Design, CFD Analysis, Fabrication, Testing and Efficiency Evaluation of Low Head Pico-Propeller turbine Without Guide Vanes

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Abstract

As the demand of the increasing energy has reached its peak, a system that sufficiently and efficiently utilizes the majority of underutilized sites is required. Among those underutilized sites , one of the major energy-abundancy lies on low-water-head sites. There are estimated to be over 25,000 water mill sites across Nepal. It is thought that at least 20 percentage of these could be possible site for low-head pico-hydro units. So, pico hydro electrification will be one of the best ideas for tapping these clean energy sources . Most of the turbine used in Nepal is medium and high head turbine which is efficient only in the region where the availability of high head is possible. Low head turbine can used in the plain region where the energy can be extracted from the water source with minimum head available.

This article includes performance evaluation of the low head propeller turbine without using guide vanes.Input parameters include water head(H) of 3.5 meters , flow rate (Q) 20lps , and target rotational speed (N) 1500rpm . The study is also on the analysis of three runner and selection of constant thickness blade (without camber) runner with optimization of blade angle and hub diameter using computational study from ANSYS CFX 16.2. The analysis was done by flow analysis on the basis of pressure distribution across the blade through which torque is calculated. Constant thickness blade was selected on the basis of torque distribution with 12 deg blade angle and 80 mm hub diameter for the fabrication and testing. The testing was conducted with the measurement of torque using brake dynamometer. The prototype was tested at the part load of 0.615 and the resulting efficiency was obtained to be 44 percentage.

Effective operation of turbine with maximum efficiency requires much reduction of energy losses . So , the working head of turbine being very low and due to the fact that guide vanes energy losses are significant , the concept of exclusion of guide vanes was finalized.

Keywords

Propeller Turbine - Guide Vanes - Constant thickness blades – Runner

1. Introduction

1.1 Problem Statement

Due to the incompetent governance and lack of fund and technology, Nepal has been lagging behind on the field the production of clean hydro-power even though it has tremendous potential.   Also, because of unavailability of the national grid all over the country, many villages had not still been able to enjoy the facility of electricity yet. Their electrification by the means of national grid transmission line is almost difficult due to the geographical , economic and political status of the country . So, we should seek the alternative source of electricity for these remote communities. The best energy solution would be the pico hydro turbines to light up these areas.[1] [2] [3] Pico hydro plant is one of the best ideas for electrification there.The hilly and the mountainous regions of Nepal have sites with high water-head, so majority of the research and study works has been confined to the development of the efficient high head turbines in these regions. Enough study and research has not been done yet for the development of

the low head hydro plants for the Terai region where the head is considerably low but the discharge is significantly high.The low-head sites includes irrigation channels ,water canals etc . Until now, we have been discarding the huge water potential of the Terai region .

1.2 Need of Research

Low head hydro systems are simpler in design , low in cost , and robust . They need to be appropriate to the place where they are to be operated . Furthermore ,the prior requirements of a low head hydro plant are safety, reliability, and low cost. They require to be maximum safe during operation , resulting almost null hazards and risks , and also these require to be durable and reliable as that of large hydro-power plants . Also they must be convenient for repair and maintenance . [4] The design must be suitable for manufacturing in a local workshop, on a one-off basis. The cost, which involves entirely initial capital, needs to be minimized to a optimum level. Upon availability of suitable water resource , a well-designed low head hydro power plant becomes much cheaper and convenient on the basis of power production , if compared to other alternative renewable resources .

Turbine operation under low head possesses the problem of low speed .As the head decreases , the fluid velocity also decreases and so does the speed of the runner . Also as the head reduces , the flow of water must increase to produce the same output which eventually increases the runner diameter , which further decreases the rotational speed of the runner [4]. Low speed input to the generator cannot produce a standard frequency AC output , which is required for the operation of readily available electrical appliances . Hence a turbine with high specific speed is required , and the turbine with this feature is the propeller turbine[5]. But , propeller turbines are used for larger systems since their guide vanes and complex blade profile make them expensive for design and manufacturing .Hence there is crucial need of a simple and efficient propeller turbine that ensures the low cost of design , manufacturing and optimum utilization of the sites that have low water heads .

Energy losses before the entry of water to the runner must be reduced for better efficiency output , since maximum energy conversion is desired only in the runner section of turbine . Guide vanes energy losses

are significant because a reasonable amount of fluid energy gets lost due to striking of high speed water with the vanes . Minor energy loss in the form of contraction loss also takes place due to the narrowing of fluid flow in the vanes passage [6]. These losses accounts for the low efficiency of turbine since the input head is relatively too low , and any cases of energy loss within the system can be threatening . Furthermore , the complexity of guide vanes design and its manufacturing also makes the initial capital of turbine production to increase . Moreover ,the twisted and airfoil blade profile of the propeller turbine makes it difficult to manufacture at local level of expertise . Therefore , research on the field of simple and efficient propeller turbine design with better efficiency and low cost of manufacturing is required . Finally , propeller turbine with constant thickness blades with the exclusion of guide vanes was ventured as a possible solution initially .

1.3 Previous Work

Several works on low head propeller turbine are done . But ,relevant projects on turbine without guide vanes are not yet still found . Simpsons and williams [6] proposed a design theory for this kind of propeller design . Upon literature review , genuine test results of those turbines is not explicitly known .

1.4 Research objectives

The general objective of the research was to design, fabricate and test the low head Pico- propeller turbine in local workshop with low initial cost of fabrication . Followed by the general objectives , specific objectives includes

- Study, design and fabricate the optimized model.

- Use of closed volute casing without guide vanes and constant thickness blades in turbine .

- Test the prototype i.e calculate the overall efficiency and make comparisons between turbine with guide vanes and the designed prototype without guide vanes in terms of overall efficiency.

2. Methodology

Desk Study And Expert Consultation

Initially ,literature review on the relevant works of propeller system was carried out and study regarding the designing and fabricating of the propeller turbine at low cost with high efficiency was conducted. Group discussion as well as discussion with various experts in the field of small hydro technology was conducted for better understanding the problem and to get the best output.

Field visit and Market research

Field visits to various places were conducted to study the present scenario of pico-propeller turbine used in Nepal. Similarly field visits to some of the manufacturers of propeller turbine was made.The availability of various materials used for fabrication of the propeller turbine was analyzed by the market research. Similarly the demand of locally fabricated turbine at reasonable price was also analyzed.

Design, drawing and Simulation

The design of propeller turbine was done mathematically for 3.5 m head, flow rate 20 l/s and target rotational speed of 1500 rpm. Design guidelines from R. simpsons and Arthur williams was followed .Design for the shaft, bearings and keys were done separetely as per design guidelines of Shigley [7]. Softwares like Solid works and ANSYS CFX was used for design drawings and simulation respectively.

Fabrication

Fabrication of the turbine components was conducted as per design drawings . With the application of locally available appropriate resources , tools manufacturing process, the turbine was manufactured . Some of the components like bearings , water seal etc were purchased and some of the components were fabricated . Finally ,all the components were assembled .

Testing and analysis

The output parameters like speed, torque and overall efficiency were tested in the test rig available at laboratory of Center for Energy studies(CES), Pulchowk , Nepal . Comparisons were made in terms of efficiency among the turbine with guide vane and without guide vanes. Finally , Conclusions were drawn on the basis of test results and comparative analysis.

3. Design

Figure 1 shows the complete flow chart for overall design procedure of the turbine. The overall parameters for the turbine design were calculated using the spreadsheet suggested by R. Simpsons and A. Williams [6]. In the figure , n_q represents the specific speed of turbine , D represents the diameter and V_{w2} represents the exit velocity of water from blades.
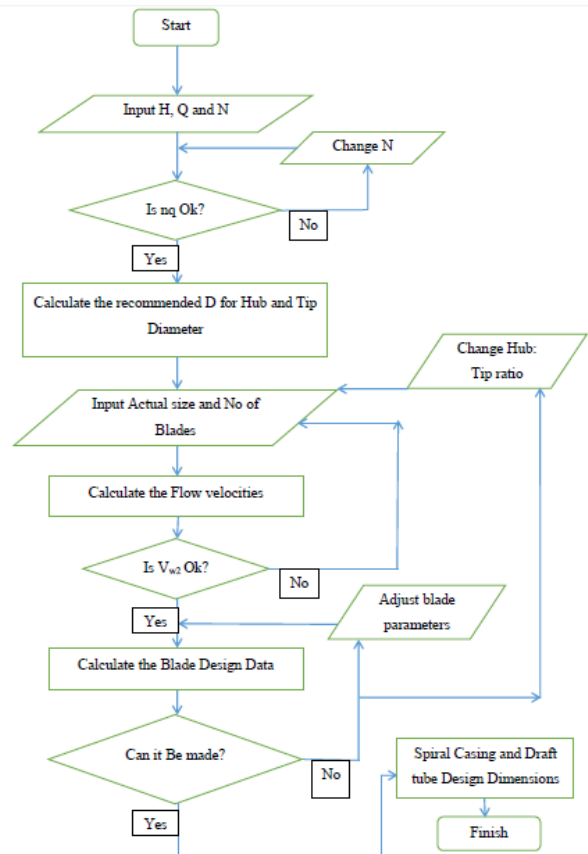

Figure 1: flowchart for overall design

Initially the design of the turbine starts with runner

followed by the blade design parameters and then the dimension of the scroll casing was calculated to give the correct swirl velocity to the runner inlet. Finally the draft tube was designed to recover the kinetic energy from runner outlet and also to maintain the uniform flow through the draft tube. This process was repeated for several iteration to obtain the best result with the dimension that was easy and suitable to manufacture accurately.

3.1 Runner design

Runner design , among the most important component of turbine design ,involves multiple steps.

Step 1

The first step was to select the key design parameters for propeller turbine i.e. Head (H), volume flow rate (Q) and rotational speed (N) for the design. Since the available turbine testing rig of CES provided a water head of 3.5m and flow of 20lps , these values were set as input parameters followed by the target rotational speed of 1500 rpm Then specific speed in terms of flow (n_q) was calculated which must be in the range of $70 < n_q < 300$ [5]

An estimate of hydraulic efficiency is required for determining turbine dimensions , which is a initial assumption . Based on the statistical data provided by Anderson , the estimated efficiency η_h was 78 percentage .

output power (p) = $\rho * Q * g * H$ =1000 * 0.02 * 9.81 * 3.5 * 0.78 = 535 W

specific seed on basis of power, $(n_p) = \dfrac{N\sqrt{P}}{H^{\frac{5}{4}}} = 229$

specific speed on basis of flow $(n_q) = \dfrac{N\sqrt{Q}}{H^{\frac{3}{4}}} = 83$ .These both falls on the range of the propeller turbine .

Step 2

This step involves the selection of recommended diameter for hub and tip of runner . For doing so, the graph based on efficient Kaplan turbine design by Will Bohl [8] is use to select the tip to head velocity ratio (K_{ug}), hub to tip diameter ratio (Dh/Dt) and the number of blades. From the graph appropriate value is chosen and use it to calculate the diameter. Given by empirical
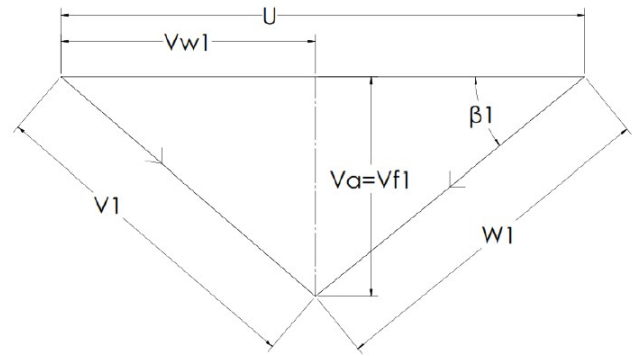

Figure 2: Blade inlet velocity Triangle

relation based on Demetriades thesis based on Bohl gragh i.e (K_{ug}) =-0.000005037 n_q^2+ 0.00647 n_p+ 0.651786 = 1.15 .

From the Graph , (Dh/Dt)= 0.7 - Input for Design

No of Blades (Z)= 5 - Input for Design

The equation for (K_{ug}) is given by

$$k_{ug} = \frac{r_{tip} * \omega}{\sqrt{2 * g * H}}$$

here ω is the angular velocity ie $\omega = \dfrac{2\pi N}{60}$. From the above equation , r_{tip} is calculated , and finally this gives the value of Dt i.e $Dt = 0.12m$. Further, from hub to tip diameter ratio , $Dh = 0.065m$.

step 3

This step involves the calculation of velocities of fluid at the entry and outlet of blade , blade inlet and exit angles . Figure 2 shows the velocity diagram of runner inlet whereas Figure 3 shows the outlet velocity triangle . V1 is the absolute velocity of fluid at the entry . Vw1 and Vf1 are the whirl component and Axial component respectively . The relative velocity makes an angle $\beta 1$ (blade angle at the inlet) with the tangential component V2, Vw2 , Va , and $\beta 2$ are the velocities and outlet blade angle respectively . U is the tangential velocity of blade , which is equal for both entry and exit sections . As it is a axial flow turbine, tangential or whirl component of velocity at outlet must be nearly equal to zero i.e our design suggest it to be 10 percent of inlet whirl component (Vw2= 0.1 Vw1)[5]
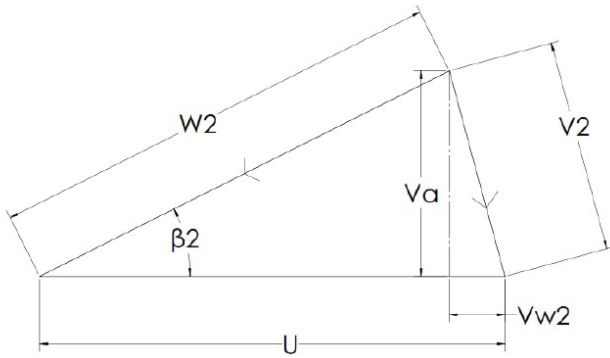
Figure 3: Blade outlet velocity Triangle

Using the Euler Turbine equation

$$g\eta_h H = UVw1 - UVw2$$

All the parameters were calculated respectively (Refer Appendix for the calculations). In the spreadsheet , the value of $V_{w1}r$ was input as a variable. An initial assumption for $V_{w1}r$ was given in the spreadsheet, based on the Euler Equation and assuming (as a first guess) that Vw2 is positive and is 0.1 of Vw1.

3.2 Blade Design Theory

Axial turbine rotor blades design requires the design of blades at the mean diameter of the rotor , with the radial variation of the parameters from hub to tip of the blade . Although not popular , free vortex law was used for the design of blades . The preliminary criteria to be fulfilled for this law are irrotational flow and constant axial velocity [9]. These conditions are genuinely met by the axial flow turbine i.e propeller turbine.

Free vortex law states that the product of tangential flow velocity and radius vector is constant . Since the radius vector goes on increasing from hub to tip , the whirl components gradually reduces . This causes fluid to enter each radial sections of the blade at different swirl angles . Furthermore , each radial section has different blade velocity (U) due to variation in radius . This results in variation of blade entry and outlet relative flow angles (β) [9]. Therefore , blade design requires analysis of as much radial sections from hub to tip as possible . For simplicity and convenience , three radial sections i.e Hub , Mid and tip sections parameters were individually calculated in the design of blades.

Blade length and shape
Numerous parameters for blade shape and length were calculated from the design spreadsheet available . These parameters include angle of attack (α) , thickness (t) , camber (m) , chord (L) , ratio of blade pitch to chord(x/L) , blade setting angle (β_{calc}), axial length of hub (L_{hub}) , arc radius (Rarc) , exxageration factor (δ) , co-effcent of lift (C_L), drag (C_D), solidity(S),and theta blade(θ) and theta ratio (θ_1). These were calculated at hub , mid and tip . Finally , three different types of blade profiles were designed : constant thickness with camber and twist , without camber and twist , and blade of variable width .

3.3 Spiral Casing Design

As the turbine was to be manufactured in local workshop with limited expertise of manufacturing constant height rectangular scroll casing was selected for design .The outer curve of scroll casing is in the form of archimedian spiral .If the inlet width of casing be L , inlet height be H and inlet velocity Vi respectively of spiral casing then it can have the following equation from equation of continuity ,

$$Q = L * H * Vi$$

(rectangular casing) The height of casing remains same within the spiral but the width goes on decreasing as proceed further with increasing angle of spiral . Also the velocity also remains same for the inlet condition of each blade and quantity of flow is decreased as per no of blades. The relation for inlet velocity is

$$Vi\alpha\sqrt{2gH}$$

$$Vi = K\sqrt{2gH})$$

where K is a design constant which was assumed to be 0.6.
Scroll Casing is now divided into 12 division maintaining the constant height (H = 85 mm) the length at each division is obtained keeping the constant flow through each region. Table 1 shows the variation of flow and length with respective to the progress of the spiral angle .

Table 1: scroll casing Dimension

Division at 30 degrre spacing	flow(Q)	Length(L)
0	20	50
30	18.33	46.19
60	16.67	41.19
90	14.99	37.79
120	13.33	33.59
150	11.66	29.39
180	9.99	25.19
210	8.33	20.99
240	6.66	16.79
270	4.99	12.59
300	3.33	8.39
330	1.66	4.19
360	0	0

3.4 Draft Tube Design

Draft tube recovers the kinetic energy of water at runner exit by converting the velocity Head of water to the pressure head . It further reduces the cavitation of turbine . A simple conical draft tube was designed. Table 2 shows the designed parameters.

Table 2: scroll casing Dimension

Flare angle (deg)	4
Height (mm)	1300
Inlet Diameter (mm)	124
outlet Diameter (mm)	153
Thickness (mm)	1.5

4. CFD Analysis and Optimization

The resulting design was simulated using Computational Fluid Dynamics (CFD). It included three steps preprocessing(specifiication of the boundary condition, solver(definition of convergence criteria and post processing (analysis of result) . Followed by simulation , optimization of blade angle and diameter of hub , was done using ANSYS CFX 16.2.

Two types of domain were created ; one fluid domain over which the water flows and another solid domain which rotates in the fluid domain as a immersed solid(see Figure 4 The mesh used for analysis is unstructured triangular mesh. Similar domain creation and mesh were used in all analysis done in ANSYS.
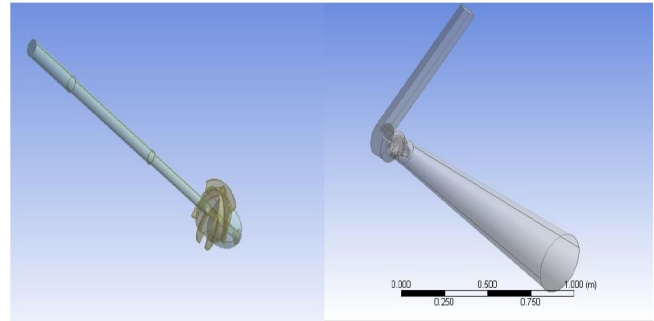

Figure 4: Fluid and solid Domain

Boundary condition is applied on the fluid domain(Figure 5). Inlet boundary condition is applied at the inlet of the scroll casing with the normal speed of about 4.669 m/s and outlet boundary condition is applied on the outlet of draft tube with static pressure of 1 atm. The water flow being in-compressible, the turbulence model K-Epsilon had been used for validation process. The maximum iteration was set to 100 with residual type RMS (root mean square) and the residual target of 1 E-4 for convergence of the solution.
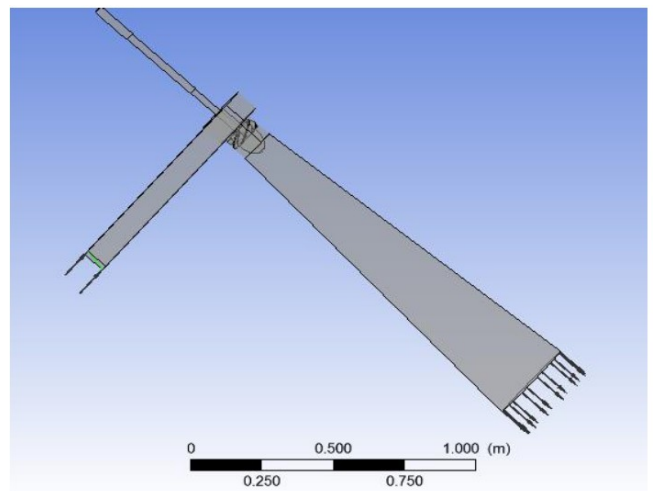

Figure 5: Inlet and Outlet boundary conditions

4.1 Simulation Result

Figures 6 , 7 shows the pressure distributions of two different types of runner respectively . These simulation result depicted the decrease in pressure at the blade passage,which is the principle of reaction turbines, thus simulating that turbine will properly operate even though guide vanes are excluded .
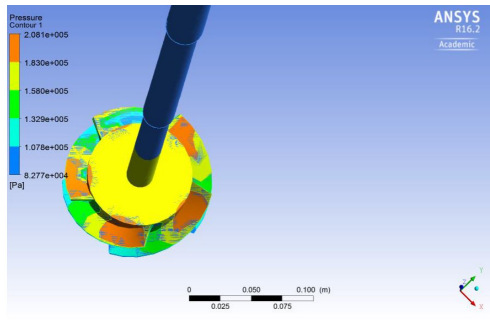
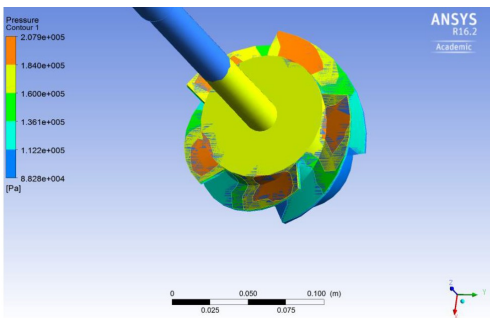**Figure 6:** Pressure Contour for runner with camber

Figure 7: Pressure Contour for runner without camber

The free torque and pressure variations of individual runners were simulated and from Table 3 ,runner with camber and without camber has nearly the same torque but as the runner with camber is difficult to manufacture , runner without camber was selected for further design.

Table 3: Torque and pressure variations comparison of runners

Runner type	P_{max}	P_{min}	Torque(Nm)
cambered	$2.081 * 10^5$	$8.277 * 10^4$	159.4
Not cambered	$2.079 * 10^5$	$8.828 * 10^4$	154
variable width	$1.740 * 10^5$	$8.482 * 10^4$	83.5

Optimization

The process was carried out by varying the blade angles from 5 degrees to 30 degrees , with the aim of obtaining maximum torque value . Figure 8 shows the graph depicting variation of torque with blade angle . Finally , optimum blade angle was found out to be 12 degrees .
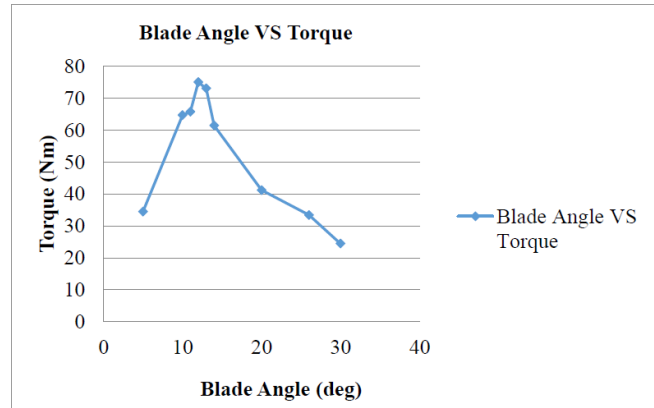

Figure 8: Graph of Blade Angle Vs Torque

Optimization of the diameter of hub was carried out to maintain the optimum hub to tip diameter ratio. For this , data was analyzed by varying the diameter of hub .From Figure 9, it was decided to use 80 mm diameter as an optimized hub diameter for fabrication and testing.
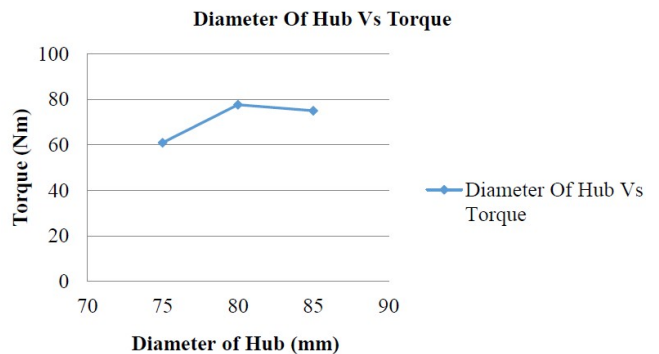

Figure 9: Graph of diameter of hub Vs Torque

5. Fabrication and Assembly

Fabrication of components was carried out in the local workshop with available machines , tools, processes and expertise . Material used for fabrication was Mild steel .

Runner The runner with constant thickness blade with no camber and twist was selected for final fabrication and testing. The cylindrical part was made through the help of the lathe machine and parabolic part of the runner made with point wise grinding of the part. The runner blade were first marked its dimension in 3 mm sheet metal after that marked dimension was cut through hand grinder in the required shape of the blade. After the hub and blade was ready, the blade was welded in the marked

position of the hub with help of arc welding and finally the runner was ready.

Spiral casing

This was most difficult part in fabrication process as there was no fabrication machine available for the spiral casing. So, it was approximated to the required shape through hammering and bending manually. The upper and below plate of thickness 4mm was cut to required shape by gas welding process and it was attached to the spiral part with arc welding process
Collar

Collar is the cylindrical shaped component where the runner of the turbine is kept . Collar was rolled to the required cylindrical shape with roller and then later attached to the scroll casing with arc welding process.

Draft Tube

As the roller was small and cone was about 1.3 m. So, the cone was divided into two part and then it was rolled differently into two frustum. The two frustum of the cone was joined with welding process.

Extender

This part was use to connect the rectangular part extrude from the casing to the rectangular part of the reducer. First, the each side rectangular was cut through sheet metal using hand grinder. Then it is welded with other rectangular parts to make a rectangular box.

Adapter

This part was made by hand fabricating with hammer and other tools. It is to use connect the cylindrical pipe from test rig to the rectangular pipe from scroll casing extender.

Bearing Block and Oil Seal Block

Cylindrical block with spacing for oil seal and bearing block were fabricated using lathe machine.

All the fabricated components were assembled finally . (Refer appendix for Assembly drawing)

6. Testing and Result analysis

Testing was carried out at CES laboratoey .Pressure gauge was used to measure the inlet head of water . Output brake torque(T) was measured using

brakedynamometer using spring balance . Speed of the turbine(N) was measured using tachometer . But , due to the malfunctioning of one among the three supply pumps , design flow rate was not obtained . So, the turbine was tested part at load conditions i.e flow rate of 12.63 lps (Q/Q_{max}=0.67).

At this test conditions , the output brake torque and RPM were calculated numerous times and the data were plotted in a graph for interpolation . Figure 10 shows the graph of correlation between output speed and torque . Figure 11 shows the graph of correlation between torque and output power.
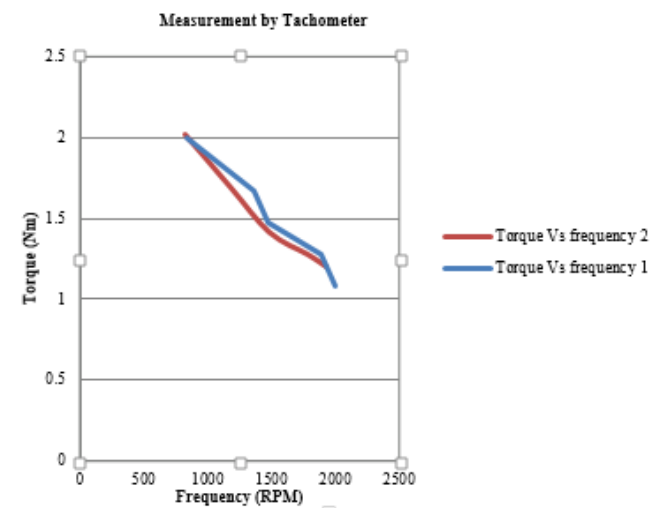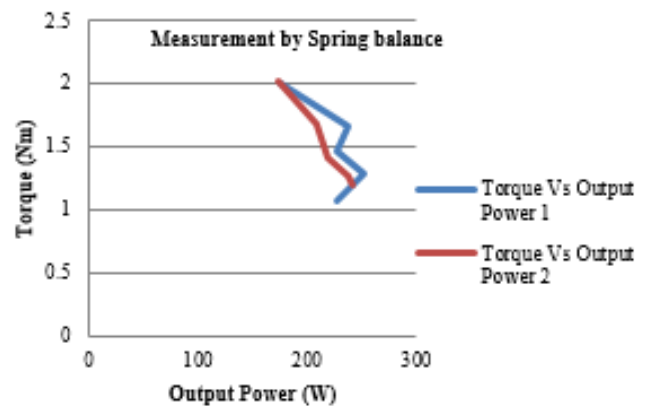

Figure 10: : Graph of RPM vs outpot torque

Figure 11: : Graph of RPM vs output torque

From the test data , the average shaft powerP_{shaft} was encountered to be 200 W.

Input power $(P_{in})= \rho * Q * g * H = 447$ w.

The overall efficiency of turbine is given by the equation [5]

$$\eta = \frac{P_{shaft}}{P_{in}} * 100$$

From the efficiency equation , the part-load efficiency of turbine was found to be 44 percentage.

From the available chart of part load flow $(Qo/Qmax)$ vs overall efficiency (η_o) for a fixed blade propeller with guide vanes [10], it was observed that the part load efficiency at flow 0.615 Q_{max} is about 50 percent . Efficiency from testing result of the turbine was found out to be 44 percent . This result concludes that the efficiency of a propeller without guide vanes is actually less than the efficiency of propeller turbine with guide vanes but remains tentatively in range of that of turbine with guide vanes.

The overall efficiency at full load cannot be estimated without proper testing procedure .Meanwhile, it can be understood that the overall efficiency of Pico propeller without guide vane is for sure greater than 44 percent ,since the partload efficiency is always less than the full load efficiency [11] [10].

7. Conclusions

The conclusions deduced from the project are summarized in the points below as

- There are numerous suitable sites for the pico hydro installation in Nepal. Pico hydro can be a suitable solution to harness such energy potential.

- Propeller turbine with a runner with constant thickness blade without guide vane was designed. The turbine was manufactured locally with low cost of fabrication and , limited manufacturing resources

- Upon testing, Part-load overall efficiency has come out to be 44 percentage . The full load efficiency , which requires proper testing , can be estimated to be more than 44 percent .

- This work has shown that a simplified turbine without guide vanes and simple blade design is technically feasible .

8. Recommendations

Some of the recommendations after completion of the project can be listed as :

- There should be proper test rig for different capacities of propeller turbine

- Series of study should be done to find the efficiency of turbine with twist and cambered profile

- Further study and dense research should be conducted to obtain the high level of efficiency

Acknowledgments

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Appendix

Detail Drawings
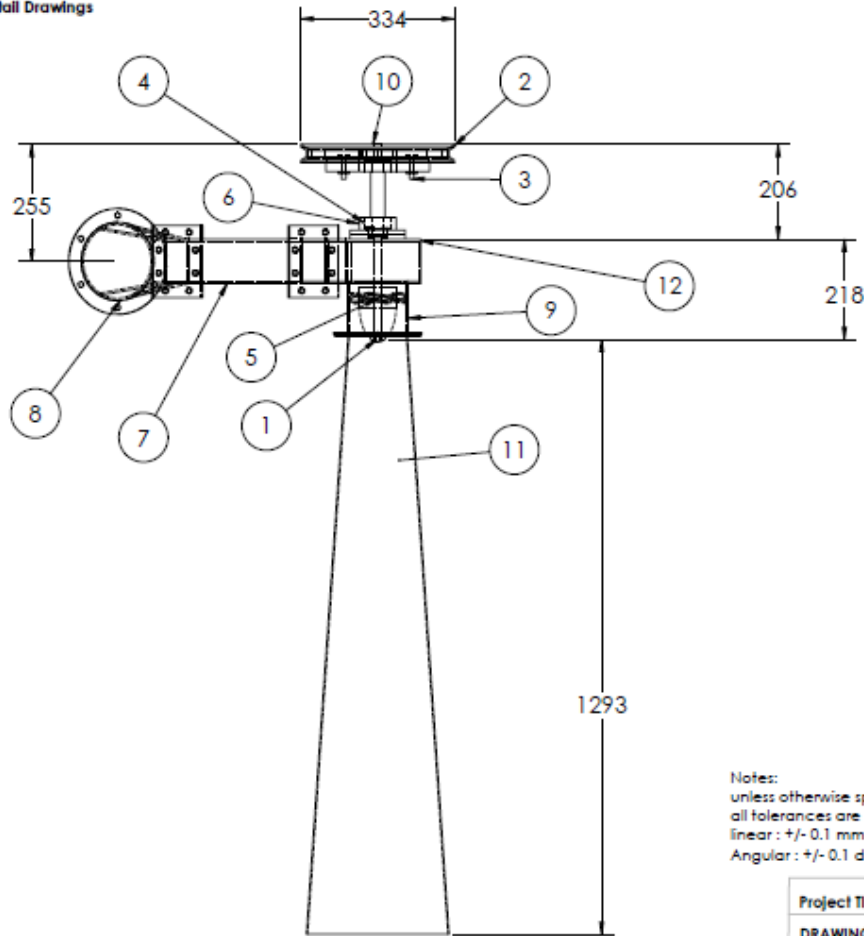
PART No.	PART NAME	MATERIAL	QTY.
12	Scroll Casing	Mild Steel	1
11	draft tube	Mild Steel	1
10	Shaft	Mild Steel	1
9	Collar	Mild Steel	1
8	Adapter	Mild Steel	1
7	Extender	Mild Steel	1
6	oil seal and bearing holder	Mild Steel	1
5	Runner	Mild Steel	1
4	Bearing	Stainless Steel	2
3	Upper Bearing Block	Mild Steel	1
2	pulley	Cast Iron	1
1	Bolt	Mild Steel	1

Notes:
unless otherwise specified
all tolerances are
linear : +/- 0.1 mm
Angular : +/- 0.1 deg

Project Title: low head propeller Turbine Group

DRAWING TITLE: Assembly drawing of Propeller Runner

SCALE	1:8	DWG SHEET NO. 1
Thapathali Campus,IOE,TU		
Dimension are in metric system		A3