{c_z}{u'}} = k_4 \frac{RPM}{\sqrt{h}} * \sqrt{\frac{Q}{\sqrt{h}}}$$

$$k_3 = \frac{2^{3/4} \sqrt{A_c}}{2\pi r_o} = 0.392, k_4 = 0.0030$$

Here $n = \omega / 2\pi$ = Revolutions per second (=RPM/60), ω = Angular speed: Rad/s

Then we have the dimensionless quantities:

v_z/v' Reduced downward speed where the blades are. A high speed makes a small turbine, but it is also more difficult to recover the velocity energy in the draft tube.

$\frac{\omega r_o}{v'}$ Reduced outer-speed of the blades. A high number gives high RPM, but also more blade friction and the shape of the blades are more important.

n_{GE} Specific speed. The radius(r_o) is not part of n_{GE} so it tells something of the relation between flow, RPM and head. Different literature have different definitions. A low value gives low RPM. Based on hydrology (but not strength and cavitation) two turbines with same n_{GE} can be made equal but with different sizes.

With variable from Table 2 one get:

RPM/ $\sqrt{h}$ =370 ->

$$\frac{\omega r_o}{u'} = \frac{RPM / \sqrt{h}}{k_1} = \frac{370}{237.6} = 1.56$$

Table 5 Dimensions numbers for different blade positions

	$Q/\sqrt{h} \text{ (m}^{2.5}\text{s}^{-1}\text{)}$	$c_z/u\hat{o}$	$\omega r_o/u\hat{o}$	n_{QE}
Pos 1	0.092	0.30	1.56	0.34
Pos 2	0.134	0.44	1.56	0.41
Pos 3	0.153	0.51	1.56	0.43
Crosssflow ¹	$0.9bD$	1.0	0.5	$0.114\sqrt{b/D}$

¹: c_z ; Measured at outlet of valve. b : Width of the rotor. D : Rotor diameter

Pos 3 is optimal position and gives the properties of the rotor. Usually the specific speed (n_{QE}) is higher for Kaplan turbines at low head. The reason for the low specific speed is explained in section 4.4.

4 Design choices made for the turbine.

4.1 Pipe turbine versus spiral casing turbine

Other development efforts (ITDG Peru) have chosen a spiral casing turbine which allow the two rotor bearings to be outside the turbine (Figure 19). The spiral casing and rotor assembly become very large and heavy components that would be difficult to transport in Afghanistan. The civil work for a pipe turbine become simpler because it confines the water in the pipe. By using a special lower bearing design, Remote HydroLight could select the lighter, more compact pipe turbine.

For a Kaplan turbine design using two bearings outside of the rotor, the first bearing must be some distance from the rotor resulting in higher forces and thus a heavier shaft is needed to get stability.



Figure 19. ITDG spiral Kaplan turbine

4.2 Vertical turbine versus horizontal turbine

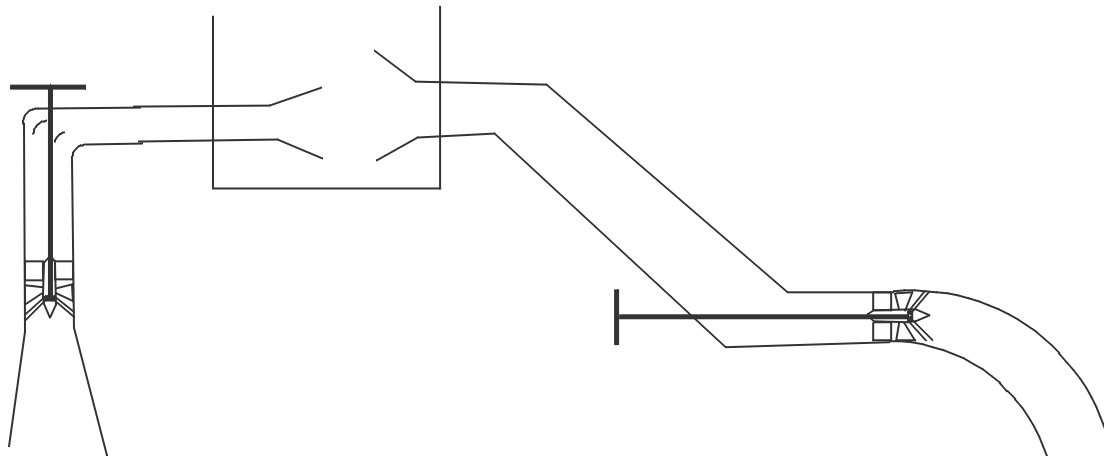


Figure 20. Vertical turbine to the left and horizontal turbine to the right

Figure 20 shows a vertical and horizontal turbine. The horizontal turbine has a horizontal axis and a horizontal alternator. The draft tube need to be bent. The vertical turbine has a vertical alternator. Generally a horizontal turbine is best for a larger project with low head where the length of the turbine and draft tube become longer than the head.

Benefit of horizontal turbine

- Can be used for large turbines at low head
- Get a horizontal alternator. The alternator we uses are made for horizontal mounting.
- Can put two bearings one each side of the shaft outside of the turbine.

Benefit of vertical turbine

- Less pipe and weight
- The draft tube is straight which is much easier to make
- Uses less space inside the power house
- Bottom bearing can use vacuum force below rotor to keep water from entering bearing (See section 5.1 about bottom bearing)

4.3 Kaplan turbine with adjustable blades or a propeller turbine with adjustable guide vanes

Generally there are four possibilities:

1: No adjustment:

The turbine is made for one flow. If the flow is different new blades could be installed. This turbine is called propeller turbine.

2: Adjustment of guide vanes

The turbine flow can be adjusted, but the efficiency curve is steep, wich results in low part-flow efficiency. This occurs because the most of the pressure drop is over the blades. This turbine is called propeller turbine. Since the blades are not adjusted is the pipe outside of the blades straight. Part low efficiency is shown in Figure 21 under propeller.

3: Adjustments of blades but not guide vanes

The turbine flow can be adjusted, and part flow efficiency is better than adjusting only the guide vanes. This turbine is called a Kaplan turbine, or single regulated Kaplan turbine. Since the blades can be rotated, the pipe surrounding the blades is spherically shaped.

4: Adjustment of both guide vanes and blades

This gives the best part flow efficiency and is usually used only on large turbines. This turbine is also called a Kaplan or double regulated Kaplan turbine.

Because the RHL turbine uses a pulley, some variation in flow is also possible by changing the pulley size.

All of these turbines are run of the river type with constant flow. It is generally no need to adjust the blades during the day. However, it is important to have high part flow efficiency since one want one turbine to be used in many places. Also one has season variations that make adjusting of the blades during different seasons. As seen in Figure 21 is the part-flow efficiency something between the propeller turbine and double-regulated Kaplan turbine.

Of that reason a turbine where blades can be adjusted where the turbine is not rotating is chosen.

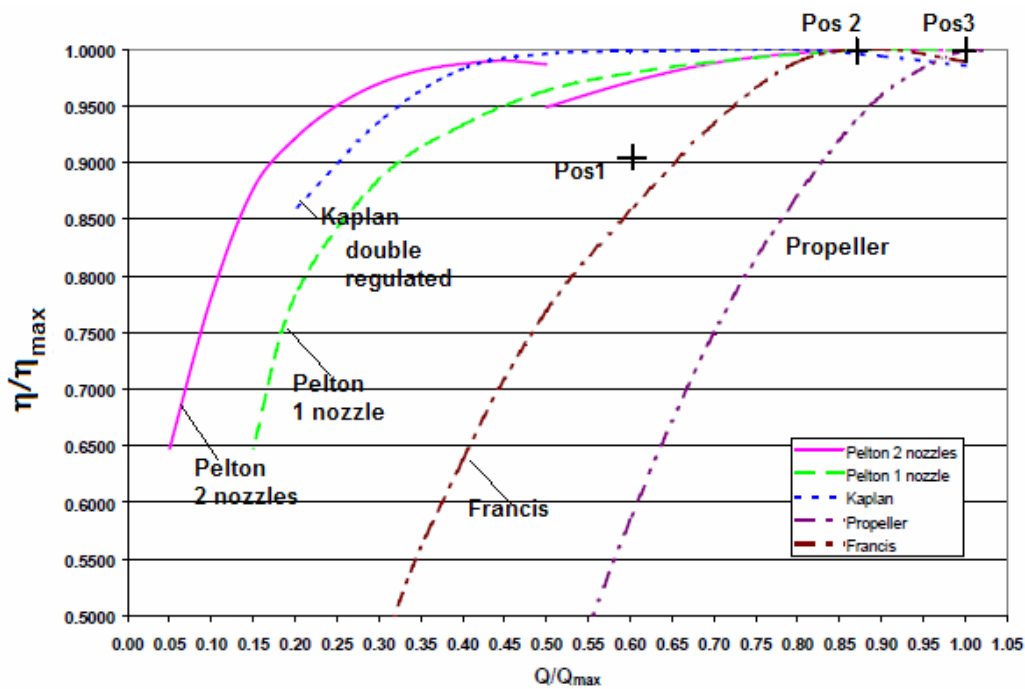


Figure 21. Part flow efficiency for different turbines (EHSA). Three blade positions of the RHL turbine are also plotted (Pos1, Pos2 and Pos 3). Only position 1 and 2 were measured at NTNU.

4.4 Specific speed and flow through the turbine

Generally low head turbines have high specific speed which makes it more compact, economical, and faster turning. This results in a low cross section area turbine with blades that rotate fast and bend the flow very little. Due to friction loss being related

to flow velocity, a high specific speed Kaplan turbine is very sensitive to the finish of the blades and shape of the blades. Due to low accuracy in making the cast blades, a low specific speed was used for the RHL turbine. The RHL Kaplan turbine is less sensitive to geometry inaccuracies and it makes it easier to make the draft tube.

The Kaplan turbine uses four blades even though most manufacturers may use 5 or 6 blades at the selected specific speed. The blades needed to be shaped long, however, the simplicity of the 4 blade hub was important due to manufacture in Afghanistan.

4.5 Direct drive versus belt and pulley drive

The flexibility of a simple belt and pulley drive system allows the optimum turbine RPM for heads between 1.5m and 6m. It also allows for the standard 4 pole 1500 RPM alternator to be used. About 5% efficiency loss is associated with a belt drive; however, special multi-pole alternators at various speeds are not available and would be too costly for the Afghan market anyway.

5 Main parts of the turbine

5.1 Bottom bearing

The bottom bearing is located below the rotor. Water containing sand, silt, and sometimes small rocks pass through the turbine. Even on large Kaplan turbines the bottom bearing can give problems if it is not designed for muddy water. Some approaches to solve the problem are listed below.

- Install a bushing that uses water to lubricate between the shaft and bushing. This requires high tolerances and is sensitive to silt and sand in the water. This was tried on the Kaplan turbine, but, failed after about 300 hours.
- Use seals (rubber, asbestos rope, leather, etc.) to keep the bearing and grease/oil separate from the water. Often the oil is pressurized to keep water leakage into the bearing. Seals work if the water is absolutely free of silt, but, this is not the case. Small flakes of silt and sand float in the moving water, eventually wearing the surface of the shaft and seal. Water will flow in and/or grease/oil will flow out contaminating the bearing and water source. It is also very difficult to repair the seal; usually the turbine has to be disassembled. For this reason it was not a good option for Afghanistan.
- Use the naturally occurring under pressure force (vacuum) below the rotor to keep unclean water from the bearing and grease holder. This method works well with the vertical shaft design, but would not work with a horizontal rotor shaft. This design has proven to work in extreme silt/sand conditions.

One of the most unique features of the RHL Kaplan turbine is the bottom bearing design. Figure 22 shows the cross-section and details of how it functions. At all times the bearing must be above the tail race water level. Usually the flange for the draft tube is above the tail race water level (See Figure 4). When the draft tube is filled with water (normal operation) there is a naturally occurring vacuum below the rotor. By having an air cavity built into the design and a source of air to this air cavity, it is possible to keep water away from the bearing. Here is how it works: The bearing is located in an upside down can that has trapped air in it and doesn't let the water to enter. An air pipe is placed in a strategic location so that air is sucked in by the vacuum and then constantly flushing down and out of the nose cone recharging the trapped air so that water does not slowly seep up and into the bearing.

The shaft end with stainless steel bearing is operating in grease that is surrounded by trapped air. Excess grease if applied gets sucked out along the same path as the air. Because the location of the bearing grease is at a dead end (no air outlet or grease outlet), the sucked in air always follows the same path out of the nose cone, carrying any excess grease. Provision was made to deal with excess grease because operators sometimes over grease. During start up and shut down the vacuum below the rotor is zero, however in this case the water falls outside of the bearing and grease cavity.

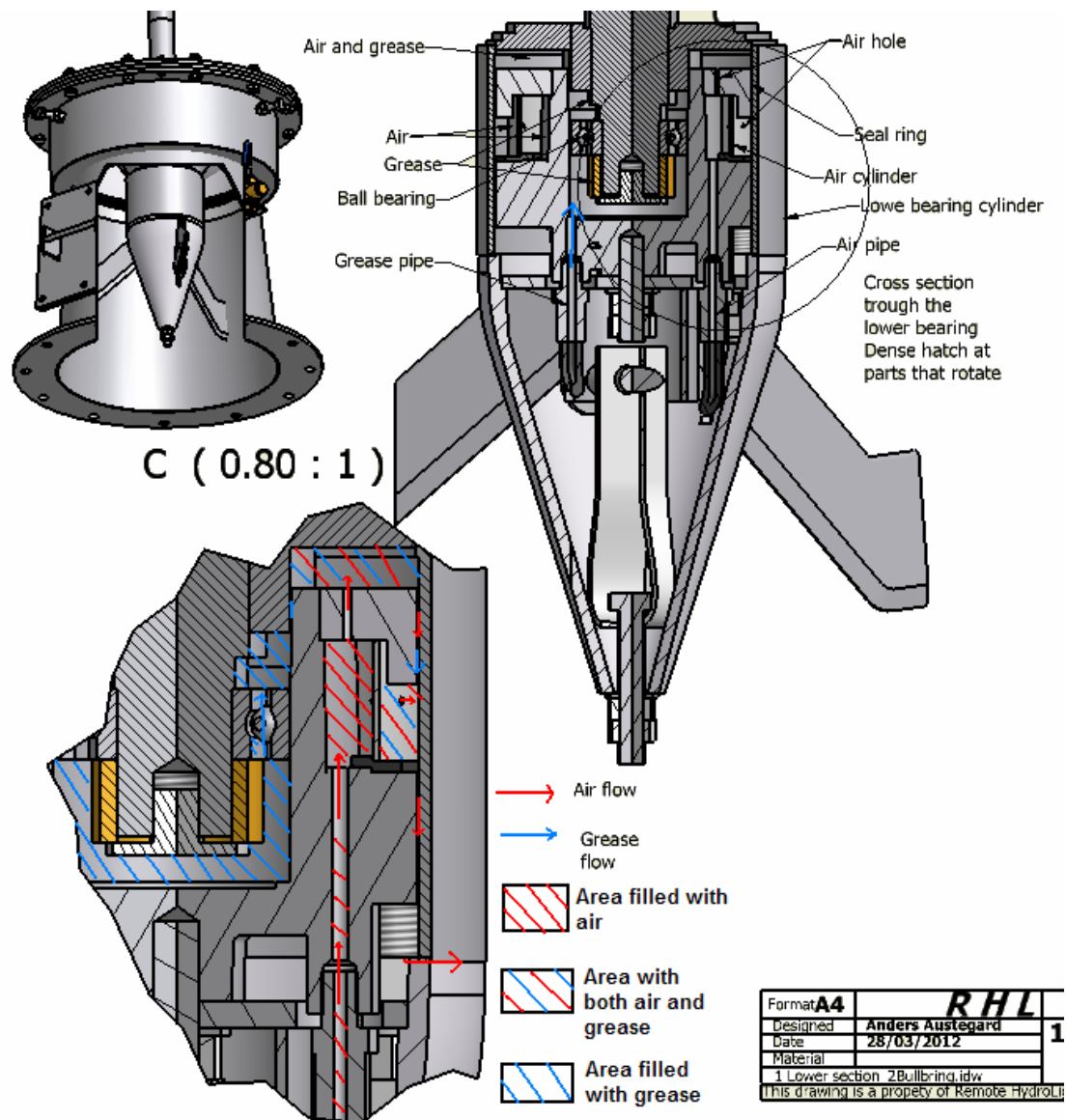


Figure 22. Bottom bearing for the Kaplan turbine.

When the draft tube gets full the suction below the rotor pulls air from outside to the inside. The air pipe is equipped with a one-way valve just in case the tailrace water gets too high for a short period of time when the turbine is stopped. The one way valve will not allow air to escape the cavity, thus keeping the water from filling the bearing cavity.

Because the air valve inlet faces downward, experience shows that dust does not go into the air pipe. The air sucked into the turbine results in a fine mist of air in the water. Water can and has reached the air cylinder cavity during operation, however, it does not reach the top of the cavity where excess grease and air passes. It is important that the path of water and air does not mix with the path of grease and air; otherwise, water can slowly get into the grease and contaminate the bearing.

A Chinese stainless steel ball bearing (available in Pakistan) is used for the lower bearing. The axial force of the water onto the rotor is carried by the top bearing.

Then the only force on the bearing is from side force from the pulley and unbalance in the rotor, and then the bearing can be quite small. The lower bearing holder allows the bearing to float (not have a vertical position)

A special procedure is used during assembly to align the shaft to the lower bearing holder. Two bearings are mounted onto the shaft and to force the shaft and bearing holder to be parallel. Adjusting of the bearing holder is done with three studs. After alignment, the extra bearing is removed and a spacer is installed.

The nose cone is fitted below the bearing holder assembly to protect the parts and provides a smooth outer surface. The nose cone does fill with sand and silt; however, this does not affect the operation of the turbine.

Make sure the stainless bearing (6206) does not have the shield or seal covering the bearing balls, so that grease can pass through. Put grease in between the bearing balls before it is installed.

The bottom bearing holder should be filled half full with grease before it is mounted, but do not add grease after it is put together. (Except for testing that the grease pipe works). The reason is that if you fill the whole cavity with grease it also fills the air cavity with grease.

5.2 Top bearing

The top bearing must be able to support the axial (vertical) water force and the radial (horizontal) belt force. The axial force can be up to 3.5 times the radial force at 6m maximum head limit of the turbine. During start up and shut down or at very low flow (air may be entering the penstock or draft tube), the axial force is almost zero and mostly a radial force is acting on the bearing. Tight tolerances for bearing alignment are not easily provided for because the castings are locally made, machining is not very accurate, and the bearing holder is mounted to a weldment. Due to the water and grease system used, the bearing had to be positioned so it did not move; therefore, it could not be mounted in rubber or some elastic system.

Some options for possible top bearings are listed below:

- One angular contact ball bearing:

This bearing is used on multi-stage submersible pumps that have mostly an axial load. This bearing is not self centering so it required accurate alignment which was difficult. It was tested in the Kaplan turbine, but, would soon fail after about 300 hours. It is suspected that when there was low axial force (very low flow, but turning) the belt force caused the bearing to twist and wear out.

- Two angular contact bearings:

This was not tested, but, would require very accurate alignment and a preload so there is no twisting.

- Taper rolling bearing:

This type of bearing has the same problems as the angular contact ball bearing design. It would require always having a axial force which means a preload design adding more complications and parts.

- Spherical roller thrust bearing:

This bearing is self aligning and very strong. It was found that only 60 mm or larger diameter bearings were available. It also needs some kind of preload system to ensure that a axial load is always keeping the rollers sitting correctly in the bearing race.

- Spherical roller bearing

This bearing is self aligning and is currently being used on the Crossflow turbine. Investigation showed it can be used in situations where axial load is present. It also has a high rating for radial load from the belts. This bearing was successfully tested and met the requirements needed for the Kaplan turbine.

5.2.1 Seal

Unlike the lower bearing and shaft which is operating in a vacuum, the upper shaft exits the turbine at a place in the pipe where water pressure is equal the pressure head. A seal is needed to make sure water does not spray all over and onto the bearing. Field testing again exposed some weakness of the first proto-type; however, re-design and re-testing resulted in a very robust turbine that is able to operate in high silt/sand conditions.

Rubber seals that use water to lubricate between the rubber and shaft would quickly wear out in the conditions this turbine must operate in. Asbestos rope forced tightly around the shaft only works for a short time, not long enough to the 24/7 continuous operation of a water turbine. Experience has shown it needs constant attention, adjustment, and would wear quickly due to silt/sand in the water. Typical village operator will not be able to maintain this type of seal.

Instead of a contact type seal, the choice was to use a controlled leakage labyrinth seal. The construction is shown in Figure 23. This became more resistant from damage due to silt and sand in the water. Of course everything needs to be done to limit the silt and sand entering the water canal. Due to rough conditions in Afghanistan (high erosion, fast run of the river canals, poor silt basin maintenance and cleaning, all night operation without monitoring, and pressure by the villagers to keep the electricity on even during muddy water conditions) our controlled leakage labyrinth seal can still gets some wear on the shaft and brass bushing where the water and sand passes. The design allows the labyrinth to be re-machined and brass bushing replaced to again give a tight fit if this would be needed. When new at 7 m head the controlled leakage seal water would measure ca 0.1 liter/second. During testing in high silt/sand conditions, wear of the labyrinth seal caused the controlled leakage to increase up to 1 liter/second and still protect the bearing from water damage.

Above the controlled leakage seal are two rotating water deflection plates that deflect the water downward and out the excess water pipe. Between the deflector plates is a rubber seal that turns with the shaft and stops water passing along the shaft. Some drops of water pass the first plate, but the top of second plate is dry. To secure the top of the seal is dry and does not get condensation large holes are in the upper bearing support pipe. A catch and drain is used to stop water or grease from spraying outside the turbine.

The bearing needs to be at least 50 mm inner diameter for capacity reasons. Due to the shaft being 40 mm, a bearing collar was necessary.

The vertical position of the shaft is set with a bolt and washers. The entire shaft and rotor can be properly adjusted up and down ± 5 mm so the rotor sits in the rotor pipe and gives minimum leakage. The rotor always turns clockwise (locking from the top) so the right treads of the bolt do not loosen.

5.2.2 Grease for bearing

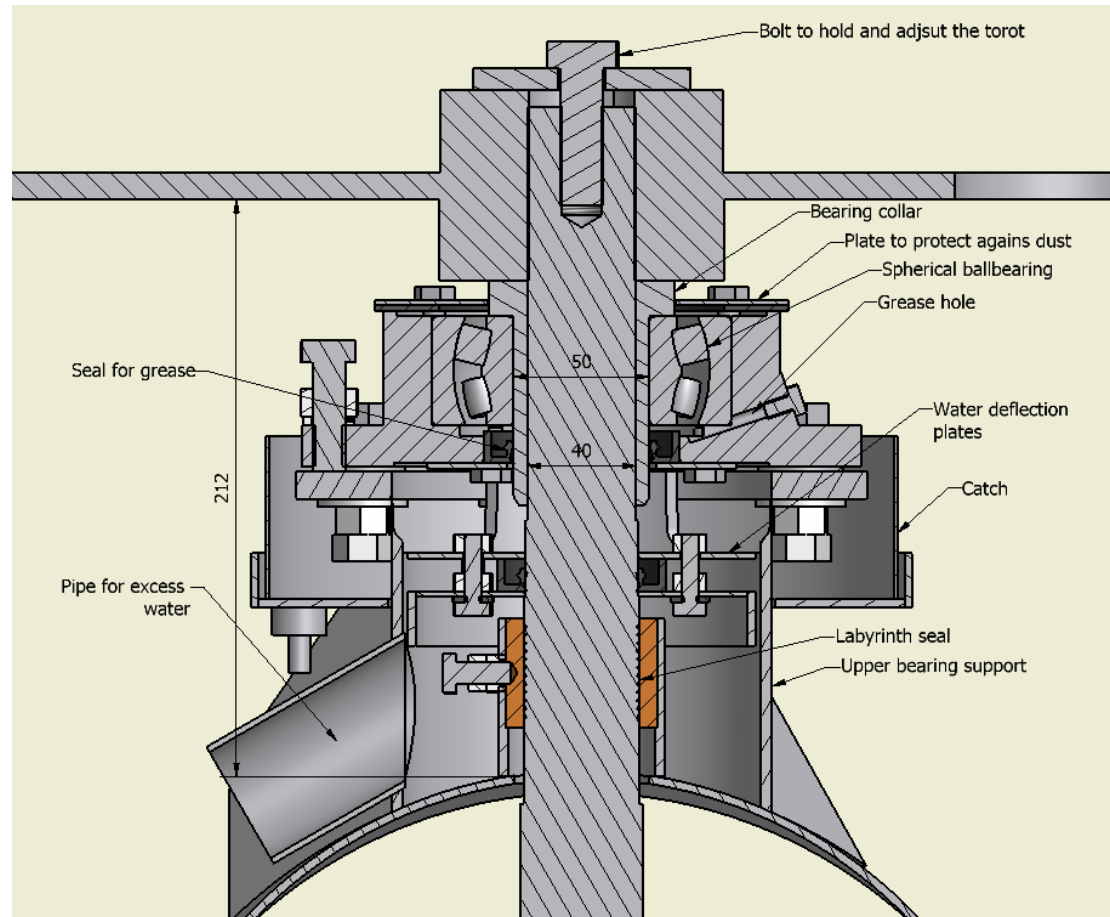


Figure 23. Upper bearing with seal assembly

The bearing is filled with grease from below the bearing. Since the grease that is available in Afghanistan is of low quality, it can become liquid at low temperature. A seal is used below the bearing so the grease does not run out when the bearing is warm. Under normal conditions the bearing get warm and it is not unusual to get 60° - 70° bearing temperature. The seal requires that the bearing collar is hardened; otherwise the seal will wear out the steel.

5.3 Rotor blades and guide vanes

Figure 24 shows the rotor blades and guide vanes. The pitch of the blades can rotate to 4 positions from lowest at position 1 to highest flow at position 4. Figure 24 shows the blade adjusted to position 3. To adjust the blades pitch, the two access doors need to be opened. The stainless steel bolts are first loosened some, the blade is repositioned, and then the 3 bolts are re-tightened.

Directly above the blades are the four guide vanes welded in the pipe made with a press from 2 mm steel plate. To keep organic material (straw, plants, etc.) from catching; the vanes were made flat on top (perpendicular to the shaft) and only four were used.

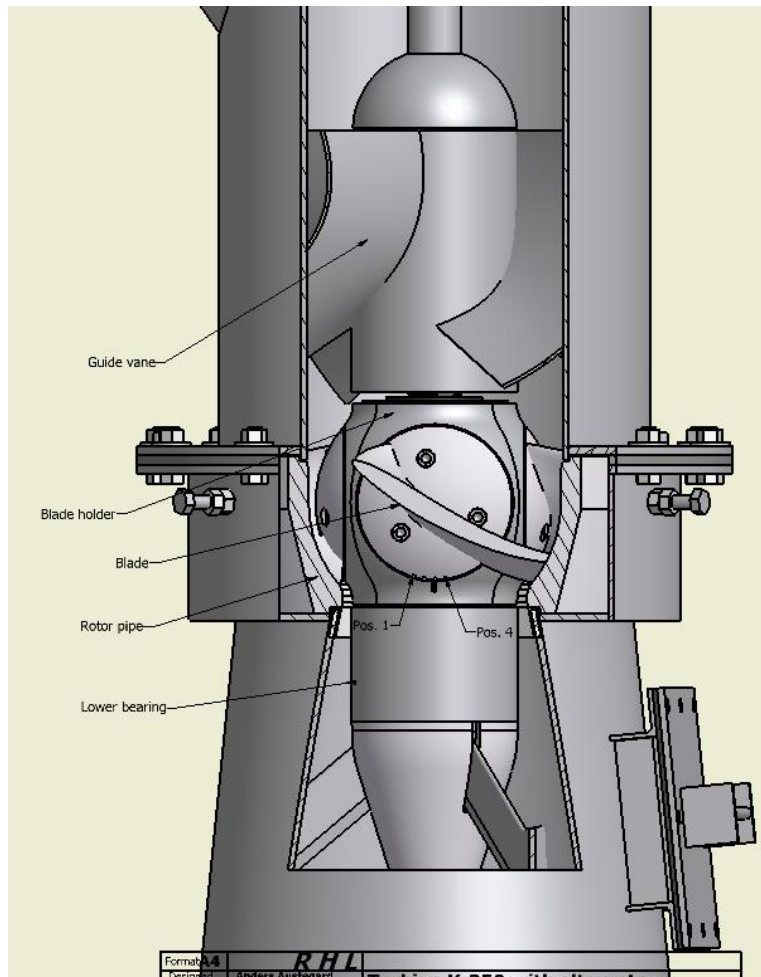


Figure 24. Blade with guide vanes.

The rotor blades are cast of aluminum. For a higher head site (5-6 m) where it is known that lots of silt/ will pass trough the turbine, the blades can be made from cast iron too. Cast iron is much easier to work with and results in a higher accuracy blade. The forces on the blade are limited and aluminum has proven to be more than strong enough and has good silt/sand resistance.

The blade holders are casted of steel that can be welded. In Afghanistan they mix iron with other materials so the melting temperature reduces and it can be cast easier.

This kind of cast steel is brittle; however, it can still be welded. Since the

adjustable blades rotate, the rotor pipe must be shaped spherical inside which is difficult to make in a lathe. The spherical surface can be casted accurately with aluminum in local casting workshops. Sand particles passing trough the turbine get pinched between the blade and rotor pipe causing wear on both surfaces. After some time the clearance grows to the size of the particle, then continues growing more slowly. It was determined by testing that cast blades wear more slowly than aluminum blades, however, they wear in high silt/sand conditions.

5.3.1 Calculating of flow around the blades

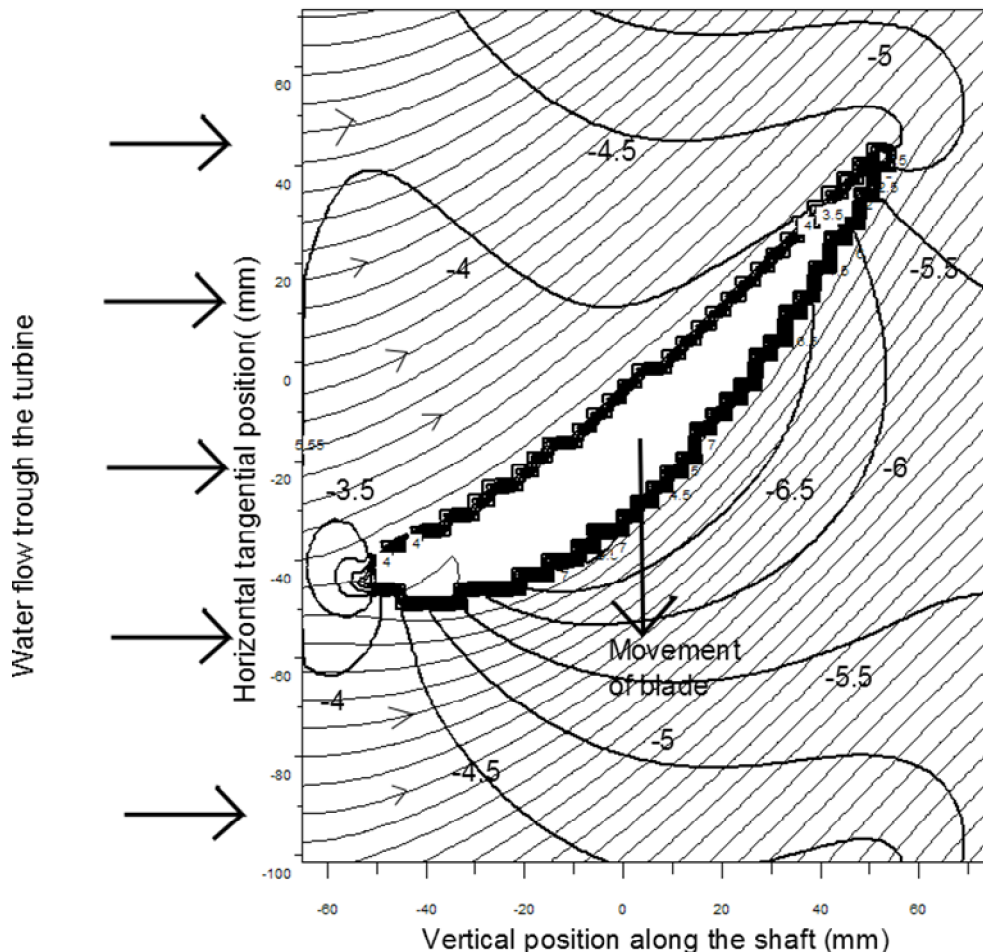


Figure 25. Calculated flow around the blade. The thin lines represent flow direction, the thicker lines with numbers represent the pressure.

To get the right shape of the blades the flow is calculated passing around the blades and in the boundary layer. Figure 25 shows an example of a calculation. The turbine is shown turned horizontal and the snap shot is taken following the blades. The calculations are 2 dimensional with spherical coordinates for a given radius, shown here near the mounting base. (The figure is some distorted at the front and back, but, correct in the middle) Calculations of the boundary layer show that separation occurs at the underside of the blade 6 mm from the end. For a profile at larger radius (slice further from the mounting base) no separation occurs.

5.4 Frame for alternator

It is expected that some Kaplan turbines will be installed by villagers themselves without outside supervision. Today many Crossflow turbines are purchased directly

by individuals and installed without any assistance. Figure 1 to Figure 5 shows the alternator placed in the frame that is part of the penstock. By having this standardized, errors in spacing, alignment, strength, and adjustment are eliminated. The prototype Kaplan had a separate cement pedestal for the alternator and it was difficult to make it correctly and keep the vibration down.

The Chinese alternator is made for horizontal mounting. For the Kaplan turbine it is mounted vertical which put additional axial force on the bottom bearing. A tapered roller bearing was installed, but, failed. Calculations showed that the small extra weight of the rotor on the bottom bearing was allowable. Testing has proven this to be a correct assumption.

6 Production of the turbine

The production of the turbine together with the order of the production steps is described together with the drawings.

7 Maintenance of the turbine

The Kaplan turbine must be maintained; otherwise it will not work after some time. The villagers are able to do the maintenance with proper training. It is important that they understand that the bottom bearing needs air.

Top bearing:

The top bearing must be greased regularly, one time each week. They should put in 10 grease pump strokes = 10 mL (10 cc) of grease. They should also check that the shaft is turning and has no horizontal movement.

Bottom bearing

The problem here is that too much grease stop the air flow and goes into the air cavity inside of the air cylinder (Part 1.01.15). This stops the air from going out and allows water to enter.

Fill two grease pump strokes (2mL) should be put in when the turbine is running one time each week. Then check if the air pipe is sucking air. If it is not sucking air try to pump air into the air pipe with a bicycle pump.

Cleaning the turbine

The Kaplan turbine can collect grass, leaf and branches. It is collected by the water guides (Part 2.03.4-6), guide vanes (Part 2.02) and the bearing support ribs (part 1.01.05). They must be cleaned regularly, and are accessed by two access doors in the turbine.

Even if there is a trash rack, some of grass is collected by the turbine. The turbine is made to minimize the collection of the grass, leaf and branches.

Variable:

- A $Q/h_N^{0.5}$ (See section 3.6)
- A Factor for loss in alternator (See section 3.8)
- A Area (m^2)

A_c	Cross section area (m^2)
B	Factor for loss in alternator (See section 3.8)
D	Pipe diameter (m)
c	Any constant
g	Acceleration of gravity, 9.81 m/s^2
h	Head, usually net head (m)
h_N	Net head, $(h_G - \Delta h_{\text{penstock}})$ (m)
h_G	Gross head, head difference between the water level in draft tube and water level in fore bay (m)
Δh	Difference in height, or head loss (m)
I	Current (A)
ID	Inner diameter (m)
k	Any constant
k_p	Pressure fall in penstock. $\Delta h_{\text{penstock}} = k_p Q^2$ (s/m^2 or $\text{m}/(\text{L/s})$)
k_r	Wall roughness in pipe (mm)
L	Length (m)
n	Rotation speed (Rev/s)
n_{QE}	Specific speed
OD	Outer diameter (m)
p	Pressure (Pa)
p_e	Environment pressure (Pa)
Δp	Pressure drop (Pa)
Δp^*	Pressure difference including the difference in head (See Appendix 1) (Pa)
P	Power, usually electric (kW)
P_{El}	Electric power (kW)
P_{Mech}	Mechanical power (kW)
PF	Power factor
ΔP	Loss (kW)
r	Radius (m)
r_o	Outer rotor radius (m)
r_i	Inner rotor radius (m)
Q	Flow (m^3/s or L/s)
$\underline{Q}$	Dimensionless flow = $Q/(r_o^2 \omega)$
Re	Reynolds number, dimensionless ($= \rho L u / \mu$)
u	Velocity (m/s) (Out)
U	Voltage (V)
v	Velocity (m/s) (Not V : $V = \text{Volum}$)
v_z	Speed downward (m/s), $Q = c_z A_c$
v'	$= \sqrt{2gh}$, velocity when all energy is velocity energy (m/s)
x	Any variables
RPM	Revolutions per minute
η	Efficiency
μ	Viscosity (Ns/m^2)
ρ	Density (kg/m^3)
π	$\text{Pi} = 3.1416$
ω	Angular speed (rad/s)
$\underline{\omega}$	Dimensionless angular speed = $r_o \omega / v_o$
Ω	Specific speed definition from Kjølle

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(Pipe friction: Colebrook and White
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Brand name

- Kaijieli Chinese, generators. STC Series, Synchronous Generators from Fujian Mindong Defeng Electric Machine CO., LTD China

Appendix 1: Dimension analysis:

The system is specified by the following input variable

r_o :	m	Outer radius of the rotor. One length scale that tell the size of the turbine.
Δp^* :	kg/ms ²	Pressure difference between outlet and inlet. $\Delta p^* = \Delta p + g\rho\Delta h$. Where Δp is pressure difference between inlet and outlet and Δh is head difference between where pressure is measured.
ω	s ⁻¹	Rotation speed (rad/s)
ρ	kg/m ³	Density water

The following variable has an effect, but is neglected:

μ	kg/ms ²	Viscosity, gives the Reynolds number. Have influence on the boundary layer and can give separation of the flow
p_e	kg/ms ²	Environment pressure, have influence when it comes to cavitation
..	m	Turbine geometry. Important, but we are here testing one turbine.

Then one have the effeciency (η)

$$\eta = f_1(r_o, \Delta p^*, \omega, \rho)$$

Have 3 dimensions: m, s, kg

With 4 input variables does one then get one (=4-3) dimensionless input variable.

For that variable is it a number of chooses, and the following variable is chosen:

$$\underline{\omega} = \frac{r_o \omega}{\sqrt{2\Delta p^* / \rho}} = \frac{r_o \omega}{v'}, \quad v' = \sqrt{2\Delta p^* / \rho}$$

v' is then the velocity one get when all pressure energy is changed to velocity energy.

For hydropower one usually uses head(h) instead of inlet pressure. $\Delta p^* = h_N g \rho$

where h_N is net head. Then one get:

$$\underline{\omega} = \frac{r_o \omega}{v'} = \sqrt{2gh}$$

Since we here only is using one turbine is r_o and g constant. In addition is one using unit RPM (Revelations/min) instead of ω . Then one uses variable $RPM/h^{0.5}$ instead of $\underline{\omega}$. Then one get for efficiency:

$$\eta = f_1(r_o, \Delta p^*, \omega, \rho) = f_1(\underline{\omega}) = f_2(RPM / \sqrt{h})$$

Similar one get for flow Q dimensionless variable:

$$\underline{Q} = \frac{Q}{r_o^2 u'} = k \frac{Q}{\sqrt{h}}$$

$$\Rightarrow \frac{Q}{\sqrt{h}} = g \left(\frac{RPM}{\sqrt{h}} \right)$$

This since r_o and g is constant.

Specific speed and other dimensionless variables:

Then one has one dimension.

$$\Omega = \frac{\omega}{v'} \sqrt{\frac{Q}{v'}} = \frac{\omega r_o}{v'} * \sqrt{\frac{v_z}{v'}} * \sqrt{\frac{A}{r_o^2}} = 1.466 * \frac{\omega r}{v'} * \sqrt{\frac{v_z}{v'}}$$

$$\Omega = n_{QE} * \pi * 2^{1/4} = 3.736 n_{QE}$$

(3)

This definition of specific speed is from Kjølle.

Crossflow:

$$\frac{\omega r}{v'} = 0.5, \frac{v_z}{v'} = 1.0, n_{QE} = 0.121 * \sqrt{\frac{b_0}{D_R}}$$

c_z : Velocity hen hittign the blades

APENDIX 2: Specific speed.

To divide between the turbines, one use specific speed. For two sites with same specific speed can one use turbines with same geometry but different size. Low specific speed gives low RPM, and s used for places with low flow and high head, high specific speed is used for sites with low head and high flow. Specific speed tells what turbine to use:

Different references give all different values for specific speed:

Two places with same

Two turbines with same specific speed will have same geometry but different size.

APPENDIX 3: Friction pipe

Friction in straight pipe

For pipe friction one can have head loss from dimension analysis:

One has the following variables:

Diameter: D (m), Roughness k_r (m), Viscosity μ (kg/m*s), Pressure fall Δp (N/m² = kg/s²m), v (m/s)

Then one can write pressure loss for a long pipe with length L :

$$\frac{\Delta p}{L} = \frac{f(Re, k_r / D) \rho v^2}{2D} \Rightarrow \Delta h = \frac{\Delta P}{\rho g} = \frac{f(Re, k_r / D) v^2}{2gD} \quad (3:1)$$

The pressure drop in a pipe is: $f(Re, k_r)$ one has the formula from Colebrook and White (Olson), for turbulent flow:

$$f(Re, k_r) = \left(1.74 - 2 \log_{10} \left(2k + \frac{18.7}{Re * \sqrt{f(Re, k_r)}} \right) \right)^{-2} \quad (3:2)$$

$$Re = \frac{\rho v D}{\mu}, v = \frac{Q}{A_c} = \frac{Q}{\pi D^2 / 4}$$

One then iterate to solve $f(Re, k_r)$

For a short pipe one get ends effect, described later. I

Friction in bend

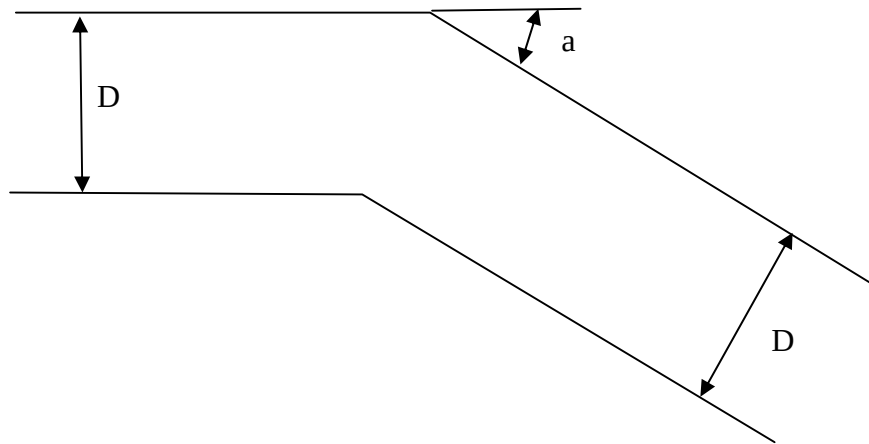


Figure 26. Bend in pipe

An approximation for pressure drop in sharp pipe bend can be found by extrapolating results from D.S. Miller:

$$\Delta h = \frac{k_b v^2}{2g}, k_b = k_{bo} C_t, v = \frac{Q}{A_c}, A_c = \pi D^2 / 4$$

$$C_t = \min \left(C_{t0}, \frac{k_{bo}}{k_{bo} - 0.2(C_{t0} - 1)} \right)$$

$$C_{t0} = \max \left(\frac{f(Re, k_r / D)}{f(10^6, 0)} - 0.3, 1 \right) \quad (3:3)$$

$$k_{bo} = \max \left(-0.3705x^2 + 0.3526x, -0.2079x^3 + 1.5897x^2 - 0.022x \right)$$

$$x = a / 100^\circ$$

Here a is the bending angle. k_{bo} : Is the friction coefficient from the bend, $f(Re, k)$ is the friction coefficient from pipe from wall friction defined in Equation (3:2). k_r is roughness of the surface.

It is actually a round bend with $r/d=0.5$ from D.S. Miller, and uses $C_t = C_{Re} * C_k$

$Re = \rho D v / \mu$ is the Reynolds number.

$f(Re, k_r / D)$ is the pipe friction and shown in Eq (3:2)

Loss in end

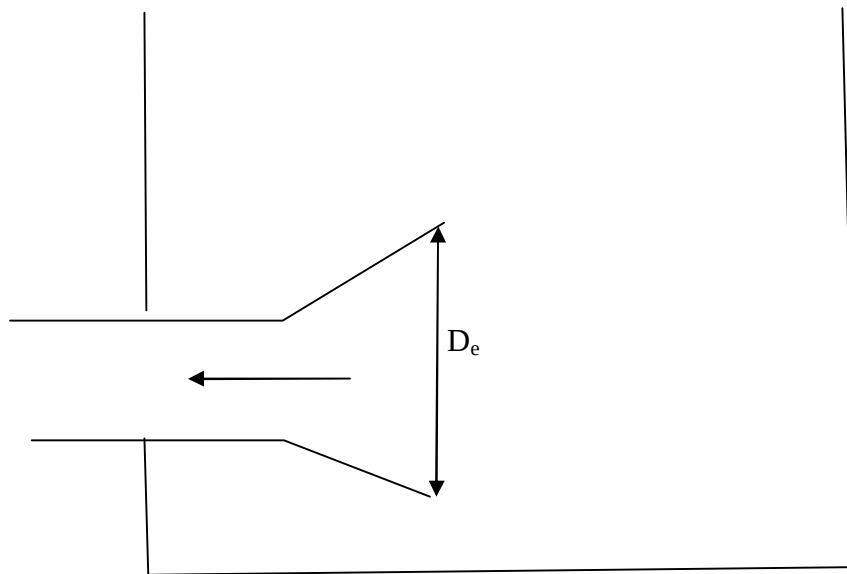


Figure 27. End of penstock

The end have area $A_c = \pi D_e^2 / 4$. For this case $D_e = 0.65\text{m}$.

This has pressure loss:

$$\Delta h_e = \frac{v^2}{2g} = \frac{Q^2}{2A_c g}, A_c = \pi D_e^2 / 4$$

APPENDIX 4: Example of calculation for Table 4. At 5 m gross head at blade position 2.

To show how the values at Table 4 are calculated it is here included an example with 5 m gross head at blade position 2.

From Table 2 one get $Q/\sqrt{h_n} = A = 134 \text{ L/sm}^{0.5}$. Where A is defined in Equation (11). From Equation(11) and that $k_p = 1.53 \cdot 10^{-6} \text{ m/L}^2$ one get:

$$q = \frac{\sqrt{h_G}}{\sqrt{1/A^2 + k_p}} = 132.2 \sqrt{h_G} = 295.6 \text{ L/s}$$

Loss in pipe: $\Delta h = k_p q^2 = 0.13\text{m}$ that gives $h_n = h_g - 0.13\text{m} = 4.87\text{m}$

Efficiency turbine is 83%, but reduced 3% as a margin = 80% Efficiency.

The mechanical power is $P_{Mech} = \eta q \rho h_n g = 0.8 \times 0.2956 \times 1000 \times 4.87 \times 9.81$
 $= 11298 \text{ W} = 11.3 \text{ kW}$.

It is 5% loss in belt so $\eta_{Belt} = 0.95$ so power to alternator is $11.3 \times 0.95 = 10.7 \text{ kW}$.

From Figure 16 one see that the 12 kW alternator have higher efficiency than the 7.5 kW alternator at 10.7 kW so the 12 kW alternator is used

From Figure 16 one gets an alternator efficiency of 0.83 at power factor of 0.8. This gives $10.7 \times 0.83 = 8.9 \text{ kW}$ electricity.

Summary:

What	Effeciency	Output power(kW)	Loss(kW)
Energy in the water, 5m, 295.6L/s	-	14.50 kW	
Loss in penstock	97.4%	14.12 kW	0.38 kW
Loss in turbine	80%	11.30 kW	2.82 kW
Loss in belts	95%	10.73 kW	0.57 kW
Loss in alternator	83%	8.90 kW	1.83 kW
Total	61.4%		5.60 kW