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Advanced Composite Pelton Wheel Design and Study its Performance for Pico/Micro Hydro Power Plant Application

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Abstract*— Recently, Advance composite materials have taken the significant share with other engineering materials due to its mechanical properties and high strength to weight ratio. Advance composite like Carbon fiber, Kevlar are not confined at the aerospace industry but gradually these are taking over the position of other industries as well. Pelton wheel is a most efficient impulse turbine for medium and high head hydro sites. It is general practice to use brass/aluminum or some time stainless steel for the construction of Pelton wheel buckets. Manufacturing buckets with Advance composite materials is not yet common though it is light, durable and corrosion resistant. If we consider generating hydro power at micro or Pico level from Municipal utility service where corrosion is a great barrier for the turbine then advanced composite Pelton may be the very good option. Pico hydro is recognized as a viable option to electrify remote areas, considering economic, environmental, and social perspectives. Recent studies by the World Bank Energy Unit (The World Bank Group Energy Unit, Energy, Transport and Water Department, 2006) found Pico hydro yielded the lowest generating costs amongst off-grid energy options. Almost all over the countries of the world there are numerous micro or Pico hydro sites particularly at the hilly areas but suitable light pelton wheels are not remarkable. In this paper endeavor has taken to design and fabricate a pelton wheel where runner and 22 buckets have been designed and developed after careful analyzing the various parameters of Composite design criterion. Kevlar 49, Chopped Glass fibers have been used as reinforcing fibers with epoxy matrix for bucket design and manufacturing. Pelton buckets are peculiar in shape and anisotropic so force of water jet on bucket is analyzed. Buckets are designed as per lamination theory and symmetric laminates using $[0/\pm 45/\bar{90}]_s$ code. In this paper for visualizing the expected performance of the wheel a 10 storied tower overhead around 50,000 liters capacity tank has been chosen as the water source, galvanized 2 inch dia steel pipe act as penstock to conduct the test. Test has been conducted at the ground floor where single nozzle has been used at the wheel. Considering 100% efficiency generated power comes 2.793 KW but deducting total head loss and considering overall efficiency 60%, generated power comes 1.5 KW. The major parameters of the designed pelton wheel are (1) PCD 32cm, (2) Nozzle diameter 2.13 cm (3) RPM 668. Finally a deviation has been highlighted with practical outcome of the wheel.

Index Terms— **Pelton wheel, composite materials, Kevlar, Pico hydro, Torque, Chopped strand mat, wet lay up.**

I. INTRODUCTION

A Composite Material is a materials system composed of a mixture or combination of two or more micro- or macro-constituents that differ in form and chemical composition and which are essentially insoluble in each other. Composites involve two or more component materials that are generally combined in an attempt to improve material properties such as stiffness, strength, toughness, etc.; the resulting properties are largely dependent on the distribution, relative amounts and geometries of the constituents. Composites are considered to be combinations of materials differing in composition or form on a macro scale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another [1] Fiber-Reinforced Composites often aim to improve the strength to weight and stiffness to weight ratios (i.e. desire light-weight structures that are strong and stiff!). Fibers are available in 3 basic forms:

- Continuous fibres are long, straight and generally layed-up parallel to each other.
- ChoppedFibers are short and generally randomly distributed (fiber glass).
- WovenFibers come in cloth form and provide multidirectional strength.

Designing the pelton wheel with advanced composite composed of designing and fabricating several components of a complete wheel starting from designing bucket, runner, nozzle, shaft, casing to tailstock to discharge the water working on the bucket. For designing the buckets and runner of the wheel chopped strand mat of kevlar49 and chopped strand Mat of glass fiber have been used with epoxy resin as matrix. Laminate Staking sequence (LSS) has been followed as per the symmetrical hybrid laminates $[0_K/\pm 45_G/\bar{90}_K]_s$ code, Where suffix G, K and S represent Glass fiber, Kevlar and symmetrical respectively. Before designing the various parameters of bucket, runner, nozzle as well as other parameters of pelton wheel onsite (Ten storied Tower Over head water reservoir tank to the ground floor) available data has been practically measured to test the performance of the pelton wheel. Test has conducted at the Water resource Lab fixing a Nozzle at the outlet 2'' diameter pipes which travel from the overhead reservoir to the ground floor taking several turn and experiencing number of 90^0 bending. To calculate the mechanical power Torque and rpm of the pelton wheel have been measured. Finally before conclusion comparisons of theoretical data and practical data have been highlighted and possible causes and remedial measures have been drawn. Future scope of works on the composite pelton wheel also stated for whom who gets interest to work ahead and go beyond.

II. METHODOLOGY

Designing a pelton wheel with advanced composite and studying its performance weather it is suitable for Pico or micro hydro application needs some sequential steps to follow such as:

- Idea about pico/micro hydro power plant for medium and high head sites.
- Design guide of Advanced composite.
- Data accusation for Pelton wheel design modelling.
- Design and manufacture of Pelton wheel bucket
- Design of wheel runner and fixation of buckets to its periphery.
- Nozzle design.
- Shaft assembly design.
- Structure design with tailstock assembly.
- Development of a torque sensor.
- Conduct of onsite test of the Pelton wheel.

III. DESIGNING THE PELTON WHEEL

Important part of Pelton wheel is the bucket; it is subjected to erosion due to impact of steady water or chemically unsuitable water. Depending on head, flow rate, stiffness and quality of water pelton wheels are designed:

A. Idea about pico/micro hydro power plant for medium and high head sites

1) Classifying Pico hydro: Hydropower converts the energy in water flows to useful forms such as electricity or mechanical work. The scales of hydropower schemes cover a broad range and are generally classified by power output as in Table I [6]. Larger schemes generally require damming to create storage capacity and regulate water flow. Given the greater amount of power generation, they are typically grid connected to supply high levels of demand. At the smallest scale are so-called "Pico hydro" systems which generate no units more than a few kilowatts. Pico hydro systems may require water storage at a non-invasive level, or may be configured as run-of-river and not require any damming.

TABLE I: POWER OUTPUT CLASSIFICATION OF HYDRO POWER SCHEME

Classification	Power output
Large	>100 MW
Medium	10-100 MW
Small	1-10 MW
Mini	100KW- 1MW
Micro	5-100KW
Pico	<5KW

2) Pico hydro for development

Recent studies by the World Bank Energy Unit (The World Bank Group Energy Unit, Energy, Transport and Water Department, 2006) found Pico hydro yielded the lowest generating costs amongst off-grid energy options (Figure 1).

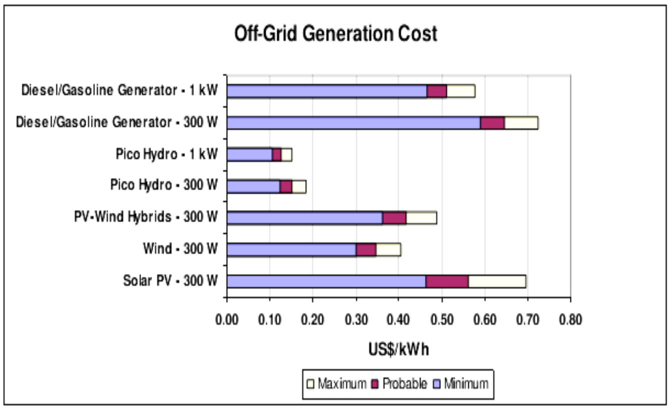

Fig 1: Off grid generation cost

Capital costs for renewable energy systems, including Pico hydro, tend to be higher than conventional fuel systems (Figure 2).

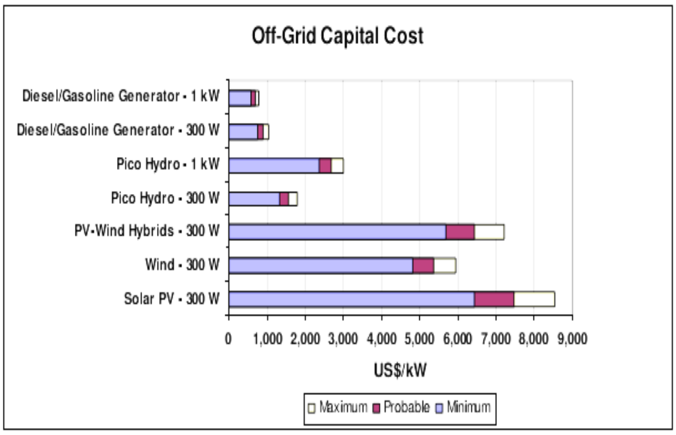

Fig 2: Off grid capital cost

A Test conducted by Pascale on life cycle analysis (LCA) comparing a 3 kW Pico hydro system, a diesel generator, and grid extension and connection for a rural village in Thailand. Measured impact categories included global warming potential, acidification potential, depletion of non-living resources, and energy demand, amongst others. The analysis found that Pico hydro had the lowest impact, by a significant margin, in all categories [7].

3) General Pico hydro principle:

Hydro energy is the term given to the process of extracting the potential energy from a flow of water over a height difference. The gravitational potential energy associated with the water is converted to mechanical energy that can be used directly or converted again into electrical energy by means of a generator. The power, P, which can be extracted from a water flow, is

$P = gQH\rho\eta$

Where η is the efficiency of the energy conversion system, Q is total volumetric flow, H is head (the actual height difference between the free surfaces of the reservoirs or channels upstream and downstream of a turbine), ρ is water density, and g is the gravitational constant (9.81 m/s^2).

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4) Pico hydro system components:
Pico hydro systems are composed of several components. They generally include the foreba, penstock, turbine, and the electrical system [10].

5) Pico hydro turbine for high and medium head:
For high/medium head and low flow applications, Pelton turbines are typically used due to ease of manufacture and maintenance and the adaptability to some variations in head and flow. Thake published a comprehensive manual for micro scale Pelton turbines covering theory, design, manufacture, installation, and maintenance [8]. Maher in collaboration with Nepalese and Colombian manufacturers extended this work for the Pico hydro scale with the "Pico Power Pack" design [9].

B. Design guide of Advanced composite

Advanced composite refer to the application where exceptionally good combination of strength stiffness and light weight are require. Advanced composite typically utilize boron, graphite or Kevlar fibbers in either a polymer or metal matrix and consequently have a much better strength and fatigue resistance than fiber glass or high strength alloys [2] For any fiber composite two main constituents are essential one/more fiber and matrix .Normally for advance d composite thermo set or thermoplastic resins are used particularly thermo set resin epoxy is used as matrix. Basing on the properties of the fibers as well as matrix following the role of mixture of the composite material products is designed. Kevlar is one of the most advanced synthetic fibers generally used in aerospace industry for its very high weight to strength ratio. Different type of Kevlar is available and basing on the applicability and property potential type of Kevlar 49 has been chosen. Mixing glass fiber with Kevlar49 reduces the cost of the product as well serve the purpose. Infect composite made of glass fiber, Kevlar49 and epoxy matrix produce a hybrid composite of elevated property above the glass fiber only composite but little lower than the kevlar49 only composite. The typical properties of glass fiber, kevlar49, epoxy matrix and their composite are furnished at the table 2[3] [4] [5] below:

TABLE II: TYPICAL PROPERTIES OF FIBER, MATRIX AND COMPOSITES

Fiber/Composite/Matrix Properties	Kevlar 49	Kevlar49/Epoxy	E Glass	E Glass/Epoxy	Epoxy
Specific gravity	1.45	1.38	2.54	1.85	1.2-1.3
Tensile Modulus ,GPa	131	75.8	72.4	39.3	2.75-4.1
Tensile strength. GPa	3.62	1.387	3.54	0.965	.055-.13
Elongation %	2.8	.016	4.8	.023	1.5-3.5
Flexural strength, MPa		1240		1020	124.1
Moisture Gain %	-	-	-	-	0.1-0.3

Basing on the properties of the fibers and matrix and considering the external forces on the product following steps may be followed for the design and manufacturing the final product of composite materials:

1) Selection of fiber, matrix and fiber and rasin volume fraction: Considering the manufacturability, ease of fabrication, availability, cost of the raw material, bonding strength, load what has to withstand by the product, life cycle of the composite strength to weight ration etc. constituents of the composite need to be selected

2) Selection of optimum fiber orientation in each ply (Lamina) and the LSS: A laminate is constructed by staking a number of laminas or plies in the thickness direction as unidirectional laminates, Angle ply laminates, cross ply laminates, symmetric laminates. From the standpoint of design as well as analytical simplicity symmetric laminates are commonly preferred over unsymmetrical laminates. The deleterious free edge effect in a laminate can be reduced through proper selection of LSS. In the following Figures [11] LSS for a Symmetrical laminates whose code is $[0/\pm\theta/\overline{90}]_s$ is shown:

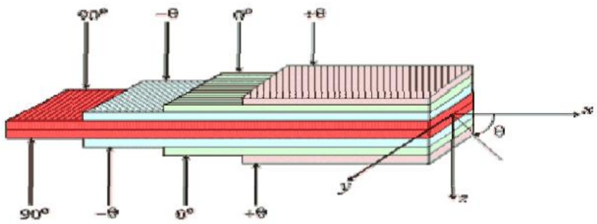

Fig 3: Orientation of the Lamina

TABLE III: LSS OF $[0/\pm\theta/\overline{90}]_s$ AND $[0_K/\pm45_G/\overline{90}_K]_s$

0	0^0 K
+θ -θ	$+45^0$ G -45^0 G
90	90^0K
90	90^0 K
-θ +θ	-45^0 G $+45^0$ G
0	0^0 K

3) Selection of number of plies needed in each orientation for determination of the final thickness of the product: Using the carpet plot for tensile modulus and tensile strength of particular composite of specific laminate family determine the ply ratio that gives minimum modulus in the axial direction and minimum allowable strength in the axial direction in case of symmetrical laminate family with 0 degree at the outer lamina orientation..

C. Data accusation for Pelton wheel design modelling

We have been selected our 10 storied tower building-1's overhead water reservoir as a source of water which flows down to ground floor gate valve through a 2'' galvanized iron pipe. For designing the size of pelton wheel with nozzle and other associated components following data shown in the table 3 have been measured:

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TABLE IV: MESURED PARAMETERS OF THE TOWER FOR PELTON WHEEL MODELLING

Parameters	Measuring units	Measured data	Remarks
Head ,H	meter	33.5	Gross head
Flow rate,Q	Litre/sec	8.5	
Velocity of the flow	Meter/sec	4.19	Pipe velocity
Diameter of the Pipe	Inch	2	
Loss due to 1xSudden contraction	meter	0.18	Total minor losses(T_M)=1.76 meters
Head loss due to 2xGate valve	Meter	0.78	
Head loss due to smooth bend 90^0	Meter	0.8	
Head loss due to roughness (GI Pipe)	Meter	$1.5\text{x}10^{-4}$	
Major loss H_L	Meter	1.18	Major Loss
Net H_n	Meter	31.5	

D. Design and manufacture of Pelton wheel bucket

Basing on the measured parameters of the tower first of all calculate the Jet velocity of the as well as optimum jet diameter of the nozzle. From the optimum jet dia, various dimensions of the bucket have been calculated as well as manufactured.

1) Designing the bucket: After calculating the dimensions of the bucket and analysing the forces on the bucket sketch of the bucket is made and necessary CAD drawing has been rendered for onward preparing the pattern as well as buckets .Following table and figure shows the details parameters of the Pelton buckets:

TABLE V: DIMENSIONS OF THE PELTON WHEEL COMPONETS

Parameters	Measuring units	Dimension
Jet velocity	Meter/sec	23.86
Jet Diameter	Centimetre(cm)	2.13
Flow rate through nozzle	M^3/sec	0.0084
Optimum Peripheral velocity	Meter/sec	11.18
PCD	cm	31.96
Force on Bucket	N	727
Bucket		
Width	cm	6.80
height	cm	5.75
Cavity depth	cm	0.72
Cavity width	cm	2.5
depth	cm	1.91
offset	cm	0.36
Bucket skin thickness	cm	1
Bucket stem length	cm	3.35
Inlet angle	Degree	3-7
Exit angle	Degree	
Point I		30-40
Point II		20-30
Point III		10-20
Point IV		5-16
Point V		0-5

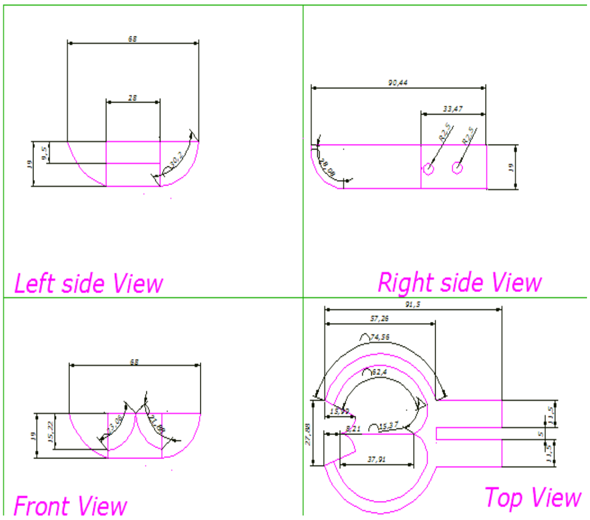

Fig 4: CAD rendered of pelton wheel bucket

2) Manufacturing of the Bucket: As per the designed CAD drawing and advanced composite manufacturing process first of all a wooden pattern has been made following the dimensions and adding a small amount of shrinkage allowance with actual dimension. E Glass Fiber, Kevlar 49 chopped mat and epoxy resin have been weighted as per the ratio of 30%, 30% and 40% respectively. Following the Rule of mixture the constituents are used for manufacture. There is various process of manufacture but hand lay-up process has been adopted for making buckets. Regarding the thickness of the bucket and strength of the bucket that supposed to sustain and neutralize the impact force of the water as well as other components of the forces Failure prediction in random fiber laminates has been analysed and symmetrical hybrid laminates $[0_K/\pm45_G/\overline{90}_K]_s$ has been followed as well as LSS also followed accordingly .The LSS is shown at the above figure 4. In the failure prediction Halpin-Kardos approach [12]estimate the ultimate strength of random fiber laminates is the same as ply –by- ply analysis used for continuous-fiber quasi-isotropic $[0/\pm45/\overline{90}]_s$ laminates. Impact properties of the composite also taken into cognizance before deciding the thickness of the buckets .Drop weight impact force and energy value of Kevlar 49/epoxy and E glass fiber/ epoxy are given at the following table:

Table VI: Impact Force and Energy Value Of E Glass and Kevlar 49 Composites

Material	Force/unit thickness,KN/mm	Energy/unit thickness/mm
Kevlar 49/epoxy 10 ply cross ply	1.16	0.284
E glass/epoxy 10 ply cross ply	2.90	0.789

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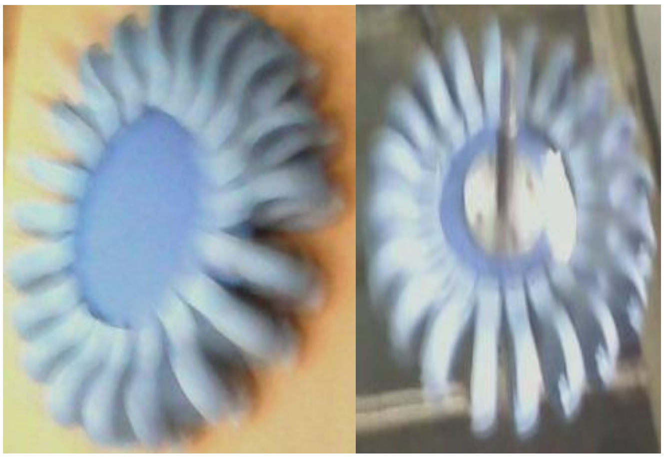

Fig 5: Manufactured Pelton wheel bucket

E. Design and manufacturing of wheel runner and fixation of buckets to its periphery

Basing on the calculated PCD, dimension of wheel runner has been calculated and same as bucket manufacturing process and taking into cognizance the same consideration of bucket design, runner has been designed and manufactured. Following CAD drawing shows the detail dimensions of the runner:

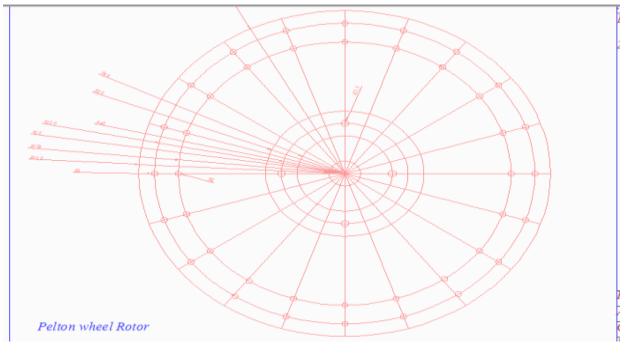

Fig 6: CAD rendered of Pelton wheel runner

Fig 7: Pelton wheel runner

F. Nozzle design

The nozzles focus and direct the flow of water so that it impacts the Pelton spoons at the PCD. The diameter of the nozzles is designed to provide a jet of water of the correct diameter at this point. A 14 degree straight taper nozzle was chosen for this design. Accord-ing to Thake, this nozzle design is thought to have the best discharge coefficient for Pelton applications [8]. The placement criteria of these nozzles is as follows:

- The nozzle exits have to be located as close to the Pelton wheel as possible to prevent the jet from diverging beyond the diameter designed for in the bucket calculations.
- The distance between the nozzle and the bucket should be 5% of the pitch circle diam-eter, plus an extra 3mm clearance.
- The distance between the center point of the nozzle exit and the pitch circle diameter,measured at a tangent to the pitch circle, should be between 50% and 60% of the pitch circle diameter.[13]

Dimensions of the nozzle is given below :

Table VII: Dimension of Nozzle

Parameter	Measuring unit	Dimension
Nozzle Diameter exit	cm	2.13
Nozzle Diameter entrance	Inch	2
Nozzle length	cm	10.03
Inner angle	Degree	14
Distance between bucket and nozzle	Cm	1.9
Distance between nozzle exit and PCD	cm	20
Speed of the nozzle	meter/sec	23.86

Fig 8: Nozzle of the Pelton wheel

G. Shaft assembly design and making

Shaft assembly include hubs, key, bearing housing with bearing etc. Shaft design may be carried out on the basis of strength rigidity and stiffness. In case of Pelton wheel shaft Only subjected to twisting moment/torque. Basing on the measured head, flow rate and overall efficiency 80%, Theoretical torque is 26.056 N-mm, accordingly diameter of the shaft become 1.5 cm. Following figure and CAD drawing of shaft with hubs are given below:

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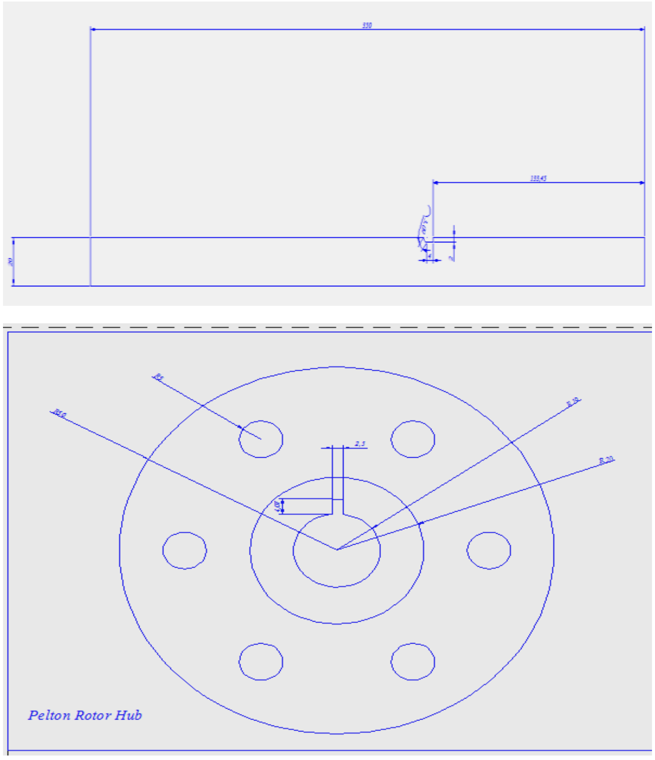

Fig 9: CAD rendered Shaft assembly

Fig. 10 Shaft assembly

H. Structure design with tail stock assembly

For smooth discharge of impact jet from the Pelton wheel a suitable structure has been designed and fabricated. A rectangular funnel has been fabricated for guiding the water from the Pelton wheel casing through the draft tube to the tail race. As thumb rule the width of the casing should be 30 times of the nozzle diameter.

I. Development of torque sensor

For measuring the torque of Pelton wheel shaft a digital torque sensor has been developed using a digital weighing scale. Load cell of the scale has been taken out and using belt pulley a torque sensor has been developed which can measure the torque up to 12 lb.-ft.

J. Conduct test of Pelton wheel

Several tests has been conducted at the site for testing the performance of the peloton wheel as a whole as well as impact force at the bucket of the wheel to observe the strength of the bucket and runner. Following data has been generated from the test:

TABLE VIII: TEST RESULT OF PELTON WHEEL

Test No	Parameter	Measuring unit	Output	Remarks
1	RPM		148	
	Torque	lb-ft	2.76	
	Flow rate	Liter/sec	2.1	
2	RPM		193	
	Torque	lb-ft	2.3	
	Flow rate	Liter/sec	3.4	
3	Torque	lb-ft	2.76	
	Flow rate	Liter/sec	4	
	RPM		290	
4	RPM		340	
	Torque	lb-ft	3.6	
	Flow rate	Liter/sec	4.5	
5	RPM		460	
	Torque	lb-ft	2.8	
	Flow rate	Liter/sec	7.5	

Fig 11: Testing Of Pelton Wheel

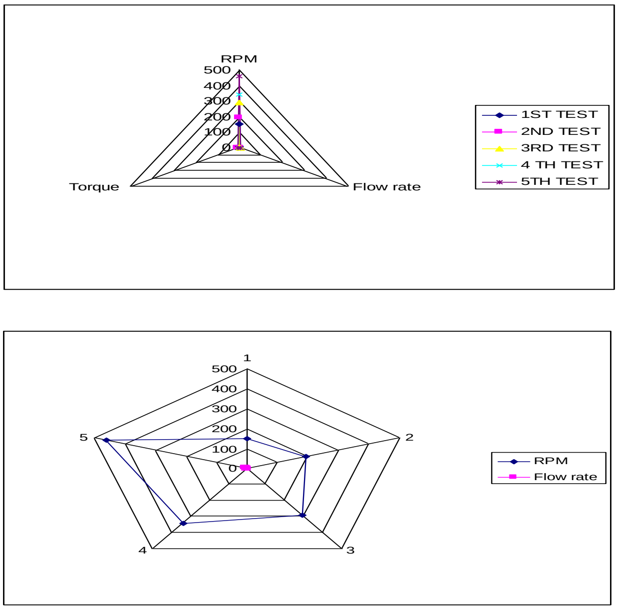

Fig 12: Relationship among rpm, flow rate and torque (top) relationship between rpm and torque (bottom)

IV. COMPARISION OF THEORITACL OUTPUT WITH PRACTICAL RESULTS

Practical output of the pelton wheel differs from the theoretical output such as the calculated torque was 26.12 N-mm but during 5 tests no such result was observer. Highest RPM was calculated 668 but at the time of test no such speed was observed:

Probable causes of deviation from the practical outcome:

- Torque sensor may not work properly as it has been developed and not calibrated.
- Casing of pelton wheel not sufficient to hold the water before discharging.
- Bearing may not work properly,
- Not using needle on the nozzle exit.
- Nozzle may not direct water properly on the cusp of the pelton bucket.
- Back pressure of the water due to less space at the casing
- Vibration of the structure
- Leakage of the water pipe before entering at the nozzle.

For overcoming the above mentioned causes following remedial steps may be taken:

Calibrate the torque sensor and compare the reading with other good torque sensor

- Casing should be robust and water sealed for sustaining and discharging water to the tail race through draft tube.
- Selection of appropriate bearing for setting the turbine shaft properly and smoothly.
- For controlling the flow and canalizing all the flow contents at the cusp of the bucket needle is require
- Proper alignment of the nozzle with the pelton wheel
- Draft tube should be wide enough to release the water instantly after striking on the buckets.
- Robust structure may be arranged to reduce the vibration
- Any type of leakage need to be stopped from the entire system.

V. CONCLUSION

Designing a pelton wheel with advanced fibers is a challenging task, proper selection of the fibers and matrix materials and following proper ply orientation and codes with LSS, a composite become a one of the strongest and high property material for turbine making composite pelton wheel can be effectively use at Corrosion enriched water site where metal wheel may eroded quickly and operation and maintenance will be challenging. In this paper sequentially we tried to highlight all the aspect of design criterion and finally deviation has been highlighted with stating probable causes and most likely remedial measure. Some recommendation as future works also included at the last for further go ahead for curious researcher.

VI. FUTURE WORK

Though designing an advanced composite pelton wheel is a new idea and hardly any work on this subject but still there are scope to work further, which not covered in this project like measuring the mechanical properties of pelton wheel bucket as well as runner as per the international accepted standard, LCA of the pelton wheel cost analysis of the pelton wheel, developing complete plug and play pelton pico power plant .Study the practical feasibility to installed at a real site and observe the viability for off grid application for rural people in the developing countries. Observe the property using natural fiber with some synthetic fibers etc.

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REFERENCES

[1] Department of Defence, USA,“Composite materials handbook”, mil-hdbk-17-5 (5), 17 June 2002.

[2] M.C Gupta, A.P Gupta., Polymer composite. Chapter 4, Design properties of composite and composite system. New age International (P) Limited Publishers 2005.

[3] P. K. Mallik, “Fiber Reinforced Composites materials, Manufacturing and Design, Chapter 2, Material.” Marcel Decker Inc. 2nd Edition 1993.

[4] Derek Hull, “An Introduction to composite materials, Chapter 1,2,3,4,8,9” Cambridge University Press,Cambridgre 1981.

[5] Prof. A K M Masud,” MSc Engg Lecture note on Composite materials” IPE Department, BUET Dhaka, 2012.

[6] Williams, A., & Porter, S. “Comparison of hydropower options for developing countries with regard to the environmental, social and economic aspects”. International Conference on Renewable Energy for Developing Countries, Washington DC, USA.2006.

[7] Pascale, A., Urmee, T., & Moore, A. “Life cycle assessment of a community hydroelectric power system in rural Thailand”. Renewable Energy, 2011, 36(11), 2799-2808.

[8] Thake, J. “The micro-hydro pelton turbine manual: Design, manufacture and installation for small-scale hydropower. London: ITDG Publishing.2000.

[9] Maher, P., & Smith, N” Pico hydro for village power.”2001.

[10] Paish, O. “Micro- hydropower: Status and prospects. Proceedings of the institution of mechanical engineers part a-journal of pp., 216, 31-40.2002.

[11] Dr P M Mohite ,Lecture note on AE-681 “Composite Materials, “ Aerospace Engineering Department,IITK,India.

[12] J C Halpin and J L Kardos, “Strength of discontinuous reinforced composite: I. Fiber reinforced composite “.polymer Engg Science, 18:6, 1978.

[13] Xenco, “Micro hydroelectric design “AITG Guatemala 2006.